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Resource-orientated Analysis of Metallic Raw Materials

Findings of CRC 525 for Aluminium

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Materie und Material
Matter and Materials

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Content

FOREWORD

Since the adoption of Agenda 21 in 1992, sustainable development is the most popular guiding principle with regard to the future of mankind. Although the concept gains increasing recognition in science, politics and business it is still very difficult to be interpreted, resulting in a large number of different interpretations. Therefore, a necessary precondition when dealing with the concept is the formulation and usage of a deap and interdisciplinary knowledge of ecological, economic, social and institutional cohesions.

The complexity as well as the inherent conflicts between the different sustainability fields complicate the evaluation of different measures and decisions that could be characterised as sustainable. Basic understanding is somewhat different between varying actors and therefore responsibilities to implement a sustainable development path are difficult to allocate.

As a matter of fact, necessary steps prior to the formulation of options for action are the analysis of the status-quo, of its driving forces, and of scenarios. Areas under investigation differ and include for example countries, regions, economic sectors, material flows as well as products. With regard to specific metallic raw material flows it may be said that the concretisation of the guiding principle is no longer in its infancies, but that further activities are necessary.

The CRC 525 *Resource-orientated Analysis of Metallic Raw Material Flows* has contributed to the concretisation of the guiding principle Sustainable Development for nonferrous metals. It aimed to identify options for the resource-sensitive supply and use of metallic raw materials.

The results of CRC 525 depict how complex a concretisation is, when taking into account conditions and characteristics like intra- and intergenerational equity, strong and weak sustainability, stakeholder participation, management rules etc. Nevertheless, the publications included in this compilation bring to light relevant sustainability aspects from different point of views. All contributions are closely related to aluminium flows and add to a clearer but inevitably not final assessment of how sustainable metallic raw material flows should and could be put into practice.

W. Kuckshinrichs
P.-N. Martens

November 2003

COLLABORATIVE RESEARCH CENTRE 525

RESOURCE-ORIENTATED ANALYSIS OF METALLIC RAW MATERIAL FLOWS -DESIGN OF METHODS AND THEIR APPLICATION-

1 Introduction

The Collaborative Research Centre (CRC) 525 "Resource-orientated analysis of metallic raw material flows – design of methods and their application" was established from January 1997 to June 2003 by the German Research Council (DFG). The long-term goal of the research program was the identification of options for a resource-sensitive supplying and processing of metallic raw materials, taking into account technical developments and economic as well as ecological aims. Important sub-goals were the design of an integrated resource management system for important metallic raw materials and the test of this management system with regard to the applicability as useful and efficient tool for decision makers.

The challenges of sustainable development facing the minerals and metals industry require a comprehensive, integrated and multi-disciplinary approach based on shared decision-making, close co-ordination and co-operation, a reliable information base, and the consideration of the competing interests of all shareholders including aspects of intra- and inter-generational equity. The integrated approach of the CRC 525 offered the opportunity to address and cope with these challenges by supporting sustainable development-based decision-making.

The research program focused on selected non-ferrous metals. In the first phase (1997 – 1999) the analysis concentrated on aluminium and aluminium alloys. In the second phase (2000 – 2003), additional to the work on aluminium, copper was included into the resource-orientated analysis of metallic raw materials.

2 Scope of the Analysis

The scope of analyses carried out by the CRC 525 reached from deposit valuation to extraction of mineral resources over processing and smelting to manufacturing and utilisation. The recycling processes for supplying secondary resources ensuing the use phase were also analysed and assessed as an integral part of the raw materials supply. Transportation processes, processes of energy supply and utilisation or disposal processes of the most important waste flows arising in any of the sub-processes along the entire process chain were included in the investigation. This procedure made it possible to analyse the influence of the technical process chain on the environment as well as economic and social aspects.

The complexity of interdisciplinary questions arising from such a topic were taken into account when selecting the participating scientists and the scientific institutions and by choosing close and co-operative working methods.

The CRC 525 was divided into 9 sub-programs with 12 participating institutes of the University of Technology Aachen and 1 programme group of the Forschungszentrum Jülich. The thematic link-up between these 9 sub-programs is represented in figure 1.

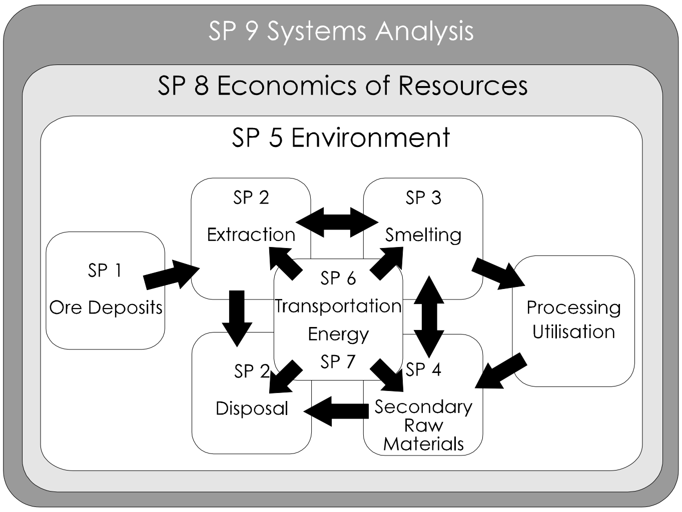

Figure 1: Link-up of the sub-programs of the CRC 525

3 Design of an Integrated Resource Management System

In the first phase (1997 - 1999) preliminary work was conducted on the design of an integrated resource management system. The developed framework was deepened and put in concrete terms in the second phase (2000 – 2002) by means of adaptation and application of the different methodological approaches. The integrated resource management system (figure 2) was based on practical experiments and computer-aided tools, which can be divided into:

- sub-program-specific information systems
- an overall information system
- sub-program-specific models
- overall process chain models and economic models

The tools supported the detailed inventory of the status-quo of the material flows of metallic raw materials. The description of the state-of-the art was carried out for:

- processes (e.g. a comparison of different electrolysis processes),
- products (e.g. an inventory analysis and an environmental impact assessment for different aluminium foils in the packaging sector and for aluminium for passenger vehicles),
- product systems (e.g. an analysis of the effects of the substitution of unalloyed primary aluminium by alloyed secondary aluminium considering open and closed loop recycling processes),
- industrial sectors (e.g. an analysis of the global distribution and merchandising of aluminium).

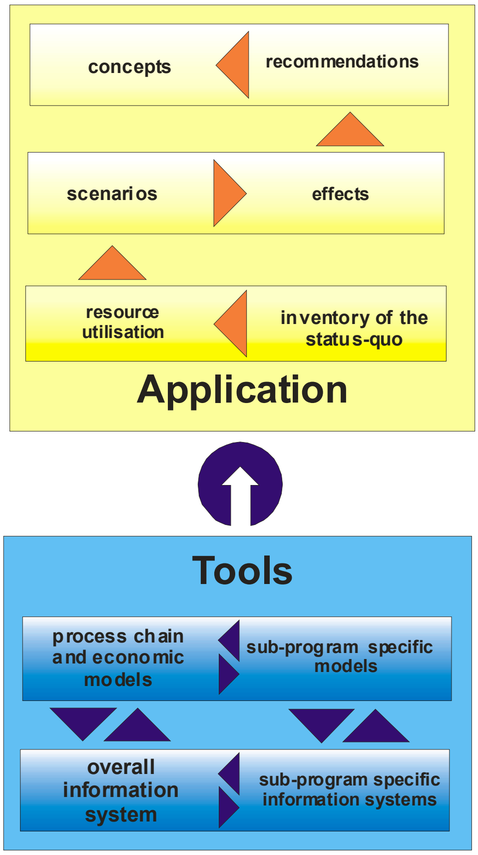

Figure 2: Design of an integrated resource management system

Main focus of the attention was always placed on the resource utilisation of materials, energy, environment, work force and capital.

Starting from the inventory of the status-quo and the analysis of the corresponding resource utilisation, scenarios were designed, comparing reference path of technical and organisational progress with goal-orientated paths considering external interventions, i.e. by political decision makers. The potential effects on the material flows, on the energy utilisation, on the location choice of mining and processing plants and on the resource productivity were examined for all scenario designs.

The results of the investigations were discussed with representatives of the scientific community, of industrial associations, of main companies and other relevant interested parties. Following the discussions conclusions were drawn and recommendations for a sustainable supplying and processing of primary and secondary metallic raw materials were given. The recommendations had either a normative, an operational or a strategic character. The proposed options for decision making deriving from the conclusions and recommendations were regarded as starting points for goal-orientated concepts in terms of a sustainable utilisation of metallic raw materials. The concepts were meant to be practice-orientated, adequate and as far as possible consensual. The resulting instrument claimed to consider the competing interests of directly and indirectly involved actors.

4 Results for Aluminium

The design of the computer-aided tools and the methodological approaches of the framework was completed for aluminium. On this basis the status-quo was worked out in the first phase of the project (1997-1999). Preliminary trends and scenarios were elaborated based on the inventory analysis and the set of tools was used for further simulations.

In the second phase (2000 – 2003) the description of the state-of-the-art for aluminium was concluded. The inventory of the status-quo was adapted by integrating the use-phase, the environmental impact assessment and the resource-orientated evaluation into the process chain analysis. Further scenarios were be designed from which conclusions and recommendations as well as options for decision making were drawn.

To a large extent the single tasks were be dealt with by Ph.D. students. Their results and the work of other participants of CRC 525 were published in numerous scientific papers on aluminium as conference papers, book chapters, and contributions to a wide range of national and international scientific journals, which for the most part were peer reviewed. For single publications, overlaps of the content could not be avoided. This is due to the long duration of the project and, especially, the inter-disciplinarity of most of the work, which made revisions of findings necessary.

A selection of the most important publications was compiled to be re-published. In a certain sense, this compilation serves as a special report of CRC 525 on aluminium, giving access to a wide range of information on aluminium from a single source.

5 Acknowledgements

Thanks are due to the German Research Council (DFG) for financial support of the project as well as the German Aluminium Association (GDA) for financial and moral support of special studies on the use of Aluminium.

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Sub-programs of CRC 525

SP 1 Ore Deposits: *Institute of Mineralogy and Economic Geology, University of Technology Aachen*

SP2 Extraction, Mineral Processing and Disposal: *Institute of Mining Engineering I, University of Technology Aachen*

SP3 Metallurgy: *Institute for Process Metallurgy and Metal Recycling, University of Technology Aachen*

SP4 Secondary Raw Materials: *Institute for Processing and Recycling of Solid Waste, University of Technology Aachen*

SP5 Environment: *Department of Engineering Geology and Hydrogeology, Department of Physical Geography and Geoecology, University of Technology Aachen*

SP6 Transportation: *Institute of Mining and Metallurgical Machine Engineering, University of Technology Aachen*

SP7 Energy: *Institute for Nuclear Reactor Safety and Nuclear Technology, University of Technology Aachen*

SP8 Economics of Resources: *Institute for Technical and Economic Co-operation, University of Technology Aachen*

SP9 Systems Analysis: *Systems Analysis and Technology Evaluation, Research Centre Juelich*

RESOURCE-ORIENTATED ASSESSMENT OF BAUXITE-QUALITY -EFFECTS ON ALUMINA PRODUCTION-*

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ABSTRACT

Bauxite is by far the most important raw material for the production of alumina and aluminium and, thus, its abundance, distribution as well as mineralogical and chemical composition greatly influences the mass flow involved with alumina production. As the quality of the bauxite ore, in general, is highly variable between individual deposits, for a global scale material flow analysis, the geological characteristics of individual deposits have to be established in a first step. Based on this data, world-wide material flows induced by the current bauxite production are investigated by employing information from more than 70 bauxite deposits. Integration of additional data from nearly 80 sites that are still in an exploration status allows the analyses of possible future scenarios for bauxite supply and resulting material flow. Comparison of the present situation with potential future scenarios indicates a possibly unfavourable trend for bauxite-quality and, thus, an increase in related mass flows.

KEYWORDS

Bauxite, geology, ore deposit, alumina

* Source: Traveaux du Comité international pour l'étude des Bauxites, des l'Alumine (ICSOBA), Vol 26, 1999, No. 30, 12th International Symposium of ICSOBA, S. 97-105.

1. INTRODUCTION

In 1997 the ‘Deutsche Forschungsgemeinschaft (DFG)’ (German Research Foundation) has established at the University of Technology Aachen (RWTH) the Collaborative Research Center 525, entitled ’Resource-Oriented Analysis of Metallic Raw Material Flows’.

Main objective of research is the development of methodologies for a resource-sensitive utilization of metallic raw materials within the framework of economic, environmental and social constraints.

In an initial phase, the program focuses on the analysis of material flow associated with bauxite and aluminium production. The evaluation of geologic characteristics of bauxite deposits and their effects on subsequent technical processes represents the first step in this analysis.

Geologic factors have a great influence on the aluminium production cycle and, therefore, the evaluation of typical characteristics of bauxite deposits and their effects on subsequent technical processes is considered of great importance. This requires a global, quantitative assessment of the distribution and quality of bauxite resources differentiated into various quality grades. Based on such analyses the adequacy of bauxite supply can be evaluated through the assessment of historical and present production figures as well as potential future trends.
The present study, in particular, is concerned with the development of methods for a mine-scale, regional, and global evaluation of bauxite-quality and related material flows. Therefore, several steps of investigations have to be performed:

1. selection of geologic criteria relevant to alumina production (e.g. the chemistry and mineralogy of the ore)
2. selection of critical indicators for the assessment of bauxite-quality (the bauxite-to-alumina ratio and the red mud-to-alumina ratio)
3. global analyses of the bauxite, alumina and red mud flows
4. assessment of possible future material flows resulting from bauxite production

2. DISTRICT-SPECIFIC BAUXITE-QUALITY

Currently, eight major bauxite districts account for nearly 80% of the world bauxite production (Fig. 1). The quality of bauxite occurring in these regions is controlled by specific geologic factors, such as chemistry and mineralogy of the ores. Thus, the amount of alumina and waste produced during the processing of bauxite from a distinct district is mostly a given fact and can only be optimized through technical processes.
Figure 1 serves to demonstrate the importance of normalizing bauxite raw data to dry-bauxite before comparing production figures from different sites. The deviation of the amount of dry bauxite from the crude bauxite, in some cases, can account to more than 20 % by weight and differs from region to region.

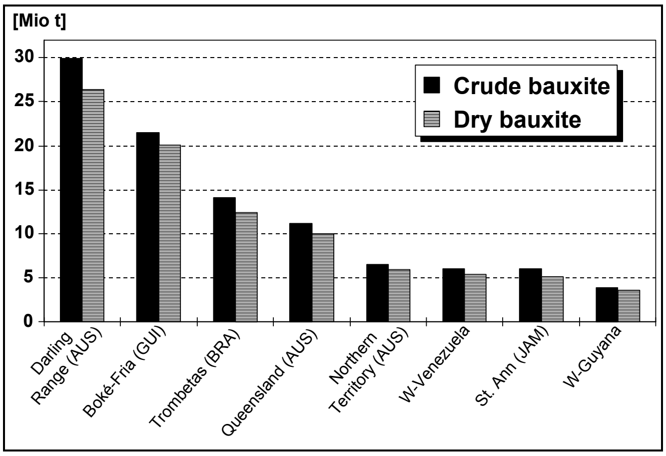

Figure 1. Annual production of eight major bauxite districts accounting for nearly 80% of the world production.

Figure 2 compares, for eight selected world-class bauxite districts, two parameters that determine the material flow involved in the processing of bauxite, e. g. the mass of bauxite and resulting red mud. The amount of bauxite needed to produce one ton of alumina and, thus, the resulting amount of red mud varies considerably for each deposit or district. This is an expression of the highly heterogeneous site-specific chemical and mineralogical characteristics of bauxite ores. Therefore, a global analysis of material flows using average data for a great number of deposits results in significant errors and misleading interpretations. Thus, an important step in the assessment of global material flows is the calculation of bauxite-quality for each deposit first, and following that, the data can be aggregated to a global model.

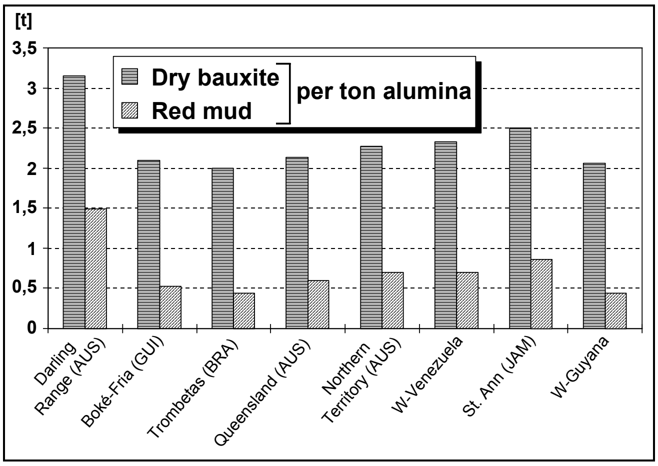

Figure 2. Bauxite required and red mud produced per ton of alumina for eight selected major bauxite districts.

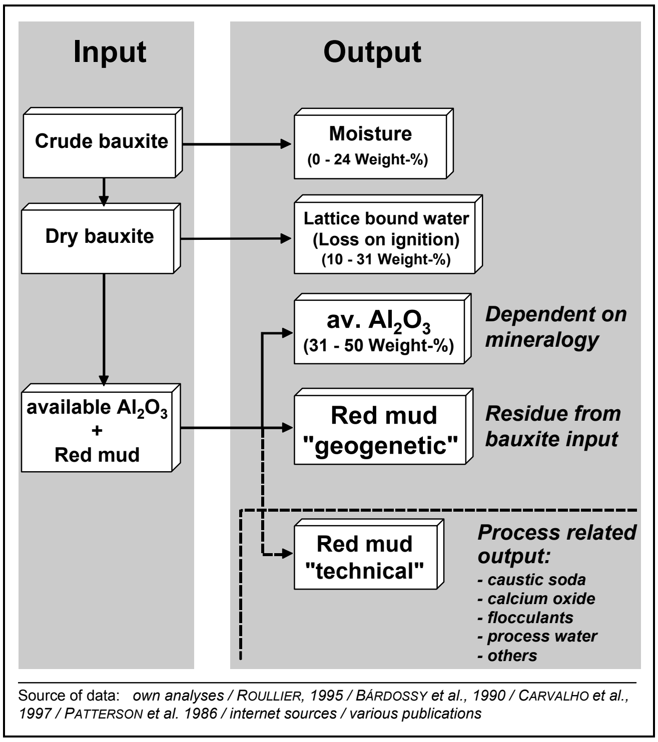

Figure 3. Calculation scheme for the amount of alumina and red mud that turn out during alumina refinery using chemical and mineralogical data.

2.1 *Calculation scheme for material flows*

Information about material flows, starting from single deposits are often not available and, thus, have to be calculated using chemical and mineralogical data of the ore. For the present study, a computer-aided mass flow analysis was performed on nearly 60 operating mines and 25 non-operating deposits on a world-wide scale.

Figure 3 illustrates in a flow sheet the calculation of bauxite, alumina and red mud quantities. In a first step, the amount of dry-bauxite is calculated by subtracting the moisture-content from the crude bauxite. Subsequently, the mass of lattice bound water (combined water), given by the LOI-content (loss on ignition), is subtracted from the dry bauxite. The remaining mass consists of the available alumina and a solid residue termed ‘geogenetic red mud’. The term ‘geogenetic’ indicates that this portion of red mud results from the bauxite input only.

The process-related „technical“ red mud which consists mainly of caustic soda, calcium oxide, flocculants, process water and others is not considered in the following assessments. However, the quantity of geogenetic red mud represents by far the highest portion of the total red mud.

2.2 *Indicators for bauxite-quality*

Based on the site-specific data two indicators can be used to illustrate bauxite-quality and resulting material flows (Table 1):

- the amount of dry-bauxite required to produce a certain amount of alumina (**bauxite-to-alumina ratio**). For the 61 bauxite deposits considered here, these ratios vary between 1.8 to 3.2, with an average value of 2.3.
- the amount of red mud resulting from the production of a certain amount of alumina **(red mud-to-alumina ratio**). These values range considerably from 0.3 to 1.5. That means, that in some cases the amount of red mud is higher than the quantity of alumina obtained from the bauxite.

Table 1. Ratios used for indicating bauxite-quality and resulting material flows.

	operating mines, n=61		
Ratio	**Min**	**Max**	∅
Bauxite / Alumina	1.8	3.2	2.3
Red mud / Alumina	0.3	1.5	0.7

The bauxite-to-alumina ratio is mainly a function of the amount of available alumina in the bauxite ore, but is also controlled by the digestion temperature of the Bayer-Process. The red mud-to-alumina ratio is also a function of the available alumina and, in addition, of the combined water content. The contained water, however, is mostly lost during the Bayer-Process and, thus, does not add to the mass of the resulting red mud.

3. GLOBAL ASSESSMENT OF BAUXITE-QUALITY

The supply with alumina or aluminium, respectively, requires the extraction of bauxite and produces a considerable quantity of waste material. The global amount of these materials depends on the quality of bauxite extracted from deposits operating at a certain point of time. Although the commencement and closure of mines is a continuous process on a global scale, material flows can be regarded as constant over short- and mid-term periods.
In the following, global material flows are evaluated using the quality indicators discussed in the previous chapter. The analyses is performed for the present bauxite production, but also considers possible future trends.

3.1 *Present bauxite production*

Figure 4 illustrates bauxite-to-alumina ratios of ore extracted from currently operating mines worldwide. The data are grouped according to the deposit type, i.e. karst bauxite versus lateritic bauxite. It can be shown that, on average, the bauxite-to-alumina ratios of lateritic bauxites are higher than those of karst bauxites. Further, the range of values is also higher. This trend can be explained by the generally lower content of available alumina in lateritic bauxites.

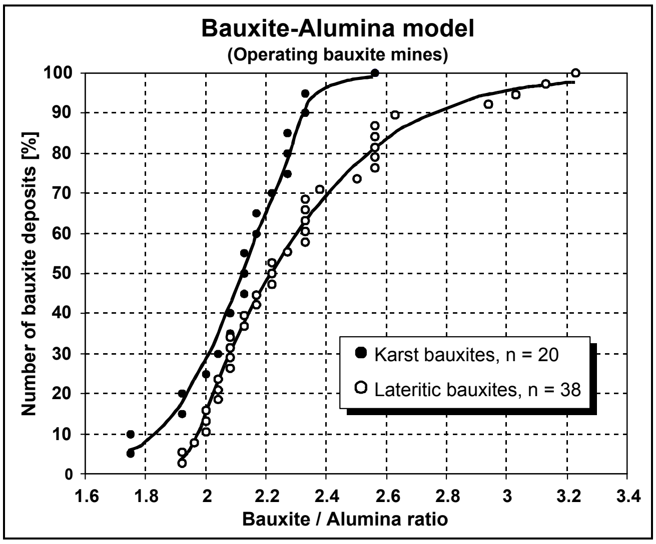

Figure 4. Global quality model (Grade model) for operating bauxite mines worldwide. Comparison of the Bauxite-to-Alumina ratio for two major deposit types.

In detail, the red mud-to-alumina ratios of lateritic bauxites are lower than those of karst bauxites for nearly 70% of the deposits, but can be very high for the remaining 30 % (Fig. 5). The reason for this increasing trend of a relatively small number of deposits, is based on the fact that in some districts bauxites with a very low content of available alumina are extracted and, thus, distort the global pattern.

In general, global quality models show significant deviations for lateritic bauxites and karst bauxites. This illustrates the necessity to take geological criteria into consideration for a global material flow analysis.

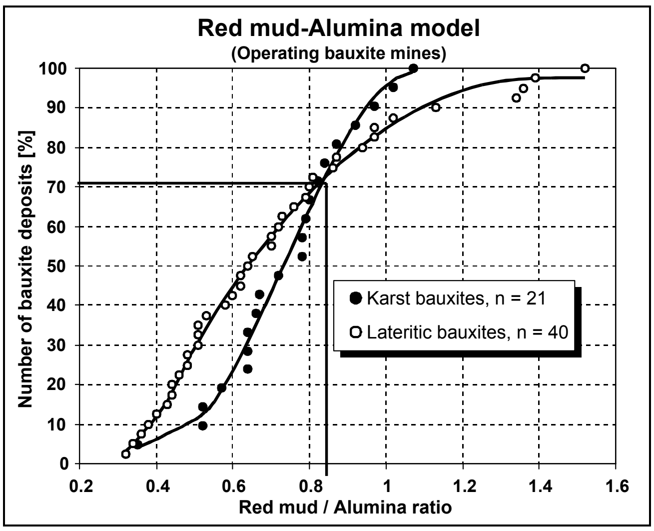

Figure 5. Global quality model (Grade model) for operating bauxite mines worldwide. Comparison of the Red mud-to-Alumina ratio for two major deposit types.

3.2 *Implications for future trends*

The global bauxite-alumina model discussed above uses available information for currently operating mines and, thus, represents material flows that occur at present or expected to take place in near future. At present, almost half of the world's known bauxite reserves are contained in deposits that are not yet in operation, but still in an exploration phase (Fig. 6). Therefore, bauxite supply and related material flows that can be expected to occur within the next decades will probably originate from these deposits.

For a prediction of potential changes of bauxite-quality in the future, bauxite occurrences with different operation status have to be compared.

Analogous to the analyses above, an assessment of possible future material flows of bauxite reserves contained in operating deposits and non-operating deposits is carried out using the quality indicators introduced in chapter 2.2.

Figure 7 compares bauxite-to-alumina ratios of operating mines with deposits that are currently in a feasibility or exploration status. It can be seen from the model that, on a global scale, bauxite-to-alumina ratios of non-operating deposits are significantly higher compared to those of currently operating mines. This suggests a potential reduction of bauxite-quality in the future, or in other words, even by keeping bauxite demand constant, the world total bauxite supply has to be increased considerably to cover the demand for alumina and aluminium.

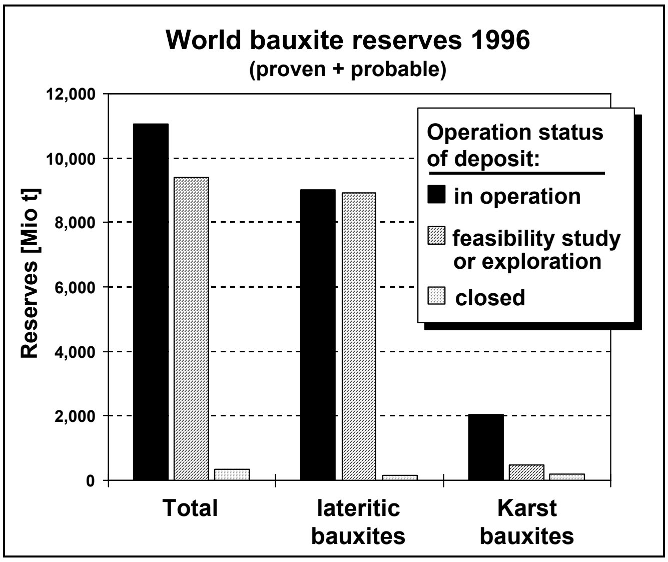

Figure 6. World bauxite reserves distinguished by the operation status of the deposits.

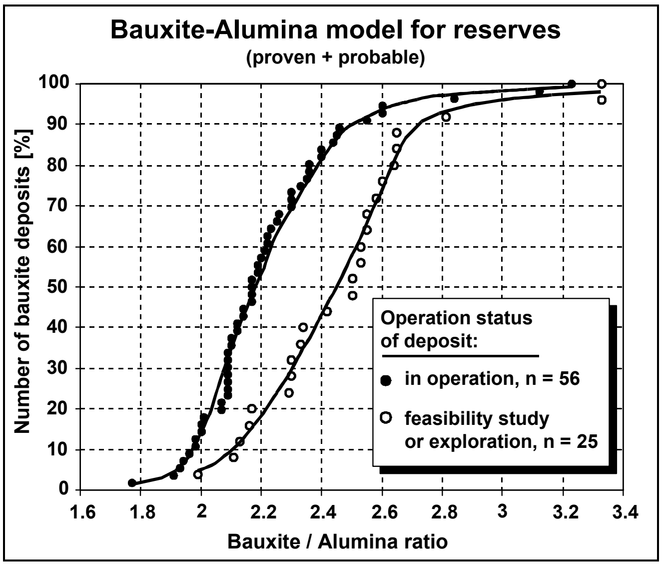

Figure 7. Global quality model (Grade model) for bauxite reserves worldwide. Comparison of the Bauxite-to-Alumina ratio for operating and non-operating deposits.

The red mud-to-alumina ratios show similar trends for both data populations (Fig. 8). Several of the potential future deposits are characterized by lower red mud-to-alumina ratios than the bulk of the currently operating mines. This suggests that an optimization potential exists for future material flows. From a geologic point of view, it can be concluded that by employing a careful selection of mine sites in future, bauxite-quality can be kept constant or even increased.

On the other hand, as emphasized by the global trends shown in figures 7 and 8, available bauxite-quality may decrease in future, if geologic criteria are neglected for site selection. For that reason, a resource-orientated analyses of potential future bauxite deposits is highly recommendable.

The global trends in bauxite-quality presented in this study are, of course, not the only decision-making criteria that have to be taken into account for a complete assessment of a deposits feasibility. But the present study represents a methodical approach for a complete assessment of single deposits in the global framework of bauxite supply.

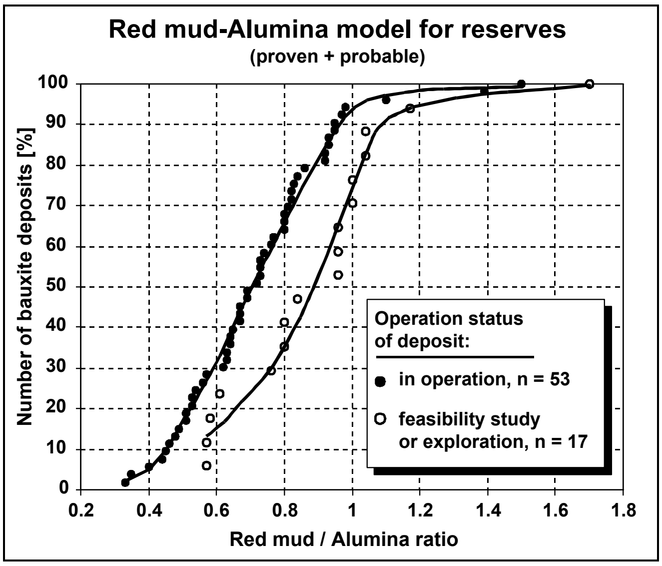

Figure 8. Global quality model (Grade model) for bauxite reserves worldwide. Comparison of the Red mud-to-Alumina ratio for operating and non-operating deposits.

4. CONCLUSIONS

The present study demonstrates that the development and utilization of a limited number of applicable indicators for bauxite-quality can be used to analyze material flows produced from a distinct bauxite. The aggregation of a great number of such site-specific data is a useful tool for the assessment of effects on a global scale. With the application of this methodological approach the following statements and trends can be pointed out:

- bauxite-quality, in the context of the present study, has a significant effect on the aluminia production-chain,
- bauxite-quality shows considerable variations for both, karst bauxites and lateritic bauxites,
- ore-qualities of potential bauxite deposits indicate a possibly unfavourable trend for the future, and
- the selection of future bauxite resources for mining should be carried out by considering the implications for global material flow.

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THE VARIATION OF ORE GRADE DISTRIBUTION IN THE LOS PIJIGUAOS BAUXITE DEPOSIT, VENEZUELA: A COMPUTER AIDED MODEL*

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ABSTRACT
The Los Pijiguaos bauxite deposit is dissected by deep erosion valleys resulting in a discontinuous bauxite blanket with the ore body being dismembered into nine isolated blocks. The grade distribution is rather heterogeneous and varies vertically and laterally within the deposit and also within single blocks or sectors. A computer-aided model of a selected part of the deposit shows regular patterns of the ore grade distribution for the investigated parameters total Al_2O_3 and total SiO_2. The ore grade quality is strictly controlled by the morphology. Morphological highs show mostly the highest ore quality and also the greatest thickness of the economically exploitable bauxite horizon. The method, which was calibrated on the production figures of an exploited part of the deposit, can also be used for reserve estimation, for mine planning and for an optimisation of ore extraction strategies.

KEYWORDS
Bauxite, ore deposit, Los Pijiguaos, ore grade, geology, mining

* Source: Traveaux du Comité international pour l’étude des Bauxites, des l’Alumine (ICSOBA), Vol 26, 1999, No. 30, 12th International Symposium of ICSOBA.

1. INTRODUCTION

In 1997 the Deutsche Forschungsgemeinschaft has established at the University of Technology Aachen in Germany the Collaborative Research Centre 525 (SFB) entitled „Resource-Orientated Analysis of Metallic Raw Material Flows“. The aim of this program is to develop operative recommendations for a resource-sensitive utilisation of metallic raw materials. The initial phase of the program is focused on the aluminium flow analyses. This phase involves geological aspects, mining, alumina and aluminium processing and includes also secondary production processes as well as tailings disposal. The evaluation of geologic characteristics of bauxite deposits and their effects on subsequent technical processes represents the first step in this analysis.

This study presents the result of a cooperation between the Institute of Mineralogy and Economic Geology of the University of Technology, Aachen in Germany and the C.V.G. - Bauxilum, Los Pijiguaos in Venezuela. The aim of the study is to evaluate variations of ore grade and ore quality of a lateritic bauxite deposit by means of an integrated computer-aided modelling of parameters such as morphological effects and variations of the thickness of the bauxite profile. The main focus is to identify regular patterns of the ore grade distribution to guarantee a constant ore quality which is one of the most important factors for the processing of the bauxite in the alumina refinery. The orebody model of the deposit was carried out using the geologic mine planning program DATAMINE™.

The mine concerned is the Los Pijiguaos bauxite deposit in the State Bolivar of Venezuela, located 500 km south of Caracas and 520 km south west of Ciudad Guayana (Fig. 1).

Figure 1: Location of the Los Pijiguaos bauxite mine.

The deposit was discovered in 1976, a feasibility study was conducted by Alusuisse in 1979, and mining commenced in 1987. The mine is operated by the state owned Corporation Venezolana de Guayana - Bauxilum-Operadore de Bauxita. The annual production amounts to 5 million metric tons of crude bauxite.

2. REGIONAL SETTING

The Los Pijiguaos bauxite deposit is geologically situated at the north-western margin of the Proterozoic Guayana Shield. It is part of the Middle-Proterozoic Cedeño Super Group which is subdivided into the Cuchivero Group and the Suapure Group. The Cuchivero Group is characterised by rhyolitic volcanic series of the Caicara Formation and large granitic intrusions. The Suapure Group consists mainly of the Parguaza Granite which is the parental rock of the Los Pijiguaos bauxite [1].

The Parguaza Granite represents a 1546 ± 20 Ma old [2] intrusive complex that covers a large area in the northwest of Venezuela. The granite is coarse to very coarse grained and shows a typical rapakivi texture, with plagioclase rims being developed around ovoid potash feldspar phenocrysts. A typical modal composition of the granite amounts to 20% Quartz, 40 % potash feldspar, 25% Oligoklas, 7% Biotite and 8% Hornblende.

The area of the Los Pijiguaos bauxite mine is situated at the northern margin of the Parguaza intrusive complex (Fig. 2).

The bauxite profile is developed at an altitude of 600 to 700 m, termed Nuria Surface, which represents an erosional surface of the Guayana Shield that formed during Late Cretaceous to Early Tertiary times [3]. At present the ore-body consists of nine isolated blocks. For mining purpose, each block is subdivided into various numbers of sectors (Fig. 3). The discontinuous bauxite blanket is a result of strong and prolonged fluvial erosion during and after uplift of the region. A large proportion of the lease area is located on separated plateau remnants whereby remaining areas are occupied by deep valleys. The whole lease area covers an area of 28.4 km^2 (Fig. 3). About 16 km^2 of the total area are not accessible for mining because of the presence of deep valleys, whereas the mineable plateaus cover an area of only 12.4 km^2. The proven bauxite reserves amount 168 mio. t with a cut-off grade of more then 44% alumina (Al_2O_3) and less than 20% total silica (SiO_2). The average Al_2O_3-content of the proven reserves is 49,5% and the average total silica content is 9,3% [4], [5].

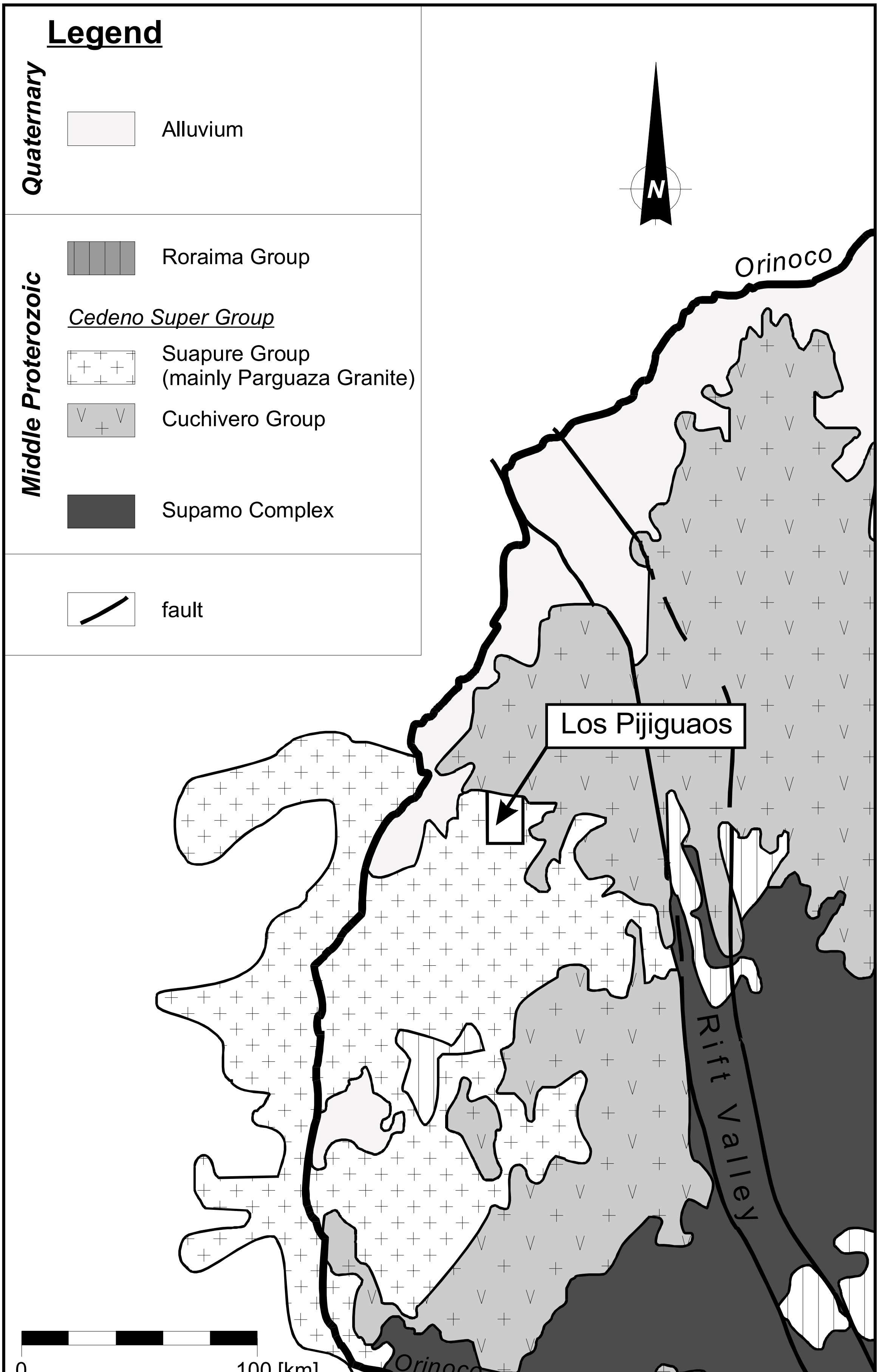

Figure 2: Simplified geological map of the western part of the Guayana shield [6].

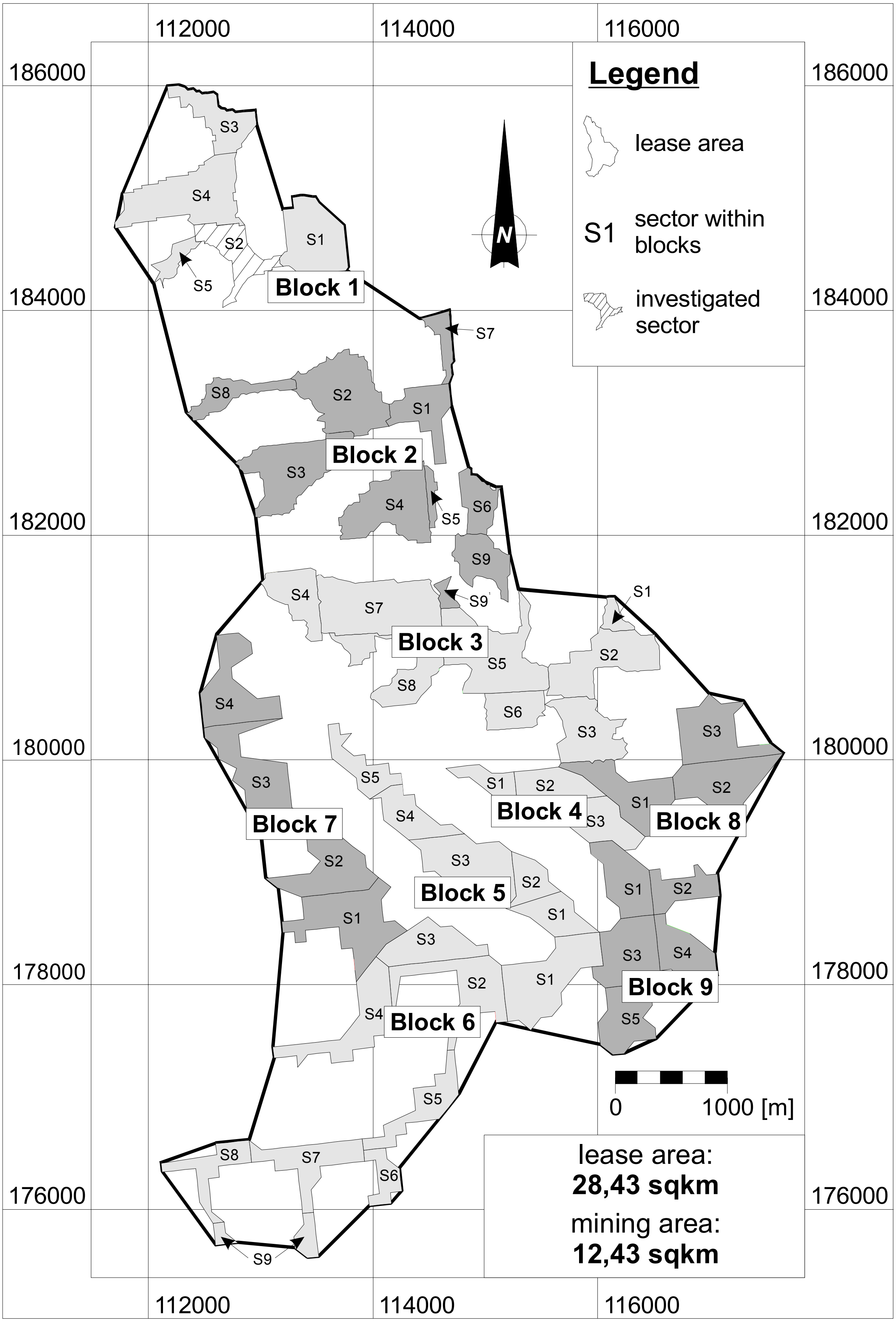

Figure 3: Plan view of the Los Pijiguaos bauxite mine.

3. BAUXITE PROFILE

Weathering of the Parguaza Granite has resulted in a typical lateritic profile. The weathering profile shows a characteristic vertical zoning, which can generally be subdivided into a concretionary zone (the bauxite horizon), a mottled zone (the saprolite horizon) and the bed rock (Fig. 4).

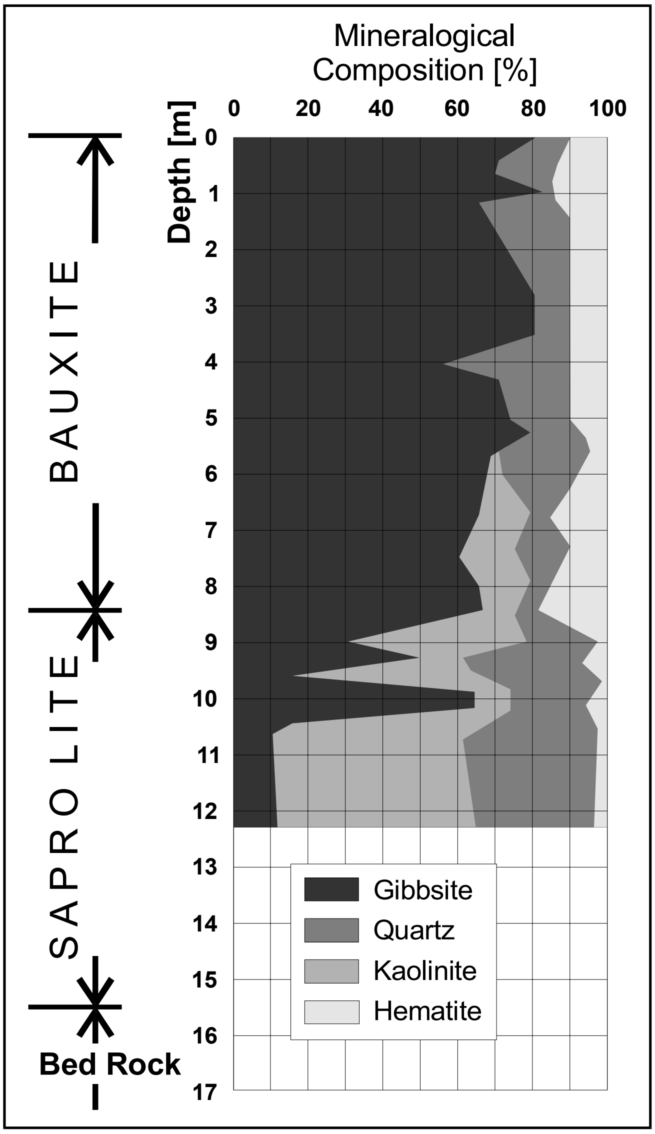

Figure 4: Schematic bauxite profile showing the generalised vertical zoning and the mineralogical composition [7].

The on average 7.6 m thick bauxite horizon consists of mainly gibbsite (60-90%), hematite (5-15%), quartz (5-25%) (Fig. 4) and traces of boehmite and kaolinite, and is characterised by four layers that include (from top to bottom):

A hard concretionary layer up to 3 metres thick, displaying spongy textures and brownish to reddish colours resulting from a slight enrichment in iron. This crust is underlain by an earthy bauxite horizon up to 2 metres thick containing partly loose pisolites. The third layer is characterised by a hard bauxite crust showing cellular textures and partly cemented pisolites. The fourth horizon is an earthy bauxite up to 4 metres thick containing disseminated pisolites and gibbsite-rich, spongy to cellular concretions [7].

The gibbsite is present as coarse crystals in the bauxite crusts and is fine grained in the earthy bauxite. The quartz is disseminated across the entire bauxite horizon. The gibbsite content decreases whereas the kaolinite and quartz content increases significantly downwards from the boundary between the bauxite and saprolite horizons (Fig. 4). The saprolite consists of an earthy aggregate of kaolinite, quartz and mica. Some bauxite concretions are observed in the upper part and a pseudo rapakivi texture is typical in the lower part of the mottled zone. Downwards, the saprolite gradually grades into the fresh rapakivi granite [8].

4. ORE BODY MODELLING

Grade distribution is very heterogeneous and varies vertically and laterally within the deposit. To identify regular patterns of the ore grade distribution, we have selected sector 2 of block 1 in the northernmost part of the mine. This sector covers an area of some 200,000 square metres. The database used for the ore-body model is based on a bore hole grid with a spacing of 25 by 25 metres. This grid contains a total of 331 exploration bore holes drilled the investigated area with depths ranging from 6 to 20 meters, with an average of 10.6 metres. From these bore holes, more than 3000 samples, with a size of one metre, have been assayed for total alumina, total silica and reactive silica contents.

The block models shown below visualise the thickness and ore grade distribution within the

bauxite horizon. The compilation and presentation of the data was done using the mining software package DATAMINE™ in conjunction with previously calculated variograms.
In the following, models are presented for each calculated parameter by a plane view of the investigated area as well as two profiles.

4.1 VARIATION IN THICKNESS

In order to determine variations in the thickness of the ore body, the cumulative thickness of the bauxite horizon for each bore hole was calculated assuming a cut-off grade of more than 44% total alumina and less than 20% total silica. Subsequently, the thickness of the economically mineable ore grade horizon was determined for blocks of the size 25 by 25 metres based on the geostatistical linear kriging method.

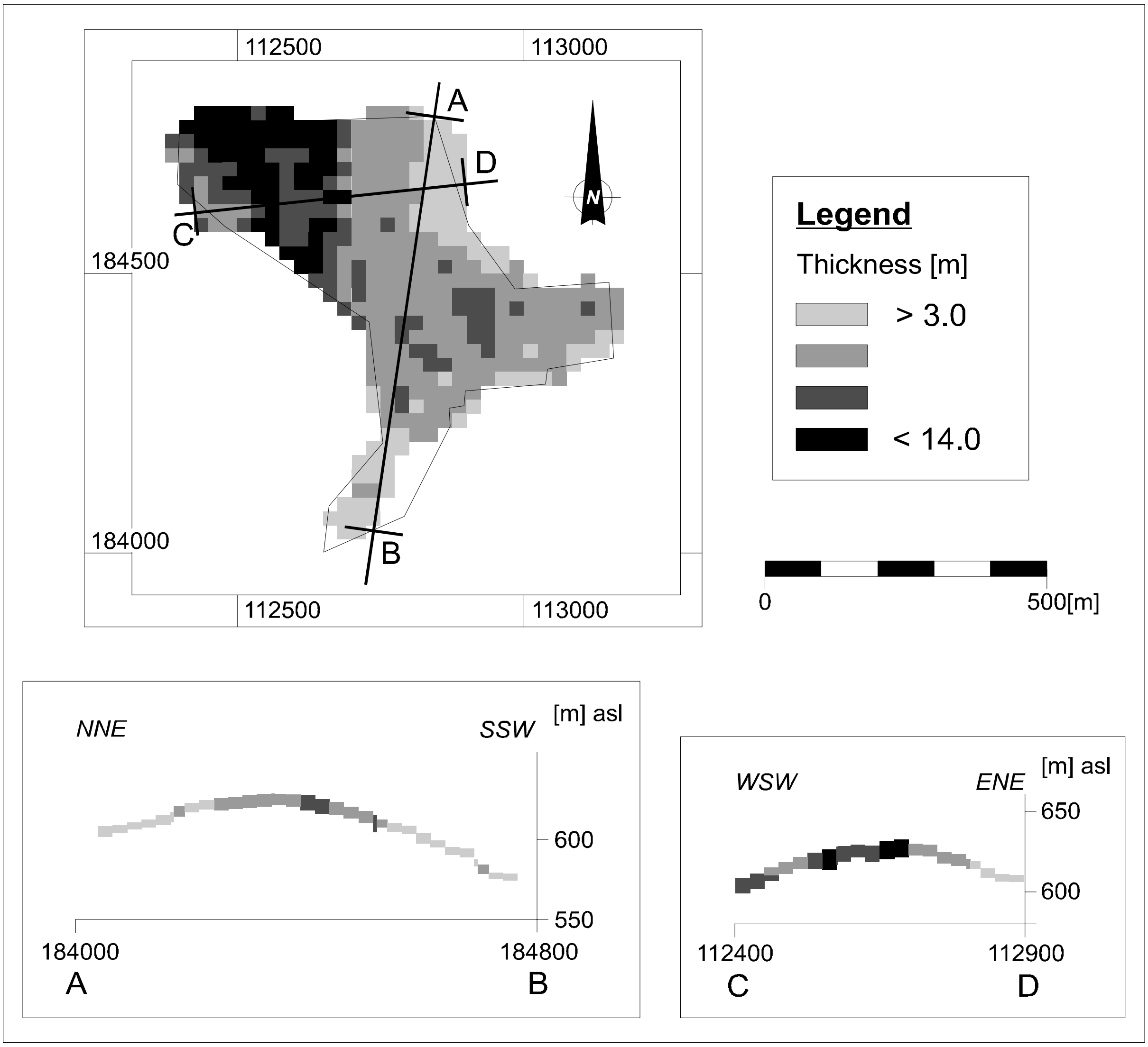

Figure 5: Illustration of the variation of thickness in block 1, sector 2 of the Los Pijiguaos bauxite mine.

In the investigated sector, the thickness of the ore horizon varies from 3 to 14 meters (Fig. 5). A comparison of the morphological characteristics with the thickness of the bauxite horizon shows that the variation in thickness is strictly controlled by the morphology. As shown in the profiles of figure 5 the greatest thickness corresponds to the highest altitude and it is markedly decreasing towards the slopes of the slightly convex plateau where the bauxite mantle abruptly pinches out at the edge of the plateau. BARDOSSY (1990) has surmised that the bauxite horizon tends to thicken along the edges of the plateau [9]. In contrast to this opinion, our observations indicate, as mentioned before, that the exploitable part of the bauxite horizon shows a significant thinning along the slopes.

4.2 ORE GRADE DISTRIBUTION

In order to estimate the ore grades, 3-dimensional blocks of the size 25 by 25 by 2 metres were defined. Experimental variograms were calculated and determined for various directions relative to the ore body extent. Subsequently, we were able to apply 3-dimensional spherical variograms to the ore body. The ore grades of the single blocks were estimated by using the geostatistical linear kriging method, and grouped for each parameter into six classes. Total Al_2O_3 and total SiO_2 distributions are shown in figures 6 and 7. In both figures, plan view representations reveal, for the uppermost portion of the bauxite horizon, the lateral grade distribution. In the profiles the vertical grade distribution is represented.

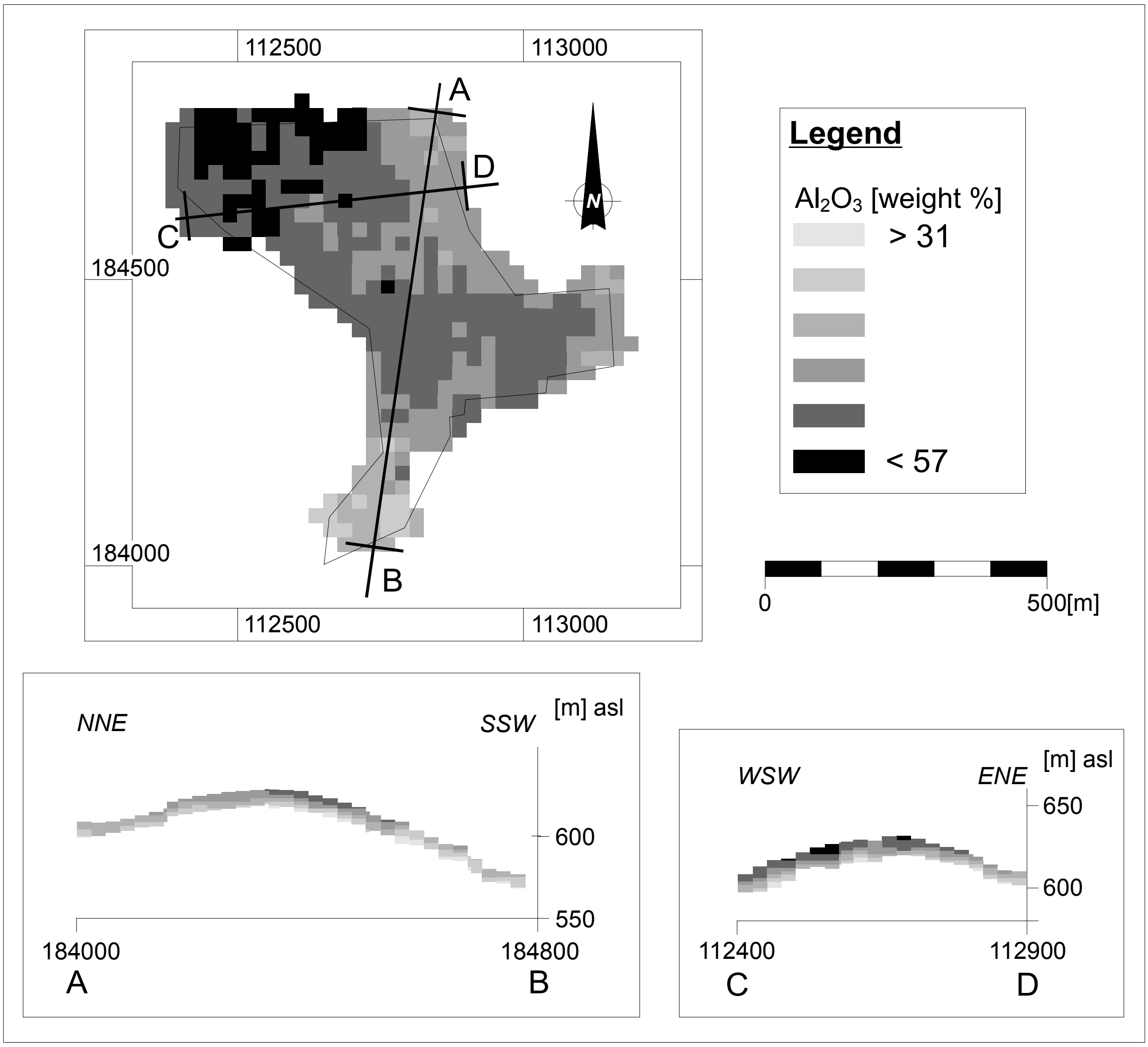

Figure 6: Illustration of lateral and vertical distribution of total Al_2O_3 in block 1, sector 2 of the Los Pijiguaos bauxite mine.

The alumina content varies from 31 to 57 weight percent. The distribution of the ore grade shows a regular pattern with the following characteristics:
Firstly, it can be observed that it is similar to the variation of thickness, and is, thus, controlled by the morphology. Morphological highs show the highest alumina content with the exception of the north-western part of the investigated area (Fig. 6). The high alumina content of this relatively low- lying area may be explained by redeposition of the bauxite. BARDOSSY (1990) already mentioned that the various bauxite textures, described before, suggest periods of laterisation alternating with periods of erosion and short transport to local depressions [9]. It is thus clear, that in these areas a secondary accumulation of alumina occurred, most probably concurrently with the on-going bauxitisation process. A second pattern exhibited by the ore grade distribution is a significant decrease of the total alumina content towards the base of the bauxite horizon. This corresponds to an increase in total silica towards the protolith.
The total silica content varies within block 1, sector 2 from 0.5 to less than 45 weight percent. The distribution of silica appears to be inversely related to alumina content, i.e. in areas where the alumina content increases the silica content decreases, and the other way round. If one assumes the cut-off grades mentioned before, in most cases the total silica content is the limiting factor for the exploitable thickness of the bauxite horizon.

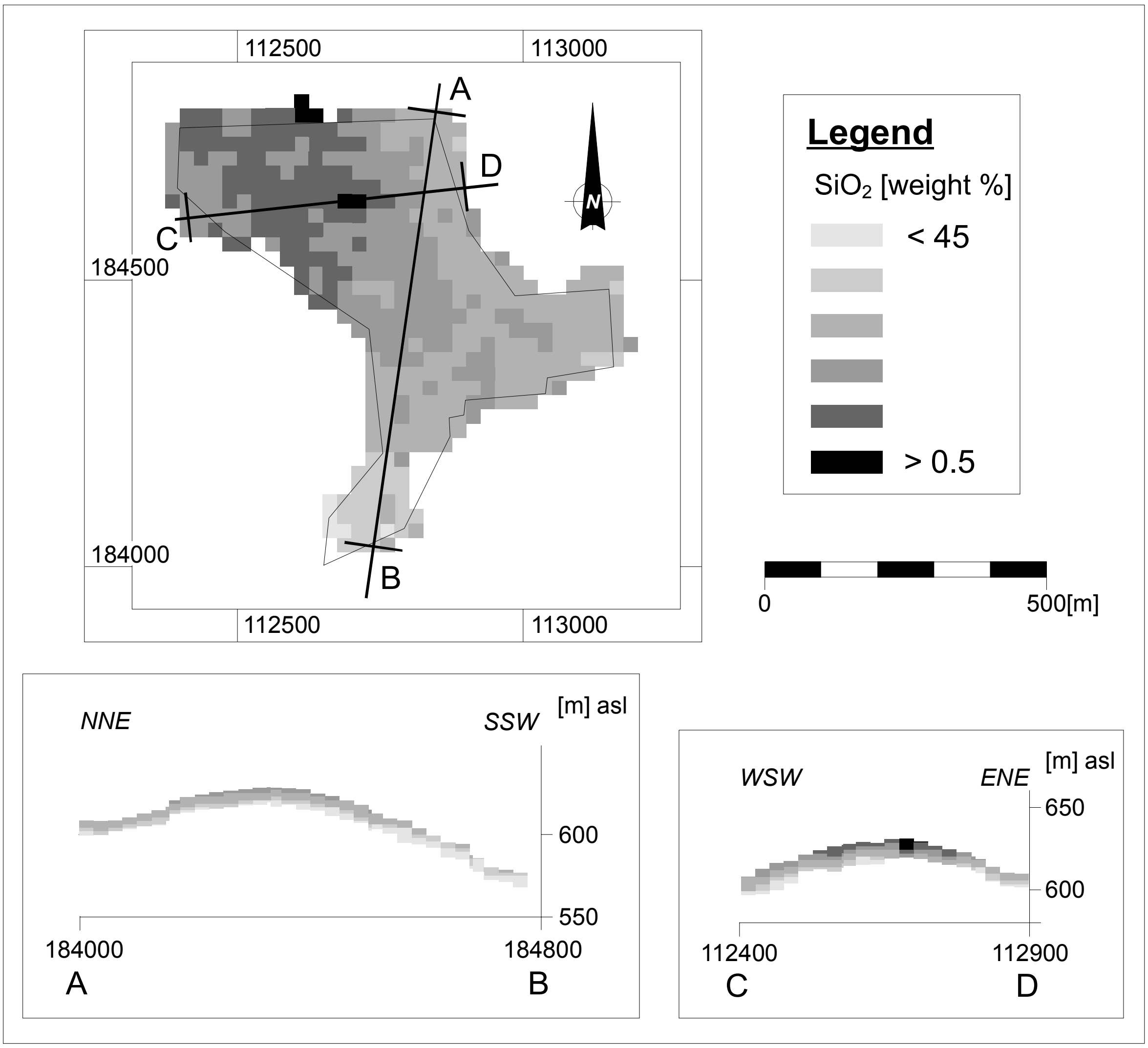

Figure 7: Illustration of lateral and vertical distribution of total SiO_2 in block 1, sector 2 of the Los Pijiguaos bauxite mine.

5. RESERVE ESTIMATIONS

The accuracy of the presented models was calibrated using the production figures obtained from the already exploited ore block. Table 1 shows the results of the comparison of the actual production data with reserves estimated by the statistical procedure outlined above. The percentage difference of the calculated tonnage as well as of the average ore grades to the actual production data is less than one per cent. It is safe to state, that calculated ore reserves and ore grade distribution patterns that are based on the 3-D ore body model provide a very accurate basis for future exploration planning and ore grade predictions.

Table 1: Comparison of actual production figures with statistically estimated ore tonnages and grades of block 1 / sector 2

Production data	Reserve estimation
3,449 [thousand t]	3,512 [thousand t]
Al_2O_3 = Ø 49.02 %	Al_2O_3 = Ø 49.11%
SiO_2 = Ø 9.62 %	SiO_2 = Ø 9.81

6. CONCLUSIONS

The present study shows that the application of computer aided modelling is an ideal method to integrate geological, genetic, mining and economical aspects of a bauxite deposit. The salient results emerging from this study are summarised below:

1. The variation of thickness and the distribution of the alumina and silica content is controlled by the morphology. Topographic highs commonly yield a better bauxite quality.
2. The ore grade distribution can be explained by a typical primary in-situ bauxitisation process, with the exception of local and minor secondary bauxite transportation within a confined area.
3. The results of this investigation can be used for further exploration in the region which may host as much as 5.000 million tons of possible bauxite reserves.
4. The methodology and the ore body model described can also be used for a very accurate reserve estimations, since the method was calibrated on the actual production figures. The ore-body model also forms the basis for mine planning and, thus, for an optimisation of ore extraction strategies.

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The geometry and anatomy of the Los Pijiguaos bauxite deposit, Venezuela

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Abstract

The Los Pijiguaos bauxite mine in the western part of the State of Bolivar, Venezuela, represents the only currently exploited bauxite deposit in the country. Since mining commenced in 1987, total crude bauxite production has amounted to more than 43 million tonnes (Mt), with a present annual production close to 5 Mt. Proven and probable reserves are around 570 Mt, at an economic cut-off grade of about 44 wt.% alumina (Al_2O_3) and a total silica (SiO_2) content of less than 20 wt.%. The orebody has an irregular, dismembered geometry as a result of strong and prolonged fluvial erosion during and after uplift of the region. The isolated minable blocks are located on plateau remnants separated by deep valleys. As a result, only half of the entire lease area is accessible for mining. Los Pijiguaos represents a typical laterite bauxite deposit that formed on a flat topped plateau from weathering of the underlying mid-Proterozoic Rapakivi-type Parguaza granite. The complete laterite profile is characterized by a vertical zonation comprising a concretionary zone (the bauxite horizon), and a mottled zone (the saprolite horizon) on granitic bed rock. The economic bauxite zone attains an average thickness of 7.6 m. On a mine scale, best ore grades and greatest thickness of the ore horizon are at topographic highs. Laterally, grade distribution is also not isotropic but follows distinct WNW–SSE trends. The spatial control on the mineralization is a result of the westerly inclination of the planation surface and the formation of major NW-striking fault systems in the region. Gibbsite is the most abundant mineral in the economic-grade bauxite horizon. The occurrence of minor nordstrandite is also restricted to that zone. Kaolinite is not present in the bauxite zone, but in the lower saprolite zone kaolinite can be more than 5 wt.%. An inverse correlation exists between gibbsite and quartz. Abundance ratios for the two minerals decrease from around 45 in the bauxite horizon to around 2 in the lower saprolite zone. Hematite is commonly more abundant than goethite. In the bauxite horizon, however, the goethite/hematite ratio is greater than 1. Anatase occurs as an accessory phase mainly in the bauxite horizon. Mass balance considerations demonstrate that bauxitization resulted in progressive desilication, hydration, and Al_2O_3 and Fe_2O_3 concentration in the residual weathering blanket. Silica as well as alkali and alkaline earth metals were almost completely leached. Mass and volume losses in the order of 61% and 77%, respectively, attest to severe mineralogical, textural, and chemical changes. From an economic point of view, the Los Pijiguaos bauxite represents a high-quality almost pure gibbsitic ore that allows processing to alumina by the low-temperature Bayer process around 140 °C. In terms of material consumption, 2.3 tonnes of dry bauxite are used for every tonne of alumina produced. The accompanying mass of red mud amounts to 550 kg per tonne alumina. The relatively high abundance of hematite in the bauxite has a positive effect on the red mud settling rate and, thus, favors a high extraction yield of the alumina plant. Los Pijiguaos is based on a huge reserve that will provide bauxite for more than 100 years at the current rate of

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mining. The entire region may contain as much as 6 billion tonnes of probable bauxite resources.

Keywords: Saprolite; Bauxite; Los Pijiguaos

1. Introduction

Bauxite is the principal ore for the production of aluminium metal via a two-stage process that involves, firstly the refining of bauxite to alumina by a wet chemical caustic leach process (the Bayer process) and, secondly the electrolytic reduction of alumina to aluminium metal (the Hall–Heroult process). Approximately 85% of all bauxite mined is converted to alumina for the production of aluminium metal, 10% is utilized for nonmetal products, and the remaining 5% is used for non-metallurgical applications such as

Fig. 1. Location of the Los Pijiguaos bauxite mine in Venezuela.

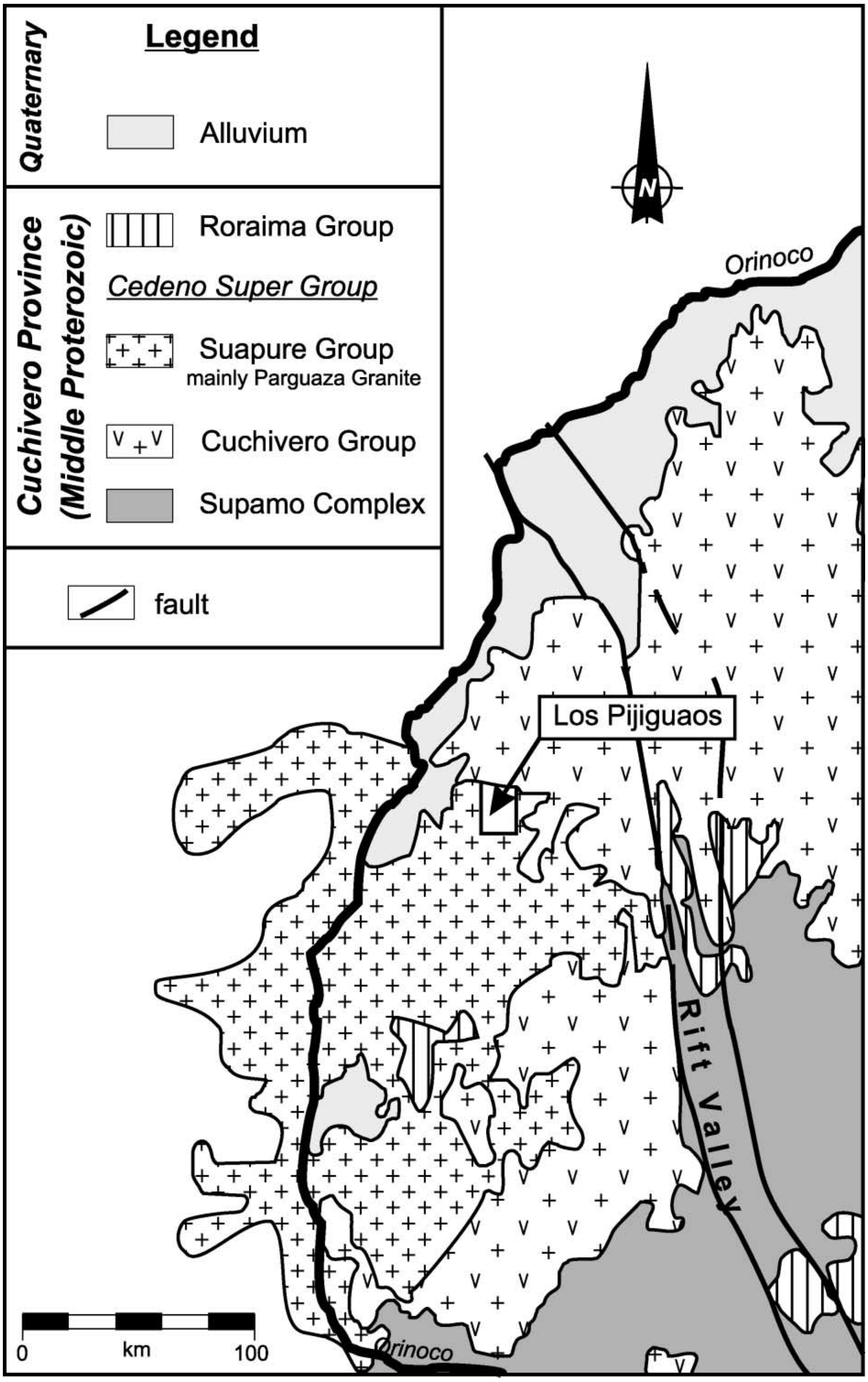

Fig. 2. Generalized geologic map of the Los Pijiguaos region.

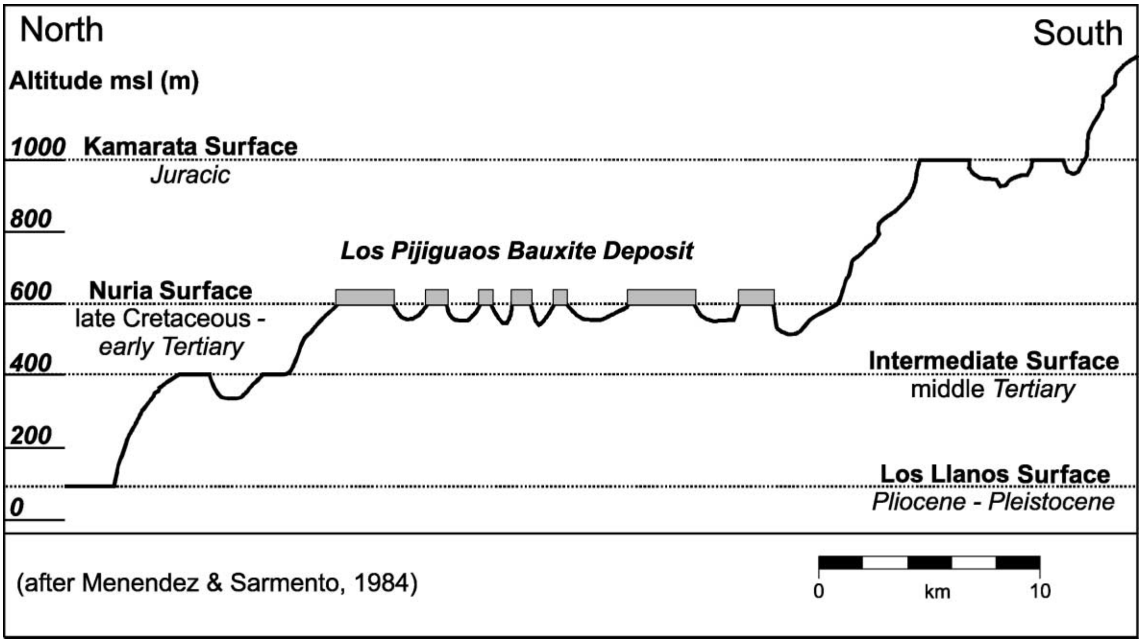

Fig. 3. Schematic N–S profile of the Los Pijiguaos region showing the position of planation surfaces.

production of refractory and abrasive materials (Plunkert, 1999). Driven by increasing demand, world bauxite production has risen over the past 5 decades from less then 5 million tonnes (Mt) per annum to about 125 Mt in recent years, with a mean annual increase over the past decade of 1.7%.

From a geologic point of view, bauxite is a residual rock that formed intermittently throughout much of the geologic record during periods of intense continental sub-aerial weathering. As such, bauxite formation is the result of distinct climatic and tectonic conditions favorable for sustaining prolonged weath-

Table 1
Representative electron microprobe analyses of major minerals from the Parguaza granite

(wt. %)	Plagioclase		Mikrocline		Perthite		Biotite		Amphibole		Ilmenite		Hematite	
	Mean ($n=12$)	S.D.	Mean ($n=16$)	S.D.	Mean ($n=10$)	S.D.	Mean ($n=10$)	S.D.	Mean ($n=9$)	S.D.	Mean ($n=11$)	S.D.	Mean ($n=2$)	S.D.
Al_2O_3	22.43	0.81	18.51	0.09	19.89	0.28	13.12	0.30	8.63	0.43	0.01	0.01	0.04	0.04
MgO	–	–	–	–	–	–	3.34	0.13	2.87	0.76	0.01	0.01	0.02	0.02
CaO	3.7	0.1	0.69	0.02	0.68	0.43	0.02	0.01	10.80	0.28	–	–	–	–
FeO	0.09	0.03	0.06	0.02	0.04	0.02	30.74	0.09	28.84	1.21	45.31	0.80	–	–
Fe_2O_3	–	–	–	–	–	–	–	–	–	–	–	–	101.63	0.02
SiO_2	64	1.64	64.37	0.33	67.18	0.47	35.80	0.36	41.97	0.60	0.02	0.02	–	–
Na_2O	7.97	0.6	0.47	0.11	9.3	0.31	0.07	0.03	1.82	0.12	0.01	0.01	–	–
TiO_2	0.02	0.02	0.01	0.01	0.01	0.01	3.83	0.38	1.96	0.22	51.69	0.53	0.14	0.17
K_2O	0.2	0.2	16.15	0.27	0.08	0.01	9.05	0.15	1.17	0.15	–	–	–	–
Mn	0.01	0.01	–	–	0.02	0.01	0.36	0.07	0.67	0.04	3.04	0.55	–	–
H_2O	–	–	–	–	–	–	3.75	–	1.78	–	–	–	–	–
Total	98.52	1.35	99.78	0.46	97.88	1.57	100.80	0.32	100.51	0.42	100.08	0.78	101.99	0.00

n = Number of mineral grains analyzed; S.D. = standard deviation; – = not analyzed.

ering processes. Bauxite deposits are commonly classified in three genetic types according to mineralogy, chemistry and host-rock lithology (Bárdossy and Aleva, 1990). Of all known bauxite deposits, about 88% belong to the laterite-type, 11.5% are of the karst-type, and the remaining 0.5% are of the Tikhvin-type (Bárdossy 1982; Bárdossy and Aleva, 1990). Laterite bauxites are derived from a variety of parent rock types and formed in a variety of paleogeographic settings during specific epochs of the earth's history. In general, however, laterite bauxites are not older than Late Tertiary in age (Bárdossy, 1995). They are preferentially developed on flat-topped plateaus and occur commonly on large continental-scale planation surfaces exposed to a tropical monsoon climate, whereby optimal hydraulic conditions are controlled by the balance between precipitation and evaporation. Laterite bauxite deposits usually have gibbsite as the principal Al mineral, but they may display a wide range of morphological and structural features (Bárdossy and Aleva, 1990).

The Los Pijiguaos bauxite deposit is in the western part of the State of Bolivar in Venezuela, some 500 km to the south of the city of Caracas (Fig. 1). It is the only currently exploited bauxite deposit in Venezuela and belongs to one of the most productive mining districts in South America. Almost all of the associated bauxite deposits are characterized by high-quality ore with total alumina (Al_2O_3) contents of around 50 wt.%. This, together with enormous quantities of proven and probable reserves, is the main reason for their present and future importance for world bauxite supply. The Los Pijiguaos region, for example, may hold the world's largest bauxite deposit, of which only a small part of the total resources has been explored sufficiently thus far (Bárdossy and Bourke, 1993).

In the Los Pijiguaos area, systematic exploration for bauxite was carried out first in 1974 by the state-owned Venezolana de Guyana (C.V.G). After the discovery of the Los Pijiguaos deposit in 1976, Swiss Aluminium (later Alusuisse Lonza Holding) conducted a feasibility study that was concluded in 1979 (Swiss Aluminium, 1979). Proven reserves were found to amount to 168 Mt of bauxite, containing on average 49 wt.% Al_2O_3 and 10.2 wt.% SiO_2. At present, the mine is operated by the state-owned C.V.G. BAUXILUM Operadore de Bauxita. Mining commenced in 1987 following an initial planning and construction phase starting in 1984. Since 1987, production increased steadily up to 1994 when the projected crude bauxite annual capacity reached more than 5 Mt. In 1998, bauxite production amounted to more than 5.2 Mt. The economic cut-off grade is about 44 wt.% alumina (Al_2O_3) at a total silica (SiO_2) content of less than 20 wt.%. (Mariño and Rodriguez, 1997; Guapes et al., 1997).

Bauxite extraction is carried out by hydraulic shovel excavators in a conventional open-pit mining operation. The overburden (average 0.5 m thick), is removed by dozers and stockpiled for rehabilitation. The ore is hauled by a fleet of 50- and 85-t dump trucks to an in-pit crushing station, from which it is transported by conveyer belt (4200 m, with a drop in

Table 2
Chemical composition of the Parguaza granite

	Ga0201	Ga0202	Ga0203	Ga0204	Ga0205
SiO_2 (wt. %)	71.53	71.01	71.07	70.09	68.18
TiO_2	0.44	0.29	0.34	0.69	0.86
Al2O_3	12.57	14.01	13.81	12.52	12.92
Fe_2O_3(T)	3.34	2.26	2.78	4.62	6.57
MnO	0.05	0.03	0.04	0.11	0.09
MgO	0.24	0.18	0.24	0.38	0.47
CaO	1.64	1.38	1.09	1.66	1.86
Na_2O	4.35	4.57	3.32	3.93	3.40
K_2O	4.83	5.72	6.18	5.65	4.63
P_2O_5	0.10	0.06	0.07	0.14	0.18
LOI	0.26	0.31	0.42	0.43	0.42
Total	99.08	99.51	98.93	99.77	99.15
Ba (ppm)	775	925	772	949	518
Sr	108	121	103	110	92
Rb	225	239	287	232	290
Pb	34	37	38	35	38
Zn	65	46	56	86	139
Th	16.3	27.7	21.4	9.90	56.8
U	5.60	4.10	4.70	4.00	8.60
Zr	323	234	282	594	745
Nb	28	20	29	53	66
Y	47	36	138	85	280
Sc	6.20	4.20	5.60	8.00	9.50
Ga	19	20	20	19	23
La	77	115	419	75.1	486
Ce	159	208	503	153	655
Nd	63.0	63.0	237	71.0	298
Sm	11.1	9.0	34.4	12.5	44.8
Eu	1.96	1.90	3.92	1.94	5.53
Tb	1.60	1.10	4.70	1.80	8.20
Yb	5.73	4.94	14.3	7.46	31.2
Lu	0.73	0.69	2.14	1.14	4.52

elevation of ca. 80 m) to the railhead stockpile in the Suapure valley (cf. Happel et al., 1999). Shipment of bauxite to the alumina refinery near the city of Cuidad Guyana (Fig. 1) involves a two-stage transport system. First, bauxite is transported by train by around 52 km to the Orinoco River port at Puerto Gumilla, where after loading onto barges, trains of 12 or 16 barges are pushed by tugs over a distance of 650 km down the Orinoco River to the alumina plant at Puerto Ordaz. Because the Orinoco River is not navigable during the dry season (from January to April), bauxite production has to be reduced and stockpiling increased.

Apart from the unavoidable land use by mining (<0.2 m^2/t Al_2O_3), the efficiency of the process and equipment has resulted only in minor and controllable environmental impacts. A rehabilitation program was implemented immediately after bauxite extraction was completed in the first few sectors of the mining area. The topsoil that was recovered and stockpiled during mining is replaced in the mined-out areas and trees are planted in regular rows. The United Nations Industrial Development Organization stated in their report (UNIDO, 1995) that the only problem with the replanted area is that, in the new vegetation little variety can be seen. It was concluded that with vigorous rehabilitation of the mined-out areas there is adequate potential for an ecologically sustainable development of the mine.

The objective of this paper is to summarize new information on the mineralogic and geochemical inventories of the Los Pijiguaos bauxite deposit and the parent Parguaza granite, and to present a new computer-based ore body model. Integration of these data, together with economic geology considerations, provides a framework that should assist in assessing the metallogeny of the region.

2. Geological framework

2.1. Regional geology

The region hosting the Los Pijiguaos bauxite deposit is underlain by the mid-Proterozoic Cuchivero Province located at the northwestern margin of the Guyana Shield. The Cuchivero Province comprises the Supamo Group, Cedeno Supergroup and Roraima Group. Los Pijiguaos is situated in the Suapure Group of the Cedeno Supergroup that also includes the Cuchivero Group (Fig. 2). The bulk of the Suapure Group is underlain by the Parguaza Rapakivi-type granite batholith. Outcrops of the smaller Pijiguaos granite are confined to the northwestern region. The bauxite horizon formed directly on the Parguaza granite that is thought to represent the parent rock to the weathering profile.

The geomorphology of the Los Pijiguaos area is characterized by an uplifted and deeply dissected, regional-scale plateau at an altitude between 600 and 700 m, termed the Nuria surface (Fig. 3). The plateau

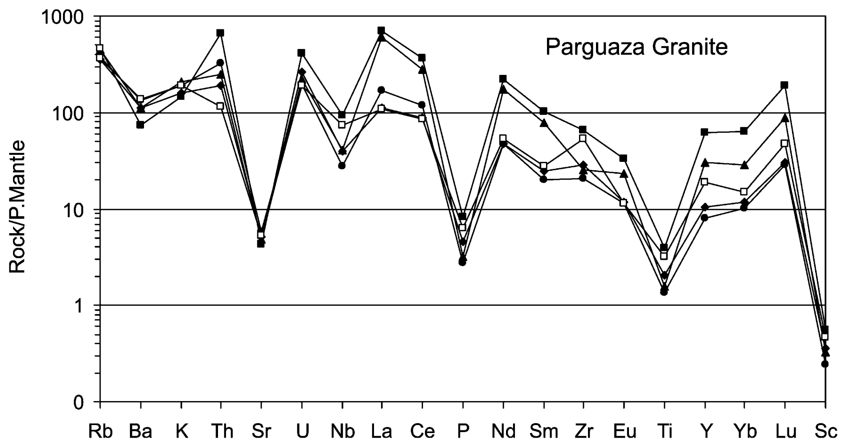

Fig. 4. Primitive mantle normalized plot of samples from the Parguaza granite. Normalizing values and element order adopted from Sun and McDonough (1989).

has an extent of 350 km^2 and is slightly tilted to the west with a slope of 2–3°. The Nuria surface represents the final stage of an intense erosional period that took place in the Guyana Shield during Late Cretaceous to Early Tertiary times (McConnell, 1968). Soler and Lasaga (2000) place the minimum age of the Nuria surface at 35 Ma, which they take as a time constraint for the beginning of bauxite formation at Los Pijiguaos.

2.2. Parguaza granite

The Parguaza granite batholith covers an area in excess of 30,000 km^2 and, thus, belongs to the largest known Rapakivi-type intrusions (Rämö and Haapala, 1993). Radiometric dating by the Rb/Sr whole rock as well as U/Pb zircon methods yielded mid-Proterozoic ages of 1545 ± 20 and 1532 ± 39 Ma, respectively (Gaudette et al., 1978). The granite is conspicuous by

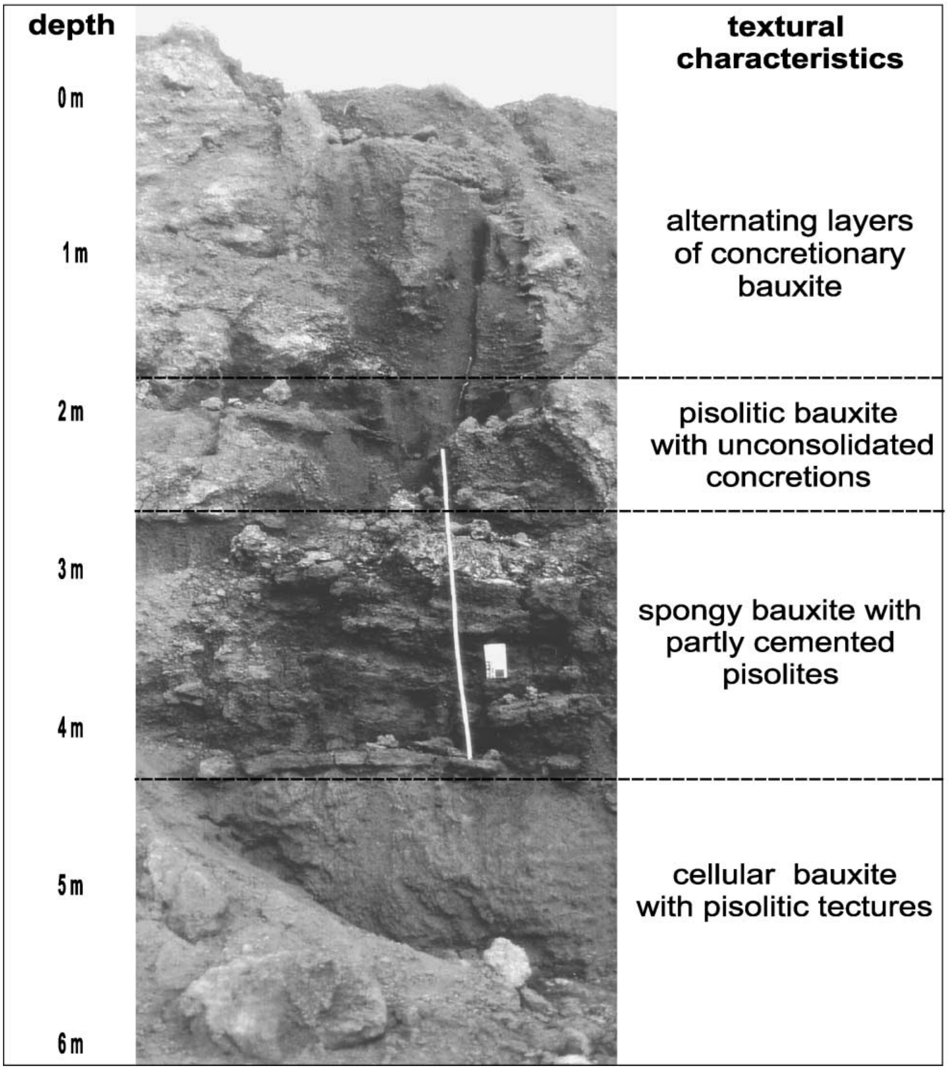

Fig. 5. View of the economic bauxite horizon at Los Pijiguaos mine (block 2, sector 3) showing typical textural characteristics and internal stratigraphy of the laterite profile.

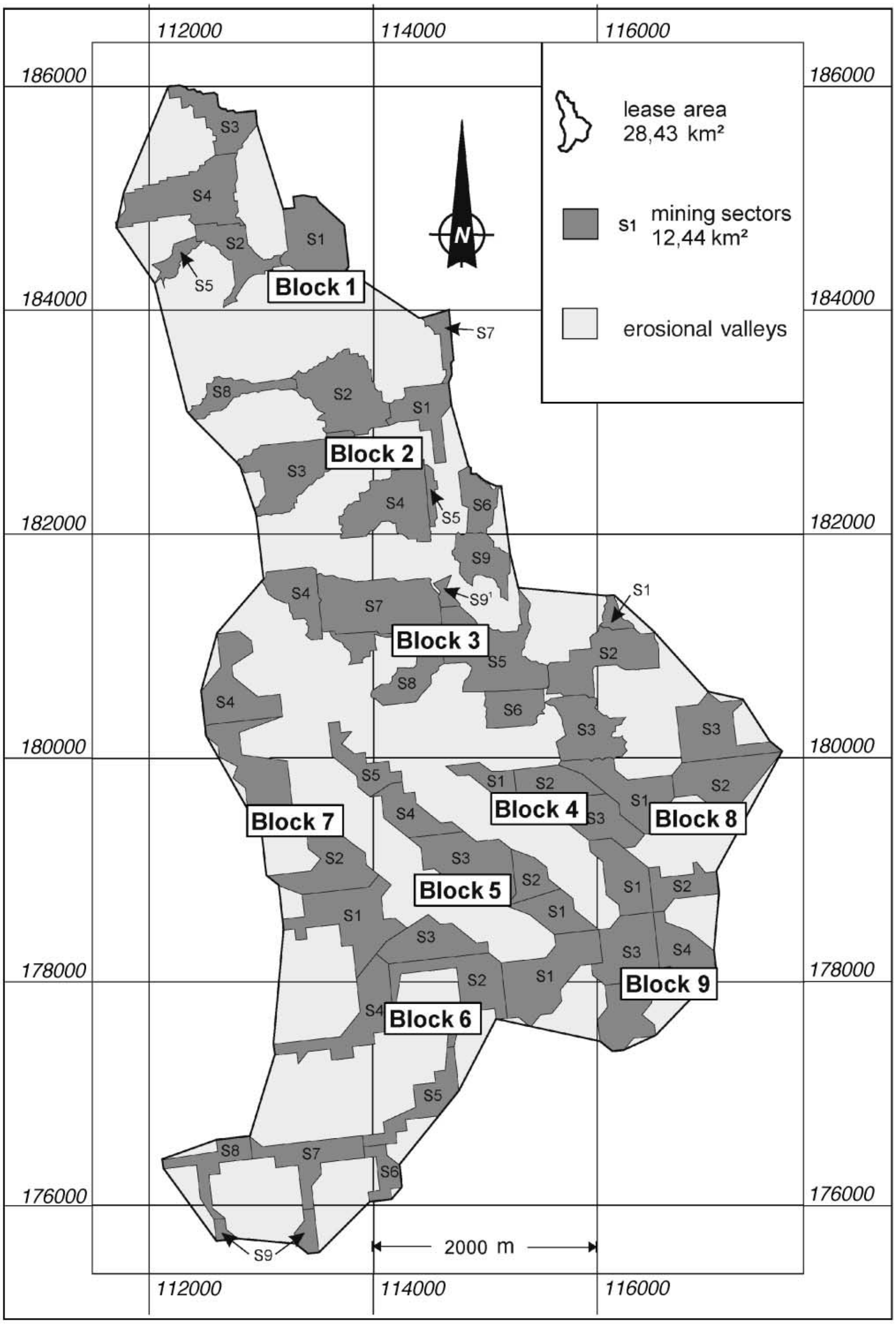

Fig. 6. Digital plan of the Los Pijiguaos Mine showing the distribution of mining blocks and sectors.

the abundance of feldspar phenocrysts showing multiple mantling, with successive zones of k-feldspar and plagioclase. Antirapakivi-type textures with alkali–feldspar enveloping ovoid plagioclase cores are also present (Gaudette et al., 1978). Modal mineralogy comprises quartz, microcline perthite, rare plagioclase of oligoclase composition, Fe-rich biotite, and edenitic hornblende. Accessory phases include apatite, sphene, ilmenite, hematite and zircon. Representative electron microprobe analyses of major and selected minor minerals are provided in Table 1.

Geochemically, the Parguaza granite is metaluminous. Total alkali contents are high and CaO is low (Table 2). On suitable trace-element discrimination diagrams, Parguaza sample plots in the fields characteristic of A-type and within-plate granites. Pronounced troughs at Sr, P, Ti and Sc occur on a primitive mantle-normalized multi-element diagram (Fig. 4) while the general pattern slopes relatively smoothly down from Rb to Yb. High field strength element (HFSE) contents are high, with Y values ranging from 36 to 280 ppm, Nb from 20 to 66 ppm and Th from 10 to 57 ppm Th. Ga/Al ratios (i.e., Ga∗10000/Al) are typically >3, as expected for A-type granites (Whalen et al., 1987).

2.3. Mine geology

Weathering of the Parguaza Granite has resulted in an expansive laterite mantle. In places, however, granitic core-stones can be found to comprise of almost fresh, unweathered parent rock. The complete laterite profile is characterized by a vertical zonation, that allows distinction of a concretionary zone (the bauxite layer), a mottled zone (the saprolite layer) and the granitic bed rock (Quintero and Marino, 1990). The economic bauxite zone has an average thickness of 7.6 m. The soil cover is thin (<1 m) consisting mainly of vegetal matter. A complete gibbsitic bauxite (sensu strictu) profile typically exhibits an internal stratigraphy characterized by four distinct zones that include from top to bottom: (a) alternating layers of hard and friable concretionary bauxite, (b) pisolitic bauxite with poorly consolidated concretions, (c) spongy bauxite containing partly cemented pisolites, and (d) cellular bauxite with pisolitic textures (Fig. 5).

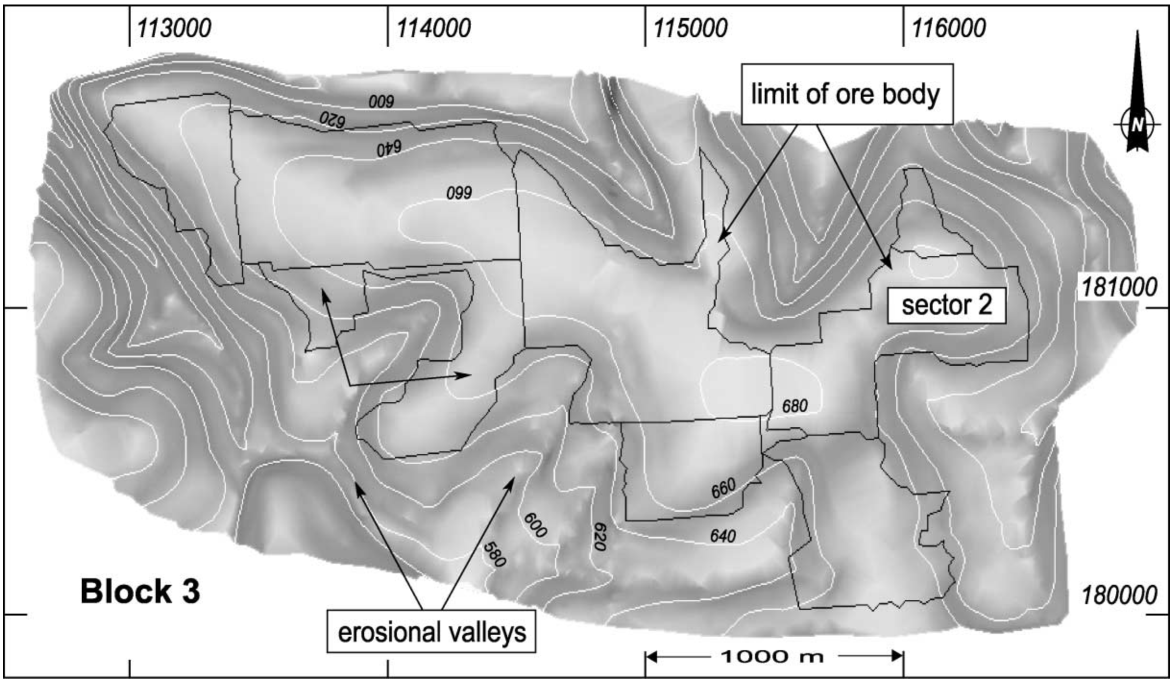

Fig. 7. Topographic model of block 3 showing the outline of mining sectors and erosional valleys.

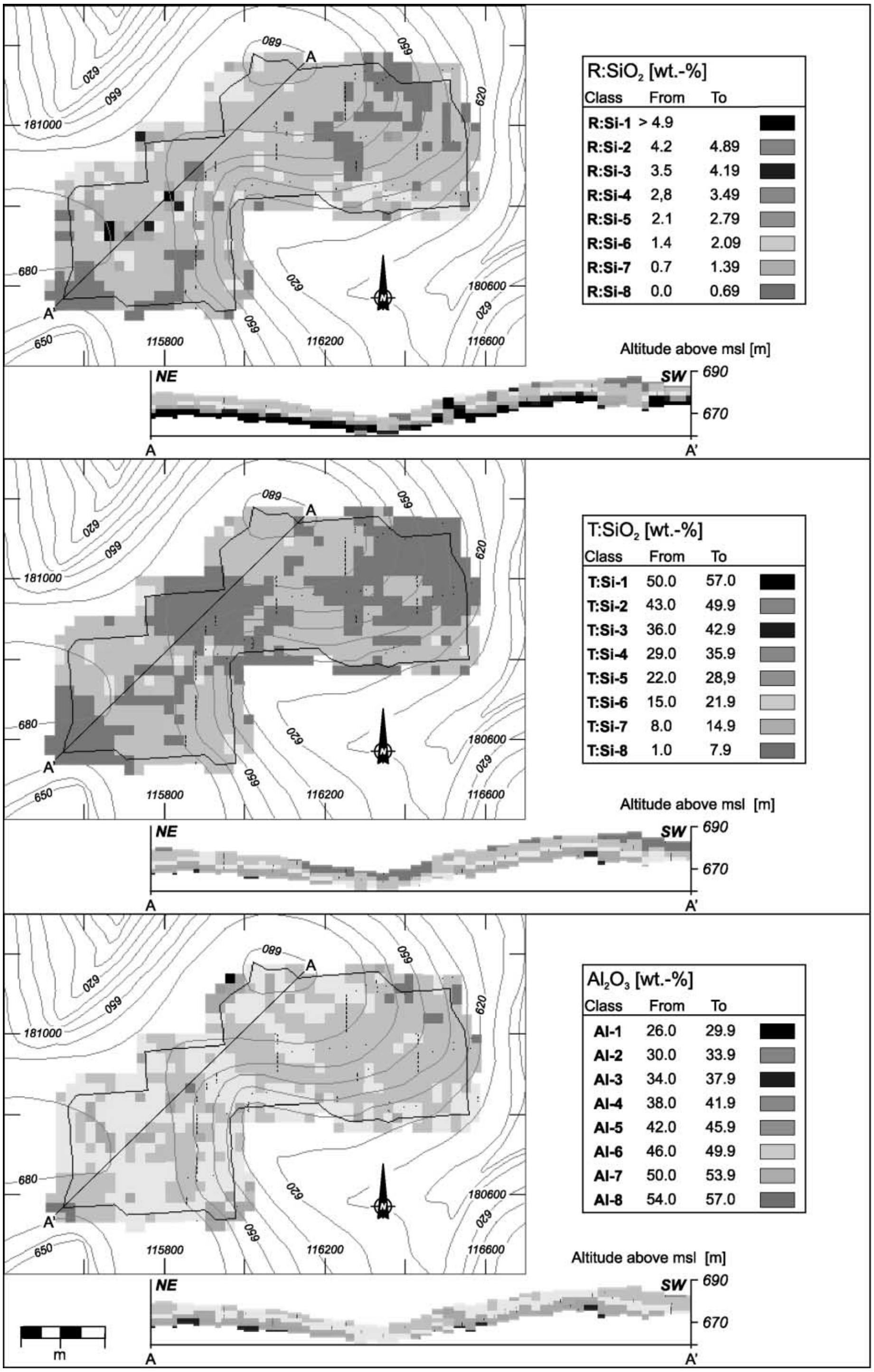

Fig. 8. Model of lateral and vertical distributions of R:SiO_2 (reactive silica), T:SiO_2 (total silica), and Al_2O_3 (block 3, sector 2).

A digital 3D model of the Los Pijiguaos mine was developed using DATAMINE™ software in conjunction with graphic support from GUIDE™, and the GUIDE® Visualization Program, on a WINDOWS NT™ platform (Datamine International, 1997, 1998). The created database contains geologic as well as spatial information of more than 10,000 boreholes drilled on a 25-m grid. The total area occupied by the mine is 28.4 km^2. The orebody, however, is not a continuous bauxite blanket, but is separated into nine isolated blocks, which, for mining purposes, are further subdivided into sectors (Fig. 6). The irregular, dismembered orebody geometry is a result of strong and prolonged fluvial erosion during and after uplift of the region. The isolated minable blocks of the lease area are located on separate plateau remnants and intervening areas are deep valleys (Fig. 7). As a result, only 12.4 km^2 of the entire lease area are underlain by bauxite.

Ore grades are locally heterogeneous and vary vertically as well as laterally within the deposit. To illustrate this fact, the distributions of reactive silica (R:SiO_2, i.e. silica present in silicate minerals, generally kaolinite), total silica (T:SiO_2, i.e. silica present

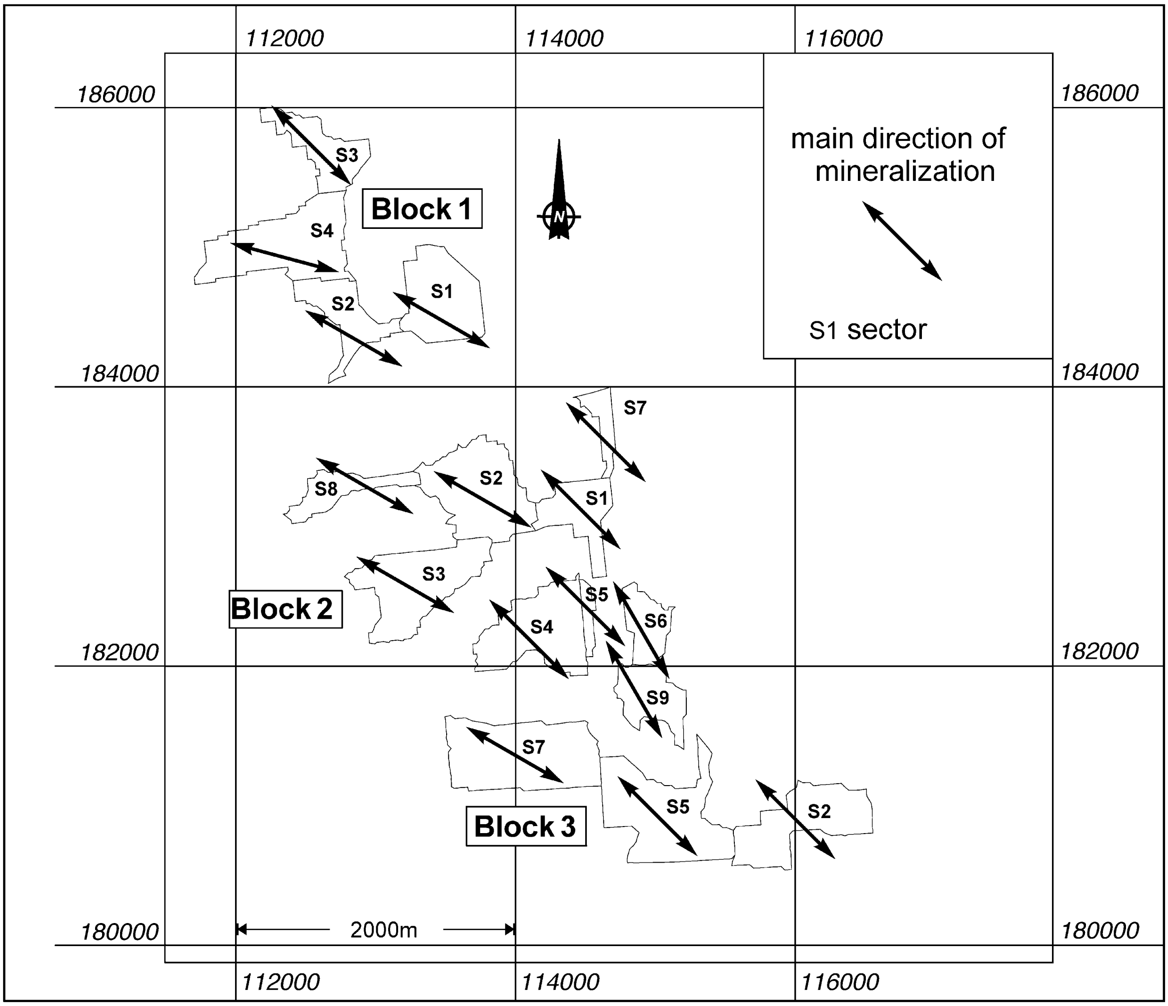

Fig. 9. Schematic map of the Los Pijiguaos mining area. Arrows indicate main direction of mineralization determined by the length of the main axis (R1) of the spherical variogram model.

in quartz as well as other silicate minerals) and total Al_2O_3 determined in block 3, sector 2 are shown in Fig. 8 (total Al_2O_3 refers to the total concentration of alumina in bauxite, whereas available alumina represents the amount of alumina extractable in solution from bauxite by the hot caustic soda leach of the Bayer process). Plan view representation portrays, for the uppermost portion of the bauxite profile, the distribution of R:SiO_2, T:SiO_2, and Al_2O_3 concentrations grouped into eight classes. The data represent average values calculated by the inverse distance weighting (IDW) method for each single block with a specified volume of 12.5 × 12.5 × 1 m. The technique used here is the 'inverse power to distance' method which applies a weighting factor that is based on an exponential distance function. The weighting factor is the inverse of the distance between each sample and the central point of an ore-block, raised to the power of 3. Only samples falling within the specified search volume, are weighted in this way (e.g., Annels, 1991). As can be seen from the figure, R:SiO_2 varies from >4.9 to < 0.7 wt.% with the majority of values falling into the R:Si-7 class. T:SiO_2 ranges from < 29 to >1 wt.%. Most of the data, however, is evenly distributed between the T:Si-7 and T:Si-8 classes. There is also a marked variation of Al_2O_3 within a single sector. Most values exceed the cut-off grade of 44 wt.% Al_2O_3 and reach more than 54 wt.% in some isolated areas at the perimeter of the mining block. The roughly convex geometry of the bauxite blanket and the corresponding spatial relationship of ore grade distributions are depicted in the vertical profiles, also shown in Fig. 8. In addition to lateral grade variations, Al_2O_3 decreases systemati-

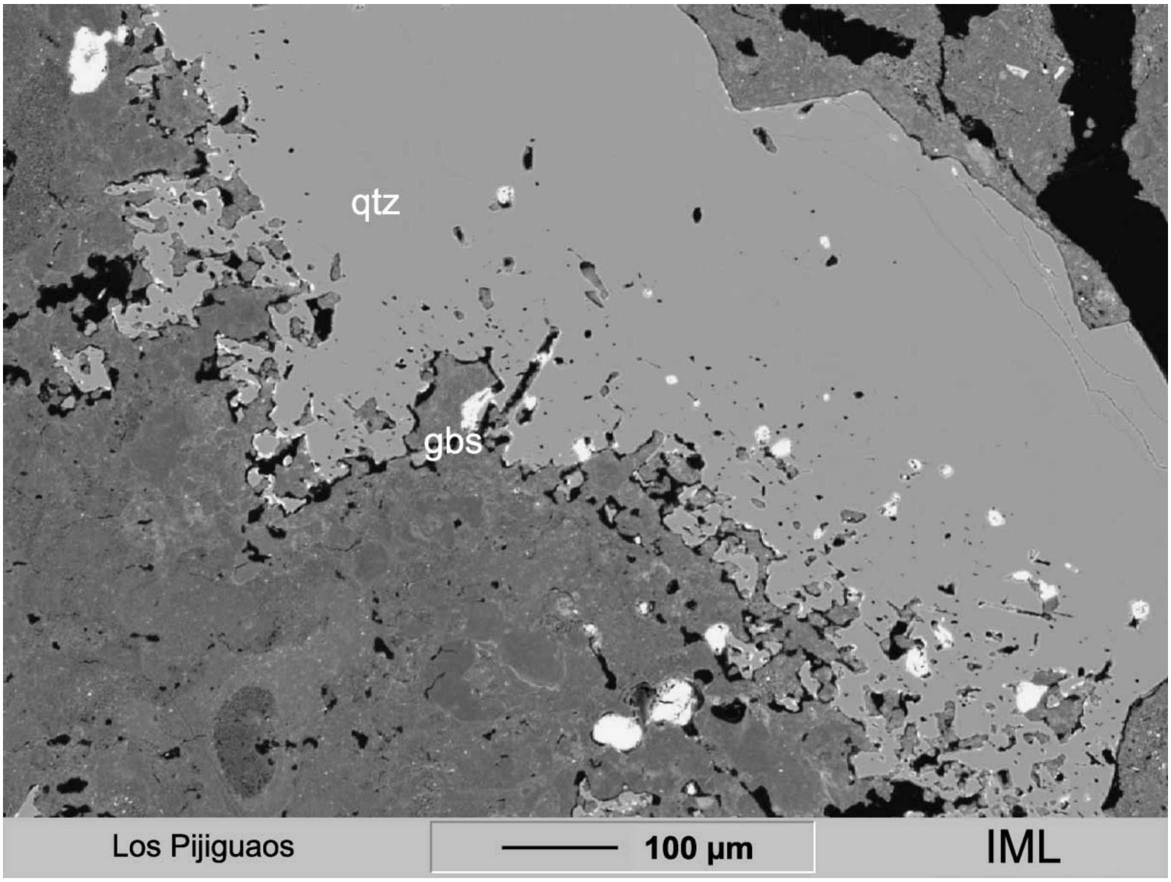

Fig. 10. Backscattered electron image of quartz (qtz) being replaced by gibbsite (gib).

cally with depth while silica concentrations increase. The thickness of the orebody varies between 8 and 9 m. On a mine scale, there is a general tendency for best ore grades and greatest thickness of the ore zone to be located at topographic highs. In some smaller depressions, ore thickness may not decrease (i.e., central portion of block 3, sector 2). This is attributable to local erosion of bauxite at topographic highs followed by transportation and deposition in adjacent depressions. Local transportation of bauxite as well as the alternation and recurrence of ore textures was also recognized by Bárdossy and Aleva (1990) who explained this by an inversion of the topography. Application of geostatistical methods, in particular, examination of semi-variograms (e.g., Lele, 1995; Annels, 1991; David, 1977) calculated for 16 sectors of blocks 1, 2, and 3 revealed that bauxite grade distribution follows distinct WNW–SSE-orientated trends (Fig. 9). The orientation of the main direction of mineralization is represented by the length of the main axis (R1) of the spherical variogram model. The obvious spatial control on mineralization is a result of spatial influences operative during the bauxitization process, such as the westerly inclination of the Nuria surface and/or the formation of major NW-orientated fault systems in the region (see Fig. 2).

3. Mineralogy

The following section provides detailed mineralogic information based on X-ray diffraction as well

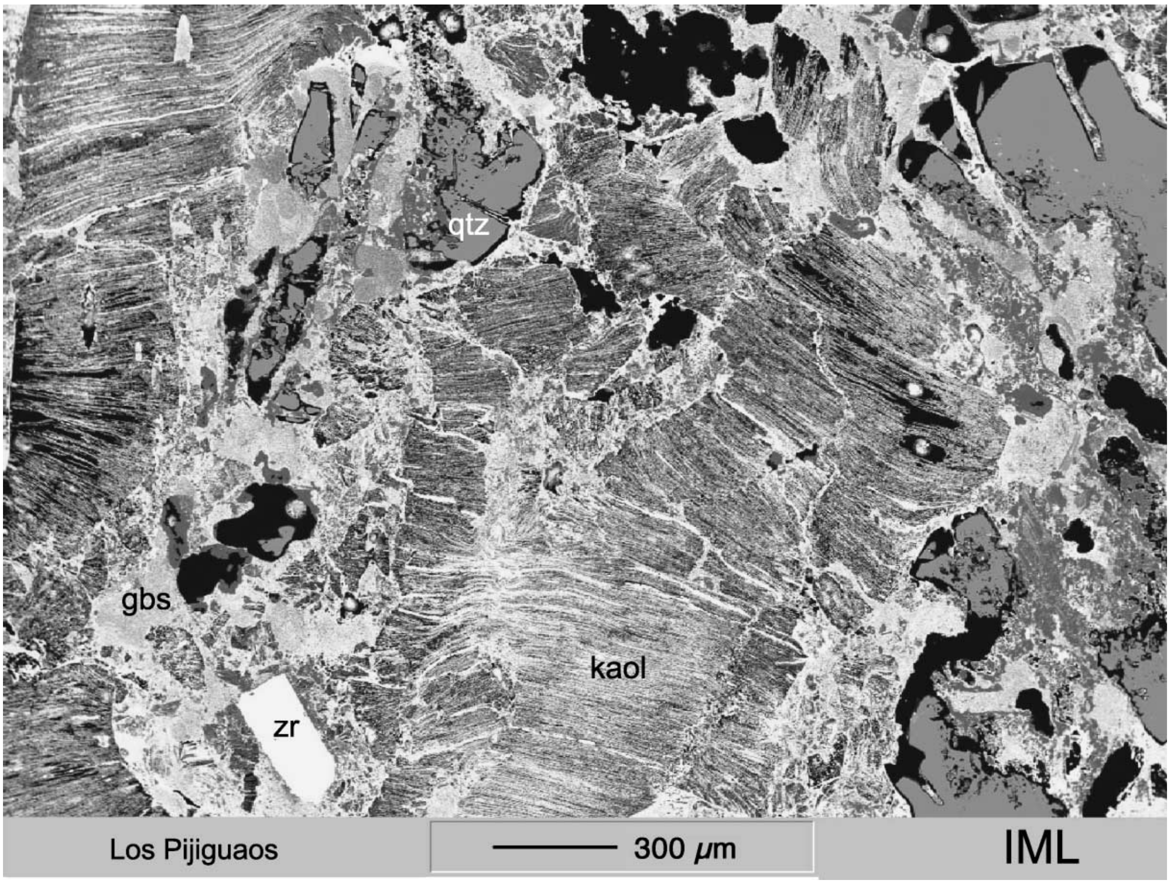

Fig. 11. Backscattered electron image showing various stages of replacement of kaolinite (kaol) by gibbsite (gib). Quartz (qtz) and zircon (zr) are also present.

Table 3
Representative electron microprobe analyses of major minerals from the bauxite profiles

(wt. %)	Gibbsite		Hydromuscovite		Ilmenite		Goethite		Fe-oxyhydroxides	
	Mean ($n=7$)	S.D.	Mean ($n=4$)	S.D.	Mean ($n=6$)	S.D.	Mean ($n=5$)	S.D.	Mean ($n=2$)	S.D.
Al_2O_3	59.85	1.82	35.95	1.53	0.03	0.02	8.17	8.93	10.26	1.15
MgO	–	–	0.07	0.07	0.01	0.00	0.01	0.00	0.01	
CaO	0.01	0.01	0.03	0.03	–	–	–	–	–	–
FeO	–	–	–	–	44.56	0.86	–	–	–	0.00
Fe_2O_3	2.76	2.39	1.71	1.71	–	–	77.40	10.89	48.60	0.16
SiO_2	0.79	0.63	44.61	1.05	0.02	0.01	1.70	2.76	0.47	0.14
Na_2O	0.01	0.01	0.25	0.12	0.01	0.01	0.08	0.13	0.07	0.02
TiO_2	0.40	0.51	0.12	0.18	52.70	0.50	0.41	0.48	3.80	0.26
K_2O	–	–	8.73	1.79	–	–	–	–	–	–
Mn	0.01	0.01	–	–	3.32	0.45	–	–	–	–
Total	63.86	2.11	91.42	2.58	100.64	0.72	87.76	2.78	63.22	1.50

n = Number of mineral grains analyzed; S.D. = standard deviation; – = not analyzed.

as electron microprobe analysis and polished section microscopy. Samples were collected from a number of mine outcrops and three boreholes (i.e., BH 1, BH 2 and BH 3) that intersect the laterite profile down to a depth of 30, 27, and 13 m, respectively (see Fig. 14). Microscopic observation identified gibbsite as the dominant Al phase present in the bauxite horizon (sensu stricto). The mineral occurs with minor quartz and rare kaolinite. Textures include corroded fragments of quartz often partly replaced by platy gibbsite as well as fractures in quartz grains filled by gibbsite (Fig. 10). In some cases it can be seen that original feldspar grains are completely replaced by platy gibbsite, whereby igneous textures such as cross-hatched twinning of microcline, narrow albite twin lamella of oligoclase and cleavage orientations are preserved. In some samples, distinct sporadic flakes of white mica were observed. Kaolinite occurs commonly as book-textured aggregates, in places alternating with gibbsite layers. Various stages of replacement of kaolinite by gibbsite are observed and in places gibbsite forms pseudomorphs after kaolinite (Fig. 11). In cellular textured bauxite samples, round or lenticular cavities can be coated with coarse, platy gibbsite. A few samples contain older fragments of well-rounded quartz grains and gibbsite aggregates that are now cemented by a matrix of fine-grained gibbsite, iron oxyhydroxides as well as small broken-up grains of quartz, ilmenite, and zircon. Evidence from this texture suggests that in some places at least, transport and re-deposition of bauxite must have had occurred. The presence of variable amounts of iron oxyhydroxides is indicated by the intense red to light brown coloration of the samples. All investigated samples contain small amounts of ilmenite, euhedral, zoned zircon, goethite, and martite, i.e. magnetite partly to completely replaced by hematite. As these

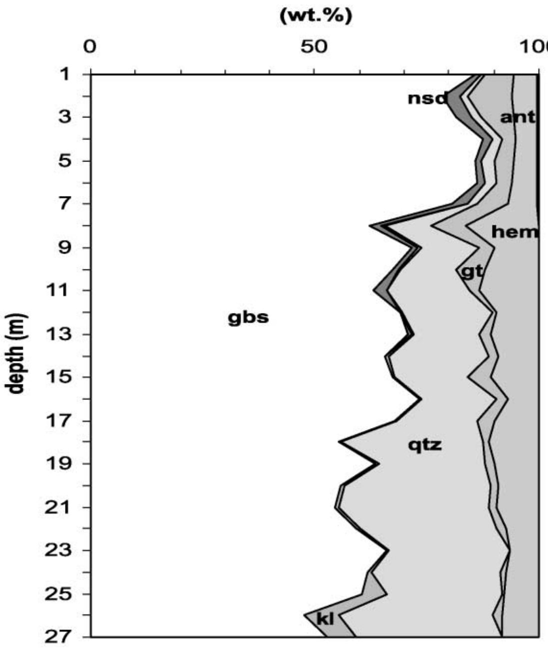

Fig. 12. Vertical distribution of gibbsite (gbs) nordstrandite (nsd) kaolinite (kaol), quartz (qtz), goethite (gt), hematite (hem), and anatase (ant) in borehole BH 2. Mineral contents were determined by the Rietveld method.

phases are also present in the Parguaza granite, they are interpreted to represent inherited, relict minerals that were not altered during the bauxitization process.

Electron microprobe analyses (JEOL JXA-8900R) of main minerals are summarized in Table 3. Gibbsite contains almost 3 wt.% Fe_2O_3 whereas Al_2O_3 is distinctly lower than the theoretical concentration of 65,4 wt.%. Since statistical data treatment failed to prove a correlation between the two variables it is not clear if Fe^{+3} substitutes for Al in the gibbsite lattice, or if Fe is present as impurities. Hydromuscovite is evidenced by lower K_2O and higher H_2O compared to muscovite. Associated high Fe_2O_3 of almost 2 wt.% may be due to Fe staining. In case of goethite, which contains up to 8 wt.% Al_2O_3, it is assumed however, that Al occurs in the crystal lattice and that the mineral represents alumogoethite. The composition of ilmenite is identical to that of the Parguaza granite (see Table 1). An unidentified iron-oxyhydroxide phase analyzed contains, in addition to 10 wt.% Al_2O_3, almost 4 wt.% TiO_2 and is, with ilmenite and anatase, the main concentrator of Ti.

Table 4
Chemical composition of bauxite and saprolite samples

	Bauxite							Saprolite						
	n	Mean	S.D	Median	G.Mean	Min	Max	*n*	Mean	S.D.	Median	G.Mean	Min	Max
SiO_2 (wt.%)	31	9.10	5.06	8.33	7.55	2.01	18.58	52	38.02	12.95	39.60	35.32	9.37	58.59
TiO_2	31	1.15	0.28	1.14	1.12	0.51	1.70	52	0.93	0.25	0.83	0.90	0.57	1.61
Al_2O_3	31	49.10	3.14	49.20	49.00	44.43	56.08	52	34.56	6.39	34.29	33.95	23.50	47.49
Fe_2O_3(T)	31	12.79	5.26	11.91	11.68	4.05	23.92	52	8.36	5.33	6.38	7.50	4.38	36.40
MnO	31	0.02	0.01	0.02	0.02	0.01	0.05	52	0.03	0.03	0.03	0.02	0.01	0.15
MgO	31	0.10	0.00	0.10	0.10	0.10	0.10	52	0.01	0.00	0.01	0.01	0.01	0.01
CaO	31	0.02	0.00	0.02	0.02	0.02	0.02	52	0.02	0.00	0.02	0.02	0.02	0.02
Na_2O	31	0.17	0.03	0.16	0.17	0.14	0.24	52	0.20	0.31	0.16	0.15	0.10	2.28
K_2O	31	0.02	0.00	0.02	0.02	0.01	0.04	52	0.03	0.01	0.03	0.03	0.01	0.09
P_2O_5	31	0.06	0.01	0.06	0.06	0.04	0.09	52	0.08	0.02	0.09	0.08	0.04	0.12
LOI	31	26.76	1.65	26.50	26.71	23.76	30.29	52	17.01	4.65	17.12	16.36	9.79	25.50
Total	31	99.20	0.36	99.27	99.20	98.49	99.75	52	99.2	0.71	99.2	99.2	97.8	101
Ba (ppm)	31	22.2	4.8	20.0	21.8	20.0	38.0	52	109	78.3	95.5	83.9	20.0	339
Sr	31	11.9	2.0	11.5	11.7	10.0	16.0	52	20.1	6.5	19.0	19.0	10.0	35.0
Rb	31	4.69	1.13	4.00	4.58	3.80	8.60	52	8.56	1.27	8.24	8.46	4.60	12.3
Pb	31	20.2	5.00	22.5	19.5	12.0	27.0	52	35.6	19.0	31.5	30.6	10.0	98.0
Zn	31	19.0	6.07	17.0	18.1	10.0	34.0	52	24.1	8.6	26.0	22.3	10.0	38.0
Th	9	166	43.1	159	160	89.6	227	26	86.8	30.8	78.5	81.5	51.8	143
U	9	7.11	2.82	6.10	6.69	4.90	14.2	26	6.53	2.69	5.00	6.00	2.90	12.40
Zr	31	1033	327	983	978	418	1735	52	802	231	699	775	527	1583
Mo	31	14.8	4.39	13.5	14.3	10.0	25.0	52	13.0	3.18	12.0	12.7	10.0	21.0
Nb	31	78.8	21.0	78.0	75.8	33.0	117	52	63.6	17.6	55.0	61.5	43.0	111
Y	31	11.2	0.69	11.0	11.1	10.0	12.0	52	11.2	1.41	11.0	11.1	10.0	14.0
Sc	9	5.21	1.25	5.10	5.07	3.70	7.30	26	6.29	1.82	6.50	6.01	4.00	9.10
Ga	9	75.1	14.3	77.0	73.6	45.0	97.0	26	54.0	14.6	47.5	52.1	36.0	87.0
La	9	36.2	19.5	29.0	31.9	18.8	73.0	26	67.6	40.2	59.4	54.5	17.6	135
Ce	9	60.8	15.2	62.0	58.8	38.0	86.0	26	143	141	95.0	103	35.0	712
Nd	9	12.1	8.62	8.0	9.8	5.0	30.0	26	26.1	15.8	21.0	21.0	8.00	54.0
Sm	9	1.75	0.94	1.41	1.56	0.99	3.62	26	3.13	1.74	2.87	2.61	0.93	6.55
Eu	9	0.36	0.12	0.33	0.34	0.26	0.59	26	0.50	0.23	0.50	0.44	0.17	0.83
Tb	9	0.30	0.12	0.20	0.28	0.20	0.50	26	0.44	0.22	0.40	0.38	0.20	0.80
Yb	9	1.97	0.57	1.77	1.90	1.38	2.88	26	1.80	0.43	1.73	1.75	1.23	2.69
Lu	9	0.32	0.11	0.29	0.30	0.21	0.49	26	0.29	0.07	0.28	0.28	0.19	0.41

n = Number of analyses; S.D. = standard deviation; G.Mean = geometric mean).

Minerals identified by X-ray powder diffraction comprise gibbsite, nordstrandite, quartz, kaolinite, goethite, hematite, and anatase, as well as rare illite/hydromuscovite, ilmenite, and zircon. Quantification of XRD analysis was carried out with the Rietveld method (e.g., Chung and Smith, 2000) utilized by the TOPAS R V2.0™ software of Bruker AXS. The results are presented in Fig. 12, where modal mineral contents of samples, which were collected at 1-m intervals from borehole BH 2, are plotted. Gibbsite abundance varies between 78 and 86 wt.% in the economic-grade bauxite zone of the profile, to a depth of 7 m below surface. From here on, the mineral decreases steadily to a minimum content of less than 50 wt.% in the saprolite horizon. The occurrence of nordstrandite is restricted to the first 10 m of the borehole, with maximum concentrations occurring in the bauxite zone. Kaolinite was not detected in the bauxite horizon (sensu stricto). The mineral never reaches more than 1 wt.% for most parts of the profile. In the lower saprolite zone, however, kaolinite abundance increases to more than 5 wt.%. An inverse correlation exists between gibbsite and quartz. Abundance ratios for the two minerals decrease from around 45 in the bauxite horizon to around 2 in the lower saprolite zone. Quartz contents vary systematically from 3 wt.% in upper portion of the profile to a maximum of 35 wt.% at the end of the borehole. Among the Fe minerals, hematite is commonly more abundant than goethite. But this is not the case for the bauxite horizon where goethite/hematite ratios are greater than 1. With increasing depth, however, there is the general tendency for hematite to become the dominant Fe phase. A significant positive correlation ($r^2 = 0.80$) exists between goethite/hematite ratios and the bulk Fe_2O_3 contents of concomitant samples. Anatase occurs as an accessory phase mainly in the bauxite horizon.

4. Geochemistry

Mean chemical compositions of 31 bauxite and 52 saprolite samples collected from three boreholes (BH

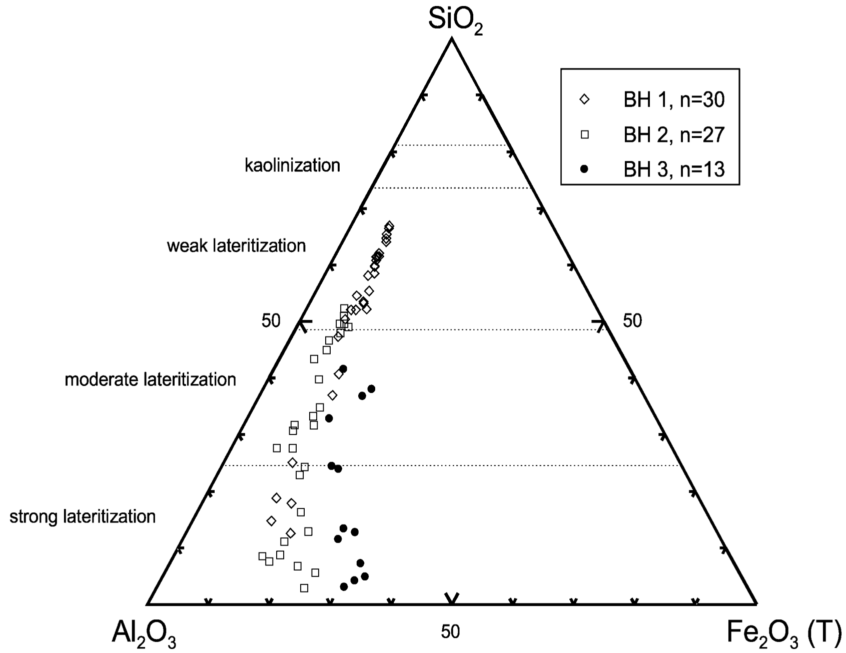

Fig. 13. Triangular plot of SiO_2, Al_2O_3, and Fe_2O_3 and sample classification according the scheme after Schellmann (1982). Samples were collected from boreholes BH 1, BH 2, and BH 3.

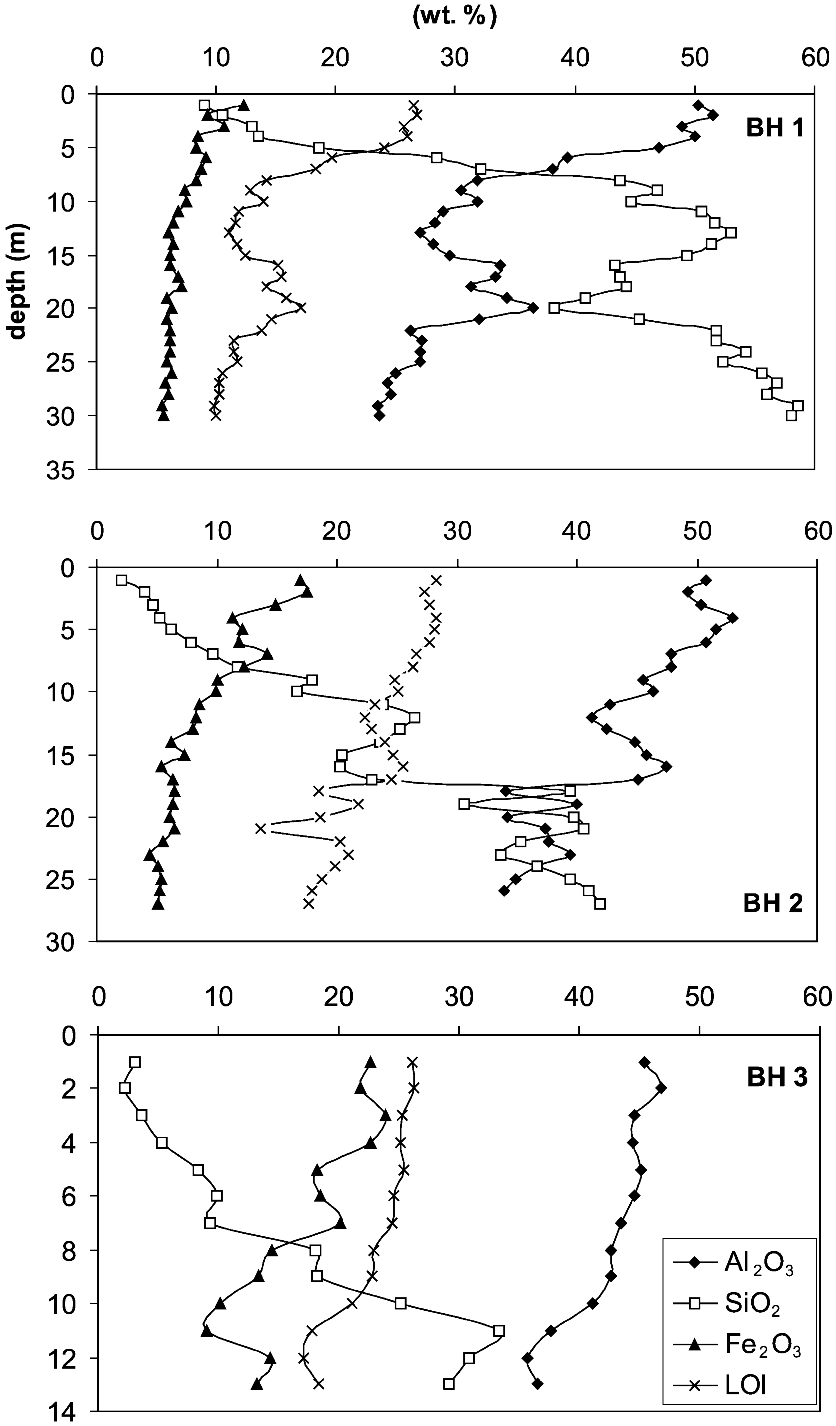

Fig. 14. Plot showing the vertical variation of Al_2O_3, H_2O, Fe_2O_3, and SiO_2 in boreholes BH 1, BH 2, and BH 3.

Table 5
Correlation matrix of element contents in bauxite and saprolite samples

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3(T)	MnO	P_2O_5	LOI	Ba	Th	U
SiO_2	1	− 0.35	− 0.25	− 0.61	0.18	0.21	− 0.58	0.29	− 0.72	0.26
TiO_2	− 0.60	1	− 0.69	0.83	− 0.55	− 0.56	− 0.42	− 0.21	0.74	− 0.77
Al_2O_3	− 0.89	0.43	1	− 0.61	0.33	0.47	0.89	0.05	− 0.33	0.50
Fe_2O_3(T)	− 0.59	0.58	0.16	1	− 0.41	− 0.52	− 0.27	− 0.20	0.83	− 0.57
MnO	0.45	− 0.09	− 0.51	− 0.07	1	− 0.10	0.19	− 0.13	0.28	− 0.58
P_2O_5	0.72	− 0.67	− 0.56	− 0.60	0.27	1	0.28	0.43	− 0.40	0.37
LOI	− 0.92	0.41	0.96	0.26	− 0.52	− 0.58	1	− 0.23	0.15	0.20
Ba	− 0.18	− 0.23	0.14	0.10	0.00	− 0.07	0.23	1	− 0.71	0.44
Th	− 0.86	0.50	0.86	0.47	− 0.55	− 0.69	0.83	0.14	1	− 0.56
U	− 0.52	− 0.20	0.67	− 0.29	− 0.59	− 0.09	0.69	0.47	0.59	1
Zr	− 0.63	0.95	0.49	0.51	− 0.11	− 0.59	0.49	− 0.09	0.65	− 0.01
Nb	− 0.69	0.95	0.54	0.56	− 0.17	− 0.77	0.53	− 0.13	0.66	− 0.07
Sc	0.62	0.10	− 0.71	0.05	0.65	0.38	− 0.76	− 0.47	− 0.75	− 0.84
Ga	− 0.83	0.89	0.64	0.70	− 0.27	− 0.84	0.65	− 0.07	0.70	0.00
La	0.72	− 0.07	− 0.76	− 0.15	0.61	0.51	− 0.81	− 0.42	− 0.81	− 0.80
Ce	0.63	− 0.24	− 0.67	− 0.20	0.89	0.41	− 0.65	0.00	− 0.61	− 0.58
Nd	0.77	− 0.14	− 0.81	− 0.22	0.61	0.58	− 0.83	− 0.35	− 0.84	− 0.77
Sm	0.77	− 0.10	− 0.83	− 0.14	0.61	0.51	− 0.85	− 0.37	− 0.82	− 0.81
Eu	0.71	− 0.01	− 0.78	− 0.04	0.62	0.43	− 0.82	− 0.43	− 0.79	− 0.86
Tb	0.68	− 0.03	− 0.76	− 0.02	0.59	0.45	− 0.78	− 0.45	− 0.77	− 0.79
Yb	− 0.20	0.78	0.02	0.83	0.13	− 0.53	− 0.07	− 0.53	0.07	− 0.62
Lu	− 0.13	0.75	− 0.03	0.77	0.15	− 0.48	− 0.13	− 0.52	0.02	− 0.63

Saprolite

1, BH 2, BH 3) and from surface outcrops are summarized in Table 4. Major element analysis was carried out by standard X-ray fluorescence (XRF). Trace elements were determined by a combination of X-ray fluorescence (XRF) and neutron activation (NAA) analysis. The data table confirms that Al_2O_3, Fe_2O_3, SiO_2 and H_2O (i.e., LOI; chiefly H_2O as the samples are free of other volatiles) are the dominant chemical components in both bauxite and saprolite samples. Distinction between the two principal rock types of the laterite profile is based on a triangular plot of Al_2O_3, Fe_2O_3, and SiO_2 shown in Fig. 13, where the samples define a trend with continuous change from SiO_2-rich to Al_2O_3-rich compositions. According to the classification scheme of Schellmann (1982), chemical variability expressed in the plot is process-related and can be explained by different degrees of lateritization, so that SiO_2-rich samples experienced weak lateritization while Al_2O_3-rich compositions are indicative of a high degree of lateritization. Interestingly, the boundary between moderate and strong lateritization corresponds roughly to an Al_2O_3 and SiO_2 content of about 44 and 20 wt.%, respectively. As these values also define the cut-off grade in the Los Pijiguaos mine, in the following only those samples are classified as bauxite, that plot in the field of strong lateritization, while samples plotting further away from the Al_2O_3 corner are referred to as saprolite. Accordingly, the thickness of the bauxite layer reaches 6 m in BH 1, 10 m in BH 2, and 5 m in BH 3. This is also shown in Fig. 14, portraying the vertical variation of Al_2O_3, SiO_2, Fe_2O_3, and LOI in the three boreholes. Most obvious is a continuous decrease of Al_2O_3, Fe_2O_3, and H_2O and a concomitant increase of SiO_2 with depth.

The relation between rock chemistry and mineralogy was further investigated using correlation analysis. Pearson correlation coefficients for both bauxite and saprolite samples are summarized in a correlation matrix (Table 5). In bauxite, SiO_2 does not show any strong positive associations with other elements. Al_2O_3 is highly correlated with LOI. Two further groups of elements can be distinguished with a high positive correlation among elements within each

Zr	Nb	Sc	Ga	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
				Bauxite							
−0.41	−0.37	0.22	−0.58	0.22	−0.25	0.24	0.26	0.18	0.37	−0.11	−0.10
0.97	0.98	−0.35	0.87	−0.81	−0.43	−0.83	−0.73	−0.75	−0.15	0.69	0.71
−0.64	−0.66	−0.09	−0.51	0.48	0.34	0.49	0.35	0.40	−0.21	−0.76	−0.81
0.84	0.82	−0.06	0.88	−0.49	0.01	−0.52	−0.42	−0.40	−0.11	0.68	0.70
−0.46	−0.50	−0.05	−0.49	−0.48	−0.38	−0.51	−0.35	−0.51	0.39	0.81	0.82
−0.58	−0.61	0.00	−0.37	0.57	0.52	0.54	0.42	0.48	−0.12	−0.76	−0.78
−0.36	−0.36	−0.40	−0.19	0.09	0.21	0.09	−0.05	0.05	−0.55	−0.66	−0.70
−0.23	−0.30	0.70	−0.22	0.94	0.79	0.92	0.91	0.93	0.52	−0.18	−0.25
0.76	0.71	−0.51	0.91	−0.74	−0.23	−0.77	−0.74	−0.65	−0.61	0.27	0.32
−0.78	−0.75	0.41	−0.61	0.58	0.02	0.68	0.58	0.56	0.10	−0.43	−0.41
1	0.97	−0.40	0.87	−0.80	−0.40	−0.83	−0.73	−0.73	−0.23	0.64	0.65
0.93	1	−0.34	0.85	−0.81	−0.47	−0.83	−0.73	−0.76	−0.13	0.69	0.72
−0.09	−0.13	1	−0.44	0.72	0.52	0.75	0.82	0.81	0.73	0.41	0.36
0.83	0.93	−0.21	1	−0.70	−0.21	−0.72	−0.69	−0.66	−0.41	0.40	0.42
−0.26	−0.32	0.93	−0.35	1	0.74	0.99	0.98	0.96	0.59	−0.18	−0.24
−0.34	−0.35	0.71	−0.41	0.62	1	0.67	0.70	0.76	0.38	−0.01	−0.09
−0.31	−0.38	0.91	−0.42	0.99	0.66	1	0.98	0.96	0.57	−0.20	−0.25
−0.28	−0.33	0.93	−0.38	0.98	0.67	0.99	1	0.96	0.69	−0.03	−0.08
−0.20	−0.23	0.95	−0.28	0.97	0.66	0.96	0.98	1	0.51	−0.10	−0.16
−0.21	−0.23	0.90	−0.29	0.87	0.69	0.89	0.89	0.88	1	0.49	0.44
0.61	0.70	0.50	0.66	0.36	0.09	0.27	0.34	0.44	0.33	1	0.99
0.58	0.66	0.53	0.60	0.40	0.10	0.32	0.38	0.48	0.32	0.98	1

group. One group comprises TiO_2, Fe_2O_3, Zr, Nb, Th, Ga. Also linked to this group are Yb and Lu, but with weaker correlation. The association of these elements is the consequence of the abundance of two or more minerals. The combination of Zr, Th, Yb, and Lu serves as an indication for the presence of zircon in the bauxite profile. TiO_2, Fe_2O_3, and Nb are typical components of ilmenite, goethite, and other Fe oxy-hydroxides (see Table 2). The latter assemblage probably also constitutes the host to Ga that is weakly negative associated with Al (cf. Hieronymus et al., 2001). In the saprolite samples, TiO_2, Fe_2O_3, Zr, Nb, Th, Ga, Yb, and Lu are also highly correlated and, thus, they point to the presence of the same mineral hosts. The occurrence of anatase, one of the main concentrators of Ti, is restricted to the bauxite zone where goethite is more abundant than hematite. This can be explained by the findings of Trolard et al. (1995) that Ti substitutes for Fe in hematite, but not in goethite. Therefore, in the saprolite Ti, is preferentially hosted in hematite in addition to ilmenite which may explain the high positive correlation between Ti, Fe, and Nb.

Similar to what was found in bauxite samples, in the saprolite Al_2O_3 is also highly correlated with LOI. SiO_2, however, shows a moderate association with P_2O_5, La, Ce, Nd, Sm, Eu, Tb in the saprolite. The latter elements correlate positively with each other and reflect the presence of apatite, which also occurs as an accessory mineral in the Parguaza granite. The fact that P_2O_5 is higher in the saprolite than in the bauxite samples (Table 4) points to the fact that apatite was not stable during the bauxitization process, but that the mineral is still preserved in the less weathered saprolite horizon. From Brazilian laterites, it is reported (Morteani and Preinfalk, 1996) that apatite was found to be the main concentrator of REE. The increasing abundance of SiO_2 in the laterite portions of the profiles (Fig. 14) reflects lesser degrees of bauxitization and preservation of apatite with depth and, thus, explains the association of SiO_2 with the P_2O_5-LREE group. In the saprolite samples, Sc also forms a strong positive correlation with the LREE. The element is commonly observed to be concentrated in REE minerals where it tends to substitute for HREE and Y. In the present samples, apatite is the principal host for LREE and probably the main carrier of Sc.

5. Source material and mass changes

From basic geologic observations described above, it is easily deducible that the Los Pijiguaos bauxite blanket can be directly related through field relations, texture, and geochemistry to the underlying Parguaza granite. Geochemical relations between parent granite and laterite cover is shown in Fig. 15. Al_2O_3 and LOI distributions follow a trend starting from granite through saprolite and bauxite towards an ideal gibbsite composition of 65 wt.% Al_2O_3 and an LOI value of 35 wt.%. From a geochemical point of view, bauxite can be taken as the product of pedogenic processes under weathering conditions that are conducive to progressive desilication, hydration and Al_2O_3 concentration in the residual soil. The TiO_2–Zr diagram also produces a highly correlated single array for granite, saprolite, and bauxite that passes through the origin. This indicates (1) that the samples

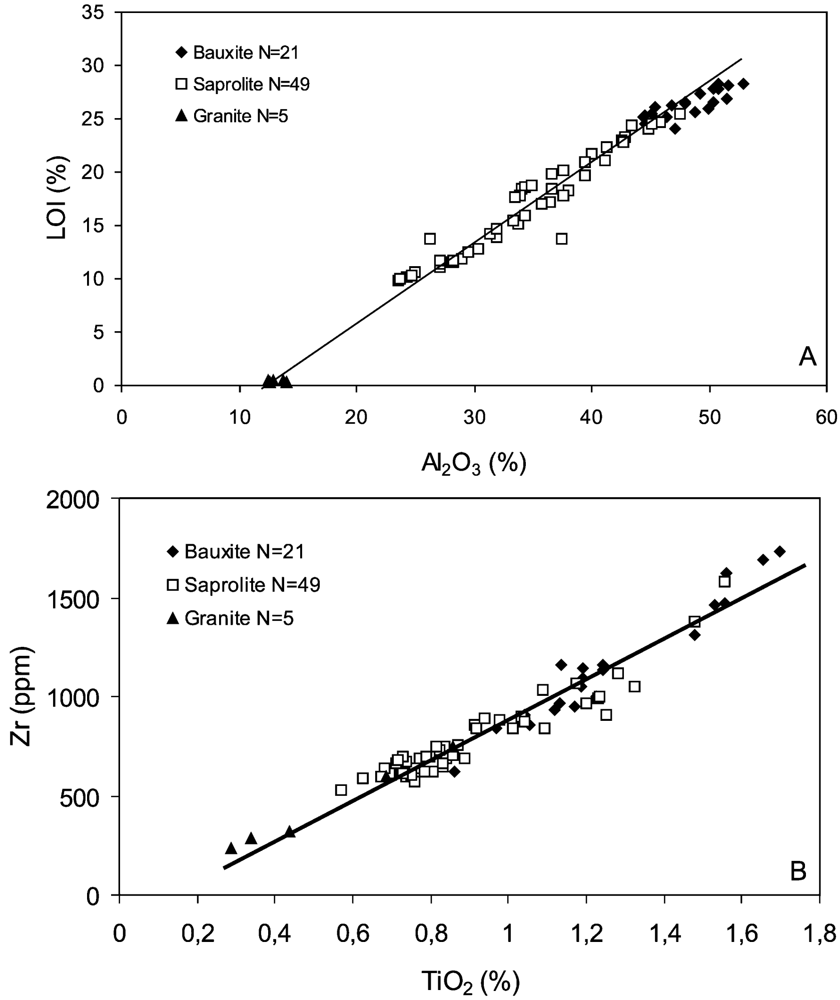

Fig. 15. Scattergram of Al_2O_3 versus H_2O (A) and TiO_2 versus Zr (B).

are related genetically and, (2) that the two elements were probably immobile during weathering.

Comparison of mean concentrations of a number of elements in saprolite and bauxite samples with that of the Parguaza granite reveals relative enrichment during bauxitization of Th, Nb, Zr, and Ti and depletion of all other elements shown in Fig. 16. However, this simple comparison does not take mass and volume change into account. As has been demonstrated for a number of geologic environments and processes, immobile elements can be used to quantify chemical modifications as well as mass and volume changes that may take place during hydrothermal alteration or mineralogical reactions associated with weathering (e.g., Baumgartner and Olsen, 1995; Grant, 1986). Fig. 17 was constructed using Grant's (1986) isocon method to graphically identify immobile elements and to quantify mass and volume changes that occurred during the lateritization process. For that reason, the two plots compare the mean chemical composition of the Parguaza granite with that of the bauxite and saprolite samples, respectively. The overall pattern is very similar and in both cases the isocon, i.e. the linear trend on which identification of immobile elements is based, is defined by TiO_2, Nb, and Zr. Components such as H_2O (i.e., LOI) and, to a much lesser extent, Al_2O_3, Fe_2O_3, Ga, and Th that plot above the isocon were gained whereas all elements that plot below the isocon were lost during bauxitization. Interestingly, the apparent addition of Al_2O_3, Fe_2O_3, Ga, and Th to the bauxite and saprolite relative to the granite points to the fact that remobilization of these elements must have taken place.

Applying relevant equations provided by Grant (1986), measured sample densities together with the slope of the isocons were used to calculate mass and volume changes that had occurred due to weathering of the Parguaza granite. In the case of bauxite (Fig. 17a), the isocon slope is 2.6—which relates to a mass loss of 61.5% and a volume loss of 76.9%. For the saprolite (Fig. 7b), the slope of the isocon is 1.8 and the mass and volume loss amounts to 44.4% and 62.9%, respectively. In a similar way, Grant's (1986) equations can be used to quantify the changes in concentrations for those elements that were mobile during the lateritization process, i.e. components that plot above or below the isocon in Fig. 17. The calculated concentration changes are illustrated for bauxite as well as saprolite samples in Fig. 18. The only component that was gained to a large degree is H_2O (LOI) due to the formation of hydrated minerals (i.e., gibbsite, kaolinite, goethite) during bauxitization. Other elements that were also distinctly enriched in the weathering mantle include Al_2O_3, Fe_2O_3, Ga and Th. The latter element, in particular, reaches concentrations of up to 227 ppm in the bauxite (Table 4). The

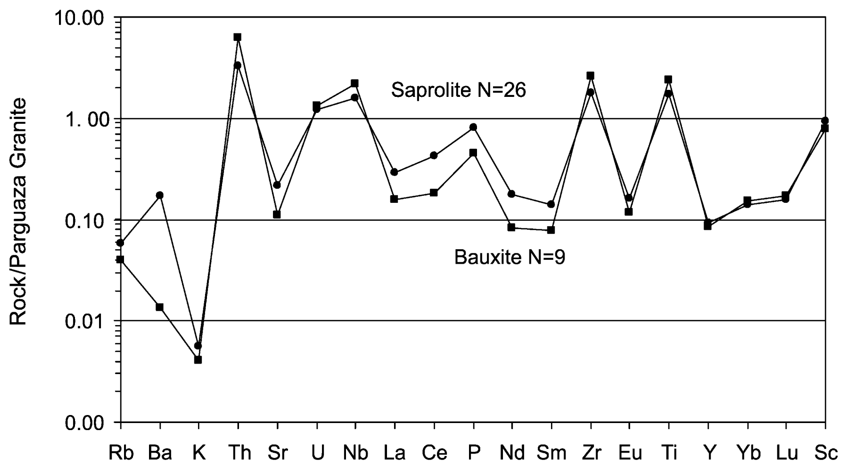

Fig. 16. Parguaza granite normalized plot of bauxite and saprolite samples.

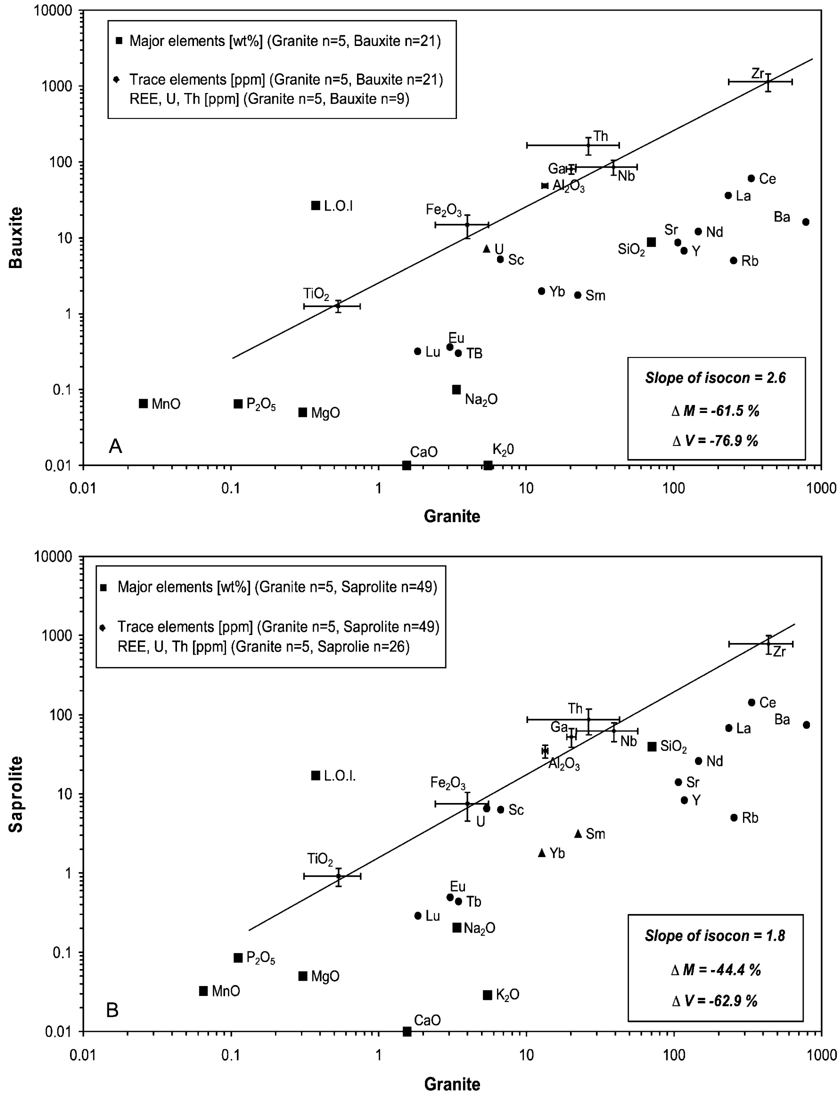

Fig. 17. Isocon mass balance diagrams (Grant, 1986) comparing mean compositions of bauxite (A) and saprolite (B) to the mean composition of the Parguaza granite. Error bars represent 1 standard deviation variance for each average group. ΔM and ΔV denote mass and volume changes, respectively.

overall pattern for the other mobile elements is that they are significantly more depleted in the bauxite than in the saprolite horizon. As can be expected, K_2O, Na_2O, Ba, and Rb are almost completely lost from the weathering profile whereas SiO_2, MnO, MgO, Y, Sr, and REE are depleted by 70 to more than 90%. Moderate depletion is observed for P_2O_5, Sc and U.

6. Discussion

6.1. Genetic considerations

The geometry and textural make-up of the bauxite blanket, geochemical trends, and mineralogical data all unanimously point to the fact that Los Pijiguaos represents a typical laterite bauxite deposit that formed on a

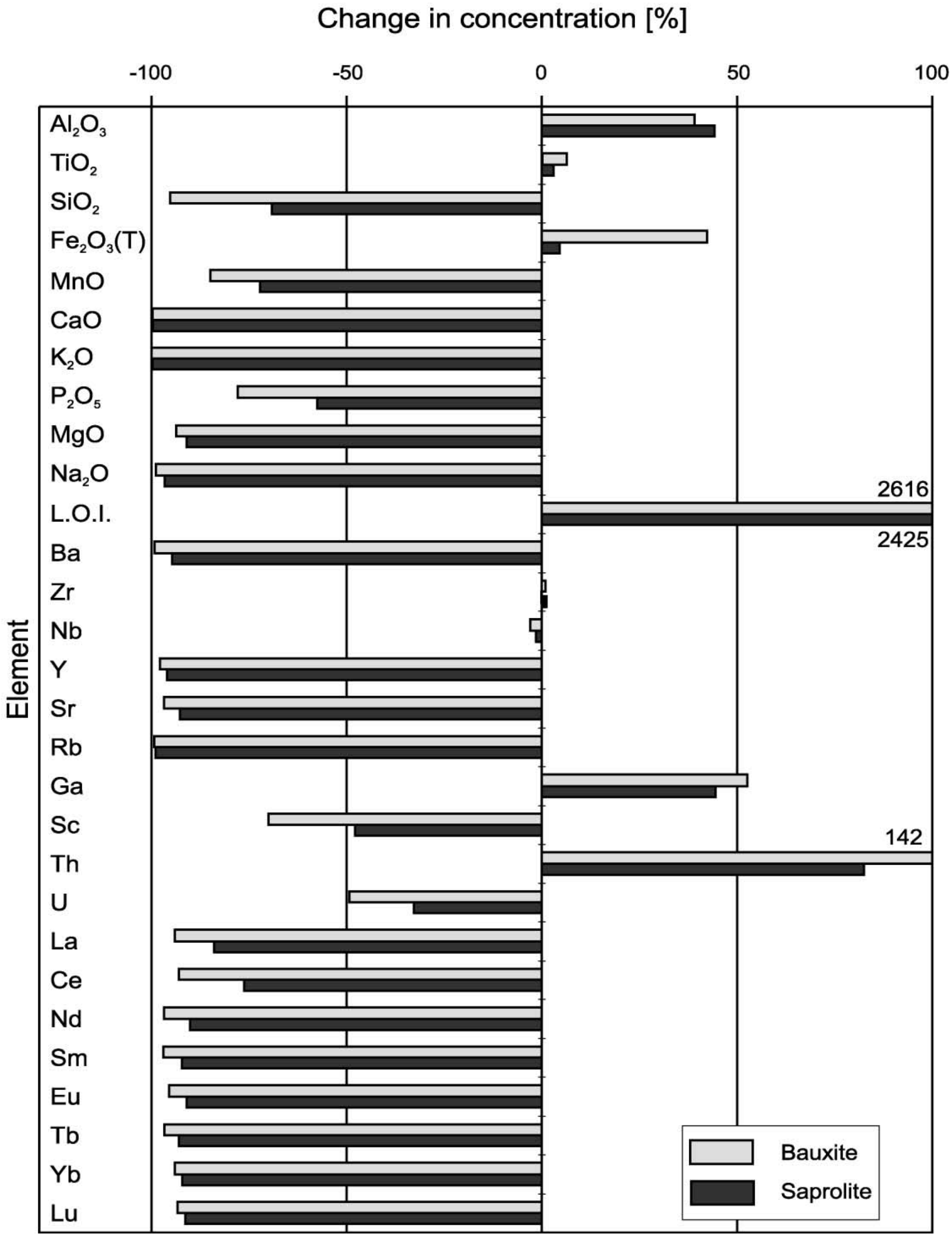

Fig. 18. Percentage mass gains and losses of mean bauxite and saprolite compositions relative to the mean Parguaza granite composition.

flat topped plateau, the Nuria planation surface, from weathering of the underlying Parguaza granite. This basic genetic model is corroborated by previous work (e.g., Soler and Lasaga, 2000; Bárdossy and Aleva, 1990; Lo Mónaco, and Yanes, 1990; Quintero and Marino, 1990; Menendez and Sarmentero, 1984). However, Bárdossy and Aleva (1990) have argued previously in that bauxite is not of a simple in-situ, residual origin, but that secondary processes such as physical disintegration, transport, and redeposition must have occurred to explain the alternation and recurrence of textural features within the profile. From their work, Soler and Lasaga (2000) arrived at a similar conclusion and stated further that the bauxitization process is still active at present.

Our microtextural observations of well-rounded quartz grains and gibbsite aggregates also provide evidence that in some places at least, mechanical transport and re-deposition of mineral grains must have occurred. In addition, decoupling of Ga from Al in the bauxite layer suggests chemical transport. Hieronymus et al. (2001) found that the contrasting behaviour of Ga and Al in bauxite is attributable to the dissolution of early formed Ga-bearing phases such as gibbsite and kaolinite, whereby Al will be redistributed in the bauxite zone while Ga will either be leached from the profile or retained by Fe oxyhydroxides. The less pronounced separation of Ga from Al in the saprolite zone is indicative that secondary chemical processes are more active in the uppermost part of the profile. Accordingly, the presence of nordstrandite, a mineral polymorphous with gibbsite, in the bauxite layer may also be taken as evidence for ongoing secondary bauxitization processes (e.g., Grubb, 1973). Reviewing experimental studies, Hsu (1977) concluded that slow aging of OH–Al polymers under acidic conditions usually yields gibbsite whereas rapid precipitation under neutral or alkaline conditions yields nordstrandite and/or bayerite.

Bárdossy and Aleva (1990) identified Los Pijiguaos as one of only two major bauxite deposits worldwide that contain hematite in abundance to goethite. Using relative intensity ratios of X-ray diffraction data, Soler and Lasaga (2000) found a positive correlation between hematite/goethite ratios and bulk rock Fe concentrations and, thus, an inverse correlation with depth. Low iron samples with Fe_2O_3 contents of less than 7 wt.% were found to be conspicuous by the absence of hematite. The authors explained this by different stabilities of the two minerals with respect to variable water activity (α_{H_2O}) in the weathering profile. In the water-saturated zone, α_{H_2O} conditions are expected to be equal to unity, which is favorable for the formation of goethite. In the unsaturated zone above the water table, α_{H_2O} is presumably smaller than unity, so that hematite is the stable Fe phase.

The Rietfeld-derived modal mineral analyses reported here yield somewhat different results, at least for the uppermost 7 m of the profile. In the bauxite layer, the abundance of goethite is generally higher than that of hematite with a maximum goethite content of 9.5 wt.% and the highest goethite/hematite ratio of 1.7. In the presumably water-saturated saprolite section, starting from 7 m below surface, however, the main Fe mineral is hematite and the goethite/hematite ratio never reaches 0.5. Contrary to the results reported by Soler and Lasaga (2000), our data set produces a significant positive correlation between goethite/hematite ratios and bulk Fe_2O_3 concentrations in concomitant samples. The data demonstrate maximum goethite/hematite ratios to correspond to maximum Fe_2O_3 contents at the uppermost portion of the bauxite section while Soler and Lasaga (2000) found the ratios to decrease with increasing Fe_2O_3. Using the same approach adopted by Soler and Lasaga (2000), i.e. plotting hematite to goethite X-ray intensity ratios versus bulk Fe_2O_3 concentrations yielded no correlation since the intensities are not directly related to mineral contents. Similarly, Asylmore and Walker (1998) found the Rietveld method to yield accurate mineralogical abundances in bauxite and laterite samples. Our results may be further substantiated by another line of evidence that is provided by the occurrence of anatase restricted to the bauxite zone where goethite is more abundant than hematite. This is explainable by the findings of Trolard et al. (1995) that Ti substitutes for Fe in hematite, but not in goethite. Therefore, in samples where goethite dominates over hematite, less Ti is taken up by Fe phases so that secondary anatase can form.

According to Trolard and Tardy (1987) and Goss (1987), the stability of goethite and hematite in bauxites and laterites depends not only on environmental factors such as water activity and temperature but also on particle size, grain shape, crystallinity, excess structural water and, in cases where the two minerals contain Al in addition to Fe, on the chemical composition of the bulk system. Trolard and Tardy (1987) predicted from thermodynamic equilibria that Al-goethite and Al-hematite can coexist at conditions of water activity lower than unity, but not in the presence of gibbsite. If, as is the case at Los Pijiguaos, the mineral association comprises Al-goethite, hematite, and gibbsite, Trolard and Tardy (1987) concluded that grain size must be the main controlling factor on mineral stability.

Mass balance calculations revealed H_2O to be the main component gained by bauxite and, to a lesser degree, by saprolite during weathering of the Parguaza granite, while silica as well as alkali and alkaline earth metals were completely leached. Accordingly, significant mass and volume losses attest to severe mineralogical, textural, and chemical changes, so that bauxitization resulted in progressive desilication, hydration, and Al_2O_3 concentration in the residual soil.

The convex geometry of the bauxite blanket and corresponding spatial relationships of bauxite thickness and ore grade distribution suggest that the spatial control on the mineralization was the result of the influence topography has on the orientation of the drainage system and thus on the bauxitization process. In addition, as was mentioned previously by Lo Mónaco and Yanes (1990), the existence of a well-developed fracture pattern in the Parguaza granite will have a control on the flow of the infiltrating meteoric waters. The observed directional trends of mineralization correlate well with the westerly inclination of the Nuria surface and the orientation of the regional fault system.

6.2. Economic geology considerations

In their assessment of the commercial potential of world bauxite deposits, Bárdossy and Bourke (1993) ranked Los Pijiguaos among the top three candidates. Their ranking was based on mineralogical and chemical parameters that control the efficacy of the Bayer process and on non-ore related criteria such as ease of mining, environmental aspects, and infrastructure. In conclusion, the authors identified the high quartz content and the presence of granite boulders in the Los Pijiguaos bauxite as well as the long and complex transport to the refinery to be the main limiting factors. Besides that, the Los Pijiguaos bauxite represents a high-quality, almost pure gibbsitic ore with mean grades of 49.46 wt.% total Al_2O_3, 48,00 wt.% available Al_2O_3, 9.33 wt.% total SiO_2, 1.74 wt.% reactive SiO_2, 12.58 wt. Fe_2O_3, 1.21 wt.% TiO_2, and 26.7 wt.% LOI. This allows the bauxite to be processed by low temperature digestion around 140 °C.

Other characteristics that can be used to evaluate bauxite quality is the ratio of material input (i.e., bauxite) and waste output (i.e., red mud) per ton of alumina produced during refinement by the Bayer process (cf. Hausberg et al., 2000). The process involves a hot caustic leach of bauxite followed by separation and precipitation of aluminium as the hydrated aluminium oxide. The insoluble residue (red mud) resulting from leaching contains significant amounts of Fe_2O_3, TiO_2, SiO_2, and complex sodium aluminium silicate compounds that represent a loss both of alumina and soda. In addition, a number of metallic trace elements such as Zr, Hf, Th, U, Nb, and REE that occur in minerals inert to the caustic leach are also concentrated in the insoluble residue. To date, only minor uses of red mud have been found so that disposal is a major environmental concern as well as a significant cost factor in the production of alumina.

In addition to mass considerations, the mineralogical composition of bauxite is one of the most important factors that significantly influence red mud properties and potential environmental impacts (Hausberg et al., 2000; Li and Rutherford, 1996). For instance, because of its derivation from the Parguaza granite, the Los Pijiguaos red mud may contain as much as 650 ppm Th, which amounts in proportion to the annual bauxite production to almost 900 tonnes of Th metal.

The settling behaviour of red mud from the Bayer process is another important economic factor as it controls purity, and an important environmental factor as it controls the final liquid content of the tailings for disposal. Li and Rutherford (1996) concluded from their experimental work that, in general, red mud containing hematite settles faster than that containing goethite. However, settling behaviour is also affected by grain size and degree of crystallinity. High settling rates enhance the efficacy of the separation process for the production of high-purity alumina and facilitate application of faster, cheaper, and environmentally more acceptable disposal techniques (Hausberg et al., 2000; Li and Rutherford, 1996). The mineralogic composition of the Los Pijiguaos bauxite with a relatively high abundance of hematite has a positive effect on the red mud settling rate and, thus, favours a high extraction yield of the alumina plant.

The large amount of proven reserves and the enormous amount of resources together with the huge hydro-power potential in Venezuela could contribute to make Los Pijiguaos as one of the world's principal bauxite producers. The mine is based on a large bauxite reserve, which will continue to produce ore for more than 100 years at the current mining rate. Menendez and Sarmentero (1984) considered the area of plateau remnants of the Nuria surface on which bauxite occurs to extend over a total area of 350 km^2. This would suggest that the Los Pijiguaos region contains about 6 billion tonnes of possible bauxite reserves.

7. Conclusions

Los Pijiguaos represents a typical laterite bauxite deposit that formed on a flat-topped plateau from weathering of the underlying Parguaza granite. Microtextural observations of well-rounded quartz grains and gibbsite aggregates provide evidence that bauxite is not of a simple in-situ, residual origin but that secondary processes such as physical disintegration, mechanical transport and re-deposition of mineral grains must have had occurred. In addition, the formation of nordstrandite and the observed decoupling of Ga from Al in the bauxite horizon suggests post-bauxitization chemical transport.

Gibbsite is by far the dominant mineral in the economic-grade bauxite zone. The occurrence of nordstrandite is restricted to the bauxite layer, whereas kaolinite was not detected in this zone. In the saprolite layer, kaolinite abundance increases to more than 5 wt.%. An inverse correlation exists between gibbsite and quartz. Abundance ratios for the two minerals decrease from around 45 in the bauxite mantle to around 2 in the lower saprolite zone. Among the Fe minerals, hematite is commonly more abundant than goethite. However, in the bauxite horizon goethite/hematite ratios are greater than 1. Anatase occurs as an accessory phase mainly in the bauxite zone.

Mass balance calculations show that H_2O represents the main component gained by bauxite and to a lesser degree by saprolite during weathering of the Parguaza granite. Bauxitization resulted in progressive desilication, hydration, and Al_2O_3 and Fe_2O_3 concentration in the residual soil. Silica as well as alkali and alkaline earth metals were completely leached. Mass and volume losses in the order of 61% and 77%, respectively, attest to severe mineralogical, textural, and chemical changes.

The convex geometry of the bauxite blanket as well as lateral and vertical variations of bauxite thickness and ore grade suggests that there was a spatial control on the mineralization. This can be related to the influence topography has on the orientation of the drainage system and thus on the bauxitization process. The thickness of the orebody varies between 8 and 9 m. On a mine scale, there is the general tendency for best ore grades and greatest thickness of the bauxite horizon to occur at topographic highs. The lateral bauxite grade distribution is also not isotropic but follows distinct WNW–SSE-orientated trends. The obvious spatial control on the mineralization correlates with the westerly inclination of the Nuria surface and the presence of major NW-orientated fault systems in the region.

From an economic point of view, it can be concluded that the Los Pijiguaos bauxite represents a high-quality almost pure gibbsitic ore with mean grades of 49.46 wt.% total Al_2O_3, 48.00 wt.% available Al_2O_3, 9.33 wt.% total SiO_2, 1.74 wt.% reactive SiO_2, and 12.58 wt. Fe_2O_3. This allows the bauxite to be processed by low-temperature digestion around 140 °C. In terms of material consumption, 2.3 tonnes of dry bauxite are used for every metric ton of alumina produced. The concomitant mass of red mud amounts to 0.55 tonne per tonne alumina. The relatively high abundance of hematite in the bauxite has a positive effect on the red mud settling rate and, thus, favors a high extraction yield of the alumina plant.

Los Pijiguaos is based on a large reserve that will produce bauxite for more than 100 years at the current rate of mining. The entire region may contain as much as 6 billion tonnes of probable bauxite reserves.

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THE MATERIALS FLOW OF BAUXITE*

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ABSTRACT

A mass-balance study of bauxite, the primary ore of Al, was performed to analyze the first stage of materials flow associated with the aluminium processing cycle. Evaluation of ore characteristics of ca. 80 bauxite deposits world-wide allowed identification of critical parameters that affect subsequent alumina production. Aggregation of bauxite characteristics led to the definition of quality parameters that can be used to identify areas where materials flow and waste can be reduced. These parameters include mass ratios of bauxite to alumina and waste to alumina. The high variance of bauxite quality provides options for optimal mine selection. Assessment of bauxite resources traces a trend that indicates a general reduction of ore quality in the future.

KEYWORDS

Bauxite, deposits, alumina, waste

* Source: Stanley, C.J. et al. (eds.): Mineral Deposits: Process to Processing. Balkema, Rotterdam, 1129 – 1132.

1 INTRODUCTION

Materials-flow or commodity mass-balance analyses are useful techniques for tracking the flow of a mineral commodity through its entire cycle, i.e. from its source and extraction from the Earth through stages of processing, fabrication, and consumption to its ultimate disposition. This approach aims at understanding the whole system of materials flow to better manage the use of natural resources and to assess the cumulative effect that a particular raw material use has on the economy, society, and the environment.

The Collaborative Research Center 525 "Resource-Oriented Analysis of Metallic Raw Materials Flow" established by the Deutsche Forschungsgemeinschaft (DFG) at the University of Technology Aachen strives to develop an integrated resources management system that analyses and quantifies the flow of materials and energy through the entire production cycle and thus provides a scientific base for improving production and resource-use efficiency. The first phase of the program is concerned with the bauxite-alumina-aluminium cycle and related geologic, engineering, environmental, social, and economic aspects. The main purpose of the research is to identify policies and practices that make the use and production of this commodity more efficient and to identify areas where adverse impacts on the environment could be minimized.

The bauxite mass-balance study presented here considers the first stage of materials flow associated with the aluminium cycle. It represents a mine-to-gate approach and includes an assessment of geologic and mineralogic characteristics of bauxite that critically affect subsequent alumina production. The purpose of this work is to identify areas where materials flow and waste at the source of the material could be reduced and to trace trends that could have implications on bauxite supply in the future.

2 BAUXITE RESERVES

Bauxite deposits are commonly classified in three genetic types according to mineralogy, chemistry and host-rock lithology. About 88% of known deposits belong to the laterite-type, while 11.5% are of the karst-type and only 0.5% of the Tikhvin-type (Bárdossy 1982, Bárdossy & Aleva, 1990).

Bauxite is the principal ore for the production of aluminium metal via a two-stage process that firstly, involves the refining of bauxite to alumina (the Bayer Process) and secondly, the electrolytic reduction of alumina to aluminium metal (the Hall-Heroult Process). Of all the bauxite mined, 85% is converted to alumina for the production of aluminium metal, 10% goes to nonmetal uses, and the remaining 5% is used for non-metallurgical applications (Plunkert 1997). Presently identified world bauxite reserves amount to 23 billion metric tons with an estimated reserve base of 28 billion tons (cf. Plunkert 1997, Roullier 1995). Nearly half of the proven and probable reserves identified to date are contained in deposits that are in an exploration stage (Fig. 1). Bauxite supply estimates, derived from ratios between present reserves and annual production, indicate adequate bauxite supply for at least 200 years. However, as is the case with other metals, bauxite reserves are rigidly controlled by market price. If, in addition to economic factors, environmental considerations are included in bauxite reserve calculations, then the presently estimated adequacy of supply may be too high.

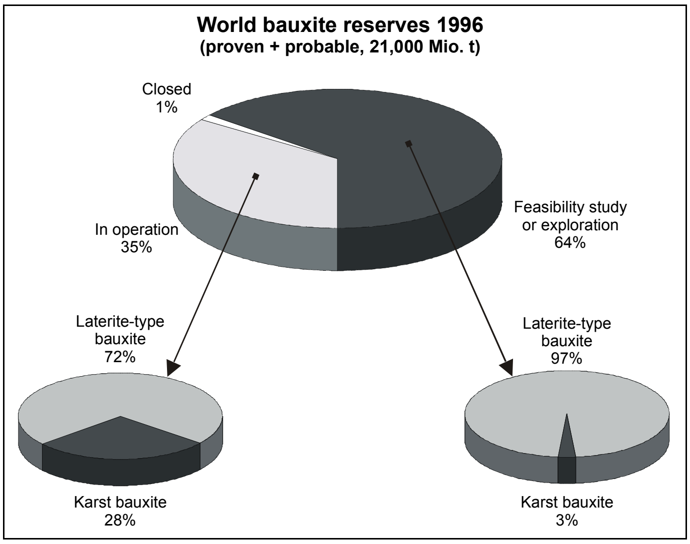

Figure 1. World bauxite reserves in 1996 (Source of data: Sehnke 1994, Roullier 1995, Plunkert 1997,U.S. Geological Survey, 1997, Carvalho et al. 1997)

3 BAUXITE PRODUCTION

In 1997, world bauxite output totaled 123 million metric tons. Although 24 countries reported bauxite mining, ca. 80% of the total ore extracted originated from 8 major mining districts (cf. Plunkert 1997).

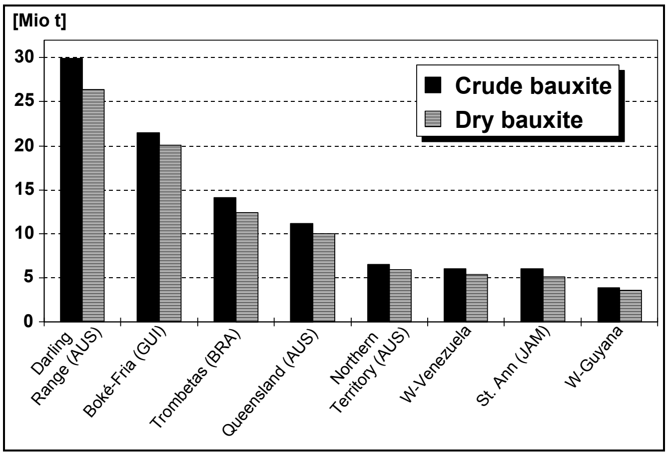

Figure 2: Bauxite production from eight major mining districts.

Figure 2 demonstrates differences in bauxite quality, i.e. moisture content, among various districts. The difference by weight between crude and dry bauxite can be as much as 20%, and characteristically varies between regions. It is clear that moisture content is a geologic factor that has an influence on the material-flow balance of bauxite. Figure 2 further indicates that Australia, Guinea, Brazil, and Jamaica are the principal bauxite producers in the world. The main alumina-producing countries are Australia, the United States, Jamaica and China. This, together with the total world output of alumina in 1997 of more than 45 million tons implies a major flow of bauxite on a worldwide scale.

4 BAUXITE CHARACTERISTICS

A number of characteristics of bauxite deposits control the efficacy of alumina processing. In that sense, bauxite quality (and thus its effect on the material-flow balance) can also be assessed by parameters such as the amount of bauxite needed to produce one ton of alumina and the amount of waste (i.e. red mud) accumulating during the Bayer Process. These parameters were calculated for the eight principal bauxite mining districts shown in Figure 2 and the data are shown in Figure 3.

It can be seen that there is a distinct variability of mass ratios for the eight districts. The variability is due to the highly heterogeneous, site-specific, chemical and mineralogical characteristics of bauxite. Low-grade bauxite produces more waste than high-grade ore and requires a higher mass input per ton of alumina produced. Bauxite from the Darling Range has the lowest available Al-content and is thus characterized by low quality indicators.

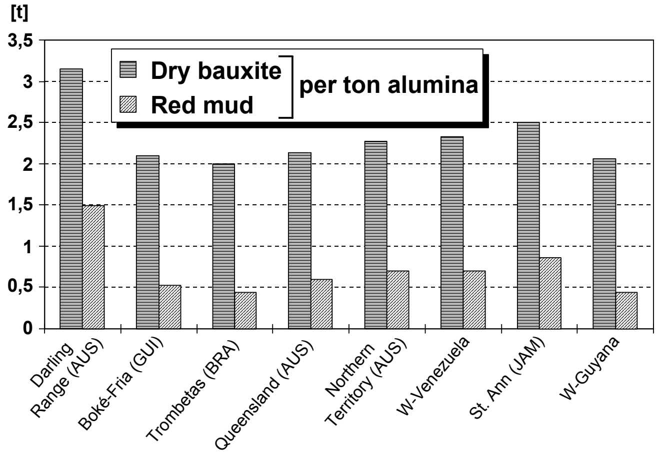

Figure 3. Mass of dry bauxite needed and red mud produced per ton of alumina.

Similar calculations were performed for 61 producing bauxite mines. The mass ratio of bauxite needed for one ton of alumina ranges from 1.8 to 3.2, with a mean value of 2.3. Accordingly, the red mud to alumina ratio also varies considerably between 0.3 and 1.5 (mean = 0.7). The mass of red mud as is calculated here, accounts for that portion of waste which results from bauxite feed only and does not consider the mass of chemicals and water added in the Bayer Process. Thus, this portion is termed 'geogenic' red mud. The data calculated for laterite- and karst-type deposits are summarized in Figure 4.

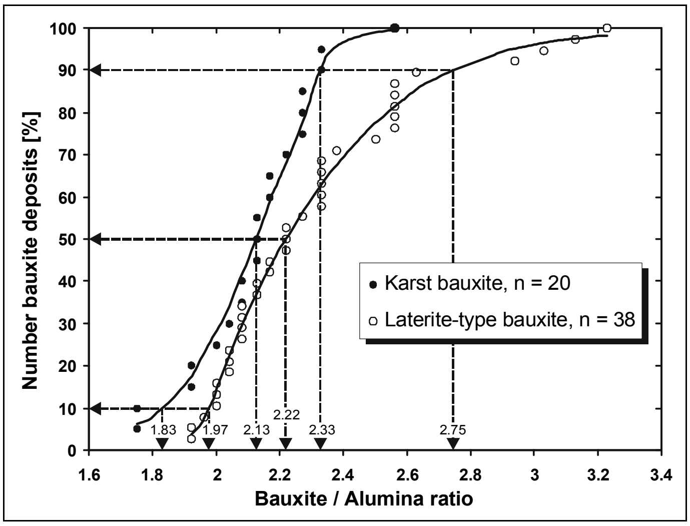

Figure 4. Cumulative percent curves of bauxite-to-alumina ratios.

On average, the mass ratios of laterite-type bauxites are higher than those of karst bauxites, with the former also showing a larger range of values. More than 95% of the karst bauxites have ratios below 2.4, while more than 20% of the laterite bauxites are characterized by ratios in excess of 2.5. This trend can be explained by the fact that the laterite-type bauxite is mined almost exclusively from shallow open-pit mines, which allows relatively simple and inexpensive extraction methods.

In a similar way, waste (red mud) to alumina ratios were calculated for bauxite from the two deposit types (not shown here). The use of laterite-type bauxite as feed for alumina production, in general, results in less waste than using karst bauxite. This is true for about 70% of currently operating mines for which the red mud to alumina ratio is less than 0.85. The remaining 30%, however, have ratios as high as 1.5.

To trace future trends in ore quality, bauxite to alumina mass ratios of producing mines were compared with ratios calculated for operations that are currently in a feasibility or exploration stage (Fig. 5). The shift of the curve to higher ratios clearly indicates that deposits to be mined in the future are generally characterized by higher mass ratios. In detail, 80% of the currently operating mines produce bauxite with ratios smaller 2.4, while 50% of the future mines will extract bauxite with ratios below that value. This suggests, in turn, a potential reduction of bauxite-quality in the future. In other words, even by taking current alumina production to be constant, future world total bauxite supply will have to be increased considerably.

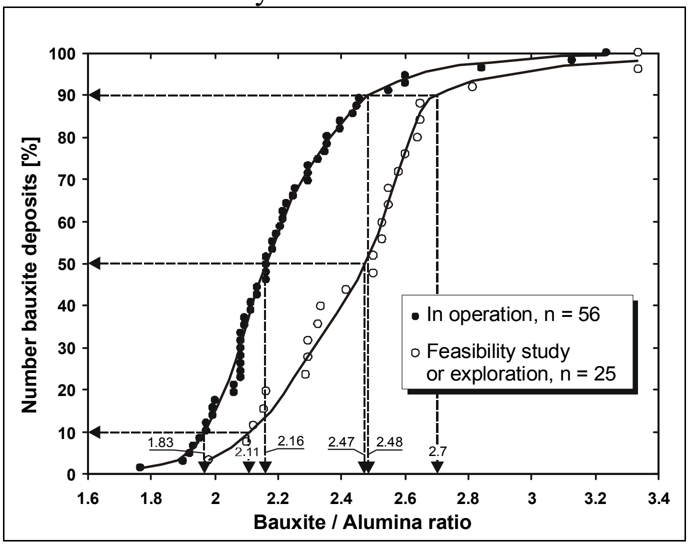

Figure 5. Cumulative percent curves of bauxite/alumina ratios for operating and non-operating mines.

Comparison of red mud/alumina ratios for the two groups of deposits show a distinct shift to higher values (Fig. 6). More than 90% of the currently operating mines produce ore with a ratio smaller than 1, a value reached by only 70% of the prospects earmarked for mining in the near future.

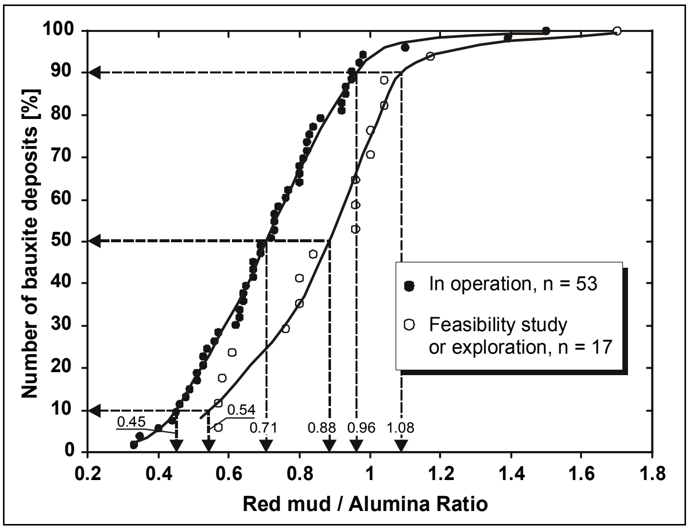

Figure 6. Cumulative percent curves of waste (red mud)/alumina ratios.

5 SUMMARY AND CONCLUSIONS

The study presented here investigates the materials flow associated with the production of alumina in a mine-to-gate approach. Based on a deposit-scale, as well as global-scale, assessment of geologic, mineralogic, and geochemical characteristics of bauxite, a limited number of parameters were distinguished that critically affect subsequent alumina production. These parameters, moisture content and available Al-content, were used to identify areas where materials flow and waste at the source of the material, i.e. the bauxite deposit, can be reduced, and to trace trends that may have implications on future bauxite supply. The main findings of the study are summarized below:

- bauxite quality, as defined here in terms of bauxite to alumina ratios as well as waste (red mud) to alumina ratios, has a significant effect on the materials flow associated with aluminia production,
- both laterite-type and karst-type bauxites show considerable variation in bauxite quality. This allows for optimal mine selection in terms of reduction of material flow and waste, if environmental concern is the major decision-making criteria,
- assessment of ore characteristics of prospects that may be mined in the future traces a trend indicating a general reduction of bauxite-quality, and
- the selection of future bauxite resources for mining should be carried out by considering the implications for global materials flow.

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ENVIRONMENTAL SIGNATURES OF BAUXITE DEPOSITS*

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ABSTRACT

Geologic-mineralogic characteristics of bauxite have an influence on the efficacy of ore extraction and alumina processing. For the purpose of this study, ten ore parameters were distinguished that serve as environmental signatures which can be used as a tool to assess geology- , mining-, and processing-related factors that influence potential environmental effects of bauxite supply. As the issue of resource scarcity, in particular with respect to nonrenewable resources, is central to the concept of sustainability, the influence of specific environmental signatures on the adequacy of word-wide bauxite supply was assessed by modeling scenarios that are beneficiation-, ore deposit-, reserve-, and sustainability-oriented. Our findings show that application of these scenario calculations results in significant depletions of available bauxite reserves and thus in an overall reduction of the word bauxite reserve life index.

KEYWORDS

Bauxite, deposits, environmental signatures

* Source: The 7th International Bauxite & Alumina Seminar, Miami, Florida, USA

Introduction

Extraction of minerals from the Earth depletes finite nonrenewable resources and worries are expressed that continuation with this practice will eventually exhaust the available supply of minerals. Although warnings about shortages of material stocks of mineral resources have been recurrent through history it can be argued that this perspective ignores the dynamics of mineral supply and that in reality the nonrenewable character of minerals may be less constraining than it might seem. In support of this opinion arguments have been expressed that current reserve estimates represent only a small portion of the mineral resources remaining in the Earth's crust, that exploration and development will lead to the discovery of previously unknown mineral deposits, and that technological improvement in exploration and extraction will increase the discovery rate as well as the available reserves of mineral deposits. The concept of sustainable development adds a further perspective to the availability of mineral supplies in that the problem of resource scarcity is also seen as an environmental issue, i.e. the impact mineral extraction, beneficiation, processing, production, use, and disposal has on the environment. This concept, therefore, intrinsically connects concerns about the limits of resource availability to concerns about limits to the sink and purification capacity of the environment. Sustainability for a specific mineral resource, such as bauxite, can be examined best in a material flow study that provides the basis for assessing the cumulative effect a particular material use has on the environment.
This approach is currently being taken by the Collaborative Research Center 525 that was established in 1997 by the Deutsche Forschungsgemeinschaft (DFG) at the University of Technology (RWTH) Aachen. The aim is to develop an integrated resources management system that analyses and quantifies the flow of materials and energy through the entire production cycle and thus provides a scientific base for improving production and resource-use efficiency and identifying areas where adverse impacts on the environment can be minimized.
The present paper defines and evaluates environmental signatures of bauxite deposits, with the focus on the adequacy of bauxite supply and examines the magnitude of the resource stock if in addition to technologic and economic factors environmental considerations are included in bauxite reserve calculations.

Reserves and Resources

Bauxite is the principle ore for the production of alumina and aluminum metal. Driven by increasing demand, world bauxite production has risen over the past 5 decades from less then 5 Mio t per annum to c. 125 Mio t in recent years.
In 1998, mine production was reported in 24 countries, but the 12 largest producing countries accounted for about 97% of the world production. Australia is currently the largest producer with about 40 Mio t of bauxite per year, followed by Guinea (16.5 Mio t), Jamaica (11.9 Mio t), Brazil (11.5 Mio t) and China (7.3 Mio t).
In 1997, proven and probable world bauxite reserves were estimated to amount to 23000 Mio t (cf. Plunkert 1997, Roullier 1995). Bauxite reserves are unevenly distributed throughout the world, with the largest reserves being located in Australia (23.7%), Guinea (19.5%) and Brazil (14.4%). Bauxite supply estimates, derived from ratios between present reserves and annual production (i.e. static life time) indicate adequate bauxite supply for at least 170 years.

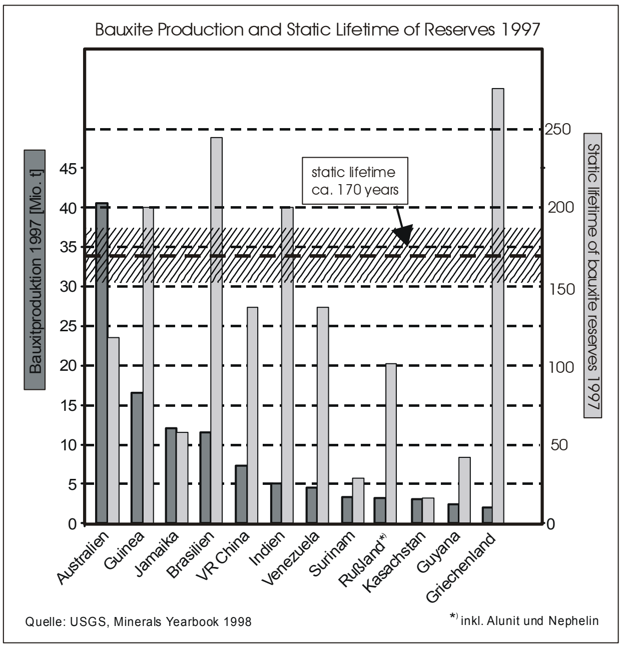

Figure 1: 1997 bauxite production by countries and static lifetime of reserves

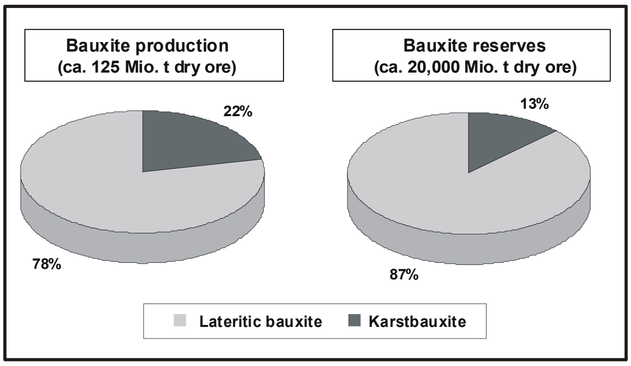

Figure 2: Bauxite deposit types of reserves and producing mines

One third of the current bauxite reserve estimations apply to deposits that are currently being mined, while the other two thirds are located in deposits that are in

exploration state, or where feasibility studies have been completed (Sehnke 1994, Roullier 1995, Plunkert 1997, U.S. Geological Survey, 1997, Carvalho et al. 1997).
About 70% of currently mined deposits belong to the laterite-type bauxite, while 30% are of the karst-type. 97% of deposits which are in exploration state consist of laterictic bauxite and only 3% of karstbauxite.

Methods employed

In a similar way, the environmental indicator system is used for describing the state of the environment in a region or country, environmental signatures of mineral deposits can be used for describing geologic, mining, and processing factors that influence potential environmental effects. In that sense, the impact can be assessed the raw material source, extraction, beneficiation, smelting, or refining of a specific mineral commodity has on the environment. Environmental signatures are defined here to include all ore deposit characteristics that are environmentally important. They reflect the influence of the physical and chemical response of the deposit to subsequent technical processes. Environmental indicators are defined to represent quantitative variables that measure the effect the use of a raw material has on the environment. They are used here to demonstrate trends.
This study is based on the evaluation of more than 170 bauxite deposits world-wide with the aim to identify environmentally important geologic characteristics.
The environmental effects resulting from mining and processing of bauxite, i.e. the Bayer-Process, were also analyzed and considered further variables that describe the generic environmental system discussed here. Linkage of geology- and processing-based variables resulted in ten pertinent environmental signatures that together can be integrated into environmental indicators for monitoring the environmental behavior of the alumina production cycle.
In practice, each of the 10 signatures can be used as a tool to help to assess for individual bauxite deposits, geology-, mining-, and processing-related factors that have a potential impact on the environment. The environmental indicators, on the other hand, comprise the grouped and weighted environmental signatures and, therefore, are characterized by a higher level of aggregation.
The indicators are used as tools to model generic scenarios that can be technology-, site-, supply-, or scarcity-orientated.

Environmental signatures

Am number of mineralogical characteristics of bauxite ores control the efficacy of alumina processing. In that sense, bauxite quality can be assessed by a number of criteria such as the amount of bauxite needed to produce one ton of alumina or the amount of waste (i.e. red mud) accumulating during the process.
For example, input and output masses to produce one ton of alumina vary considerably due to highly heterogeneous site specific chemical and mineralogical characteristics of bauxite for 8 major bauxite producing districts.

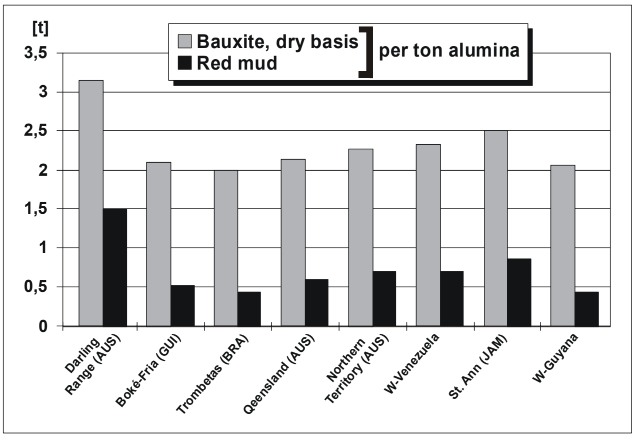

Figure 3: Bauxite and red mud per ton alumina produced

Based on pertinent geologic characteristics of bauxite deposits the following set of environmentally important signatures can be defined.

- Recoverable Al_2O_3: The mineralogical composition of the ore, in particular the amount of valuable minerals, controls the energy consumption of the Bayer-process and the yield of Al_2O_3.
- Reactive silica and (R.SiO_2) and TiO_2-content: The presence of SiO_2 and TiO_2 has a negative effect on the Bayer-Process, because their concentration in the ore strictly controls the amount of energy and flocculants used in the process.
- Bauxite/Al_2O_3-ratio and Red mud/Al_2O_3-ratio: The bauxite/Al_2O_3-ratio as well as the bauxite/rec.Al_2O_3-ratio provide information on the amount of bauxite needed to produce a given amount of aluminum oxide. These figures, therefore, are measures for the amount of bauxite that has to be mined from an ore deposit to produce one ton of rec. Al_2O_3. The red mud/Al_2O_3-ratio as well as the red mud/rec.Al_2O_3-ratio provide information on the amount of red mud that occurs when a given amount of aluminum oxide is produced.
- Ore reserves: This term refers to the economic characteristics of ore deposits and is determined by the geologically proven and economically recoverable amount of ore.
- Annual ore production: This relates to annual production figures of individual mines or the accumulated production world-wide. The static lifetime for a mineral commodity is defined by the ratio of world reserves and world production at a given year.
- Moisture content and waste/ore-ratio: The moisture content refers to the amount of non mineral-bound water in the ore. A high moisture content has a nega-

tive effect on mining and processing and transportation of the ore. The waste/ore-ratio provides a figure for the amount of country rock that has to be moved to produced a given amount of ore. This value also influences the methods employed to mine the ore.

- Land use/t rec.Al_2O_3: This ratio considers the amount of land (m²) used for bauxite mining per ton of recoverable alumina extracted. The figure varies with the geometry and thickness of the ore body as well as with the alumina content and in-situ density of the ore.

Environmental Indicators

Factor analysis was used to investigate possible relationships between relevant environmental signatures discussed before. By applying the method the total data set was reduced to seven factors. The resulting factor-loadings were then used as a measure for the significance of this factor (extracted by factor analysis) to contribute to a specific environmental indicator. In that way a total of 5 environmental indicators was defined which help to monitor the environmental behavior of bauxite deposits.

- Generic: Equal weighting of all factors
- Beneficiation-oriented: Strong weighting of factors that influence the efficiency of alumina production using the Bayer-Process.
- Ore deposit-oriented: Strong weighting of factors that influence the environmental signature of bauxite deposits.
- Reserve-oriented: Strong weighting of factors that influence bauxite reserves.
- Sustainability-oriented: Strong weighting of factors that influence all effects the use of raw materials (i.e. bauxite) has on the environment.

Bauxite availability

In the following models are shown that employ environmental signatures as well as environmental indicators as limiting conditions for the adequacy of bauxite supply under variable conditions (scenarios). The models are based on the premise that environmental signatures and indicators - in the sense of sustainability - are a reflection of the environmentally important characteristics of a bauxite deposit, and so of the quality of bauxite that is extracted from this deposit. In this context, high bauxite quality relates to positive environmental signatures/indicators while low quality refers to negative signatures/indicators. The scaling of ore-quality levels is such, that today's lowest quality (or negative environmental indicator) encountered in the 170 bauxite deposits studied is taken as zero level, while today's highest quality is set to 100%.

Environmental signatures and bauxite availability

Figure 4 presents results of a model that calculates for a set of environmental signatures adequacy of bauxite supply (availability of ore reserves) as a function of ore-quality. Also given is the static lifetime for bauxite reserves based on constant annual production of 50 Mio t Al_2O_3.
It is obvious from the graph that various environmental signatures have different effects on bauxite availability. For example, an increase by 50% of the rec.Al_2O_3–signature results in a reduction of initial bauxite reserves by ca. 55%, the same increase applied to the land-use/rec.Al_2O_3-signature reduces available reserves by 10% only. An even lower effect on resource reduction is shown for the waste/ore-indicator.
It is clear, however, that application of environmental signatures as a measures of ore-quality can have a strong effect on the adequacy of bauxite supply, if there is a demand in future– in the context of sustainability – for higher ore-quality standards. Figure 5 shows model calculations that investigate the influence of environmental indicators - again expressed in terms of ore-quality or the demand for a specific quality level on the availability of bauxite and the static lifetime of bauxite reserves.
If we assume, for example, a demand for increasing the sustainability-oriented indicator (reflected in the ore-quality) by 50%, this would then result in the reduction of bauxite reserves by 20%. Applying the same ore-quality increase for the beneficiation-, ore-deposit-, and reserve-oriented indicators the
reserve availability would be decreased by almost 50%.
The advantage of employing environmental indicators over environmental signatures is placed on the fact that the former represent a higher level of aggregation and can be used for analyzing specific scenarios by which the impact can be assessed the use of bauxite has on the environment.

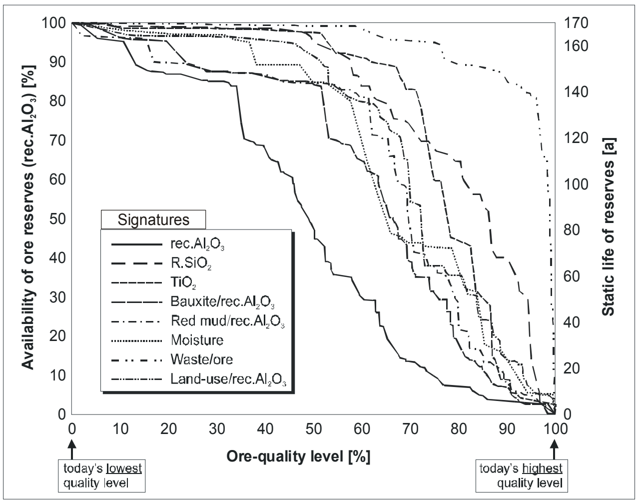

Figure 4: Reserve availability model: Availability of reserves and static lifetime of bauxite reserves as function of ore-

quality. Environmental signatures used are shown on the graph.

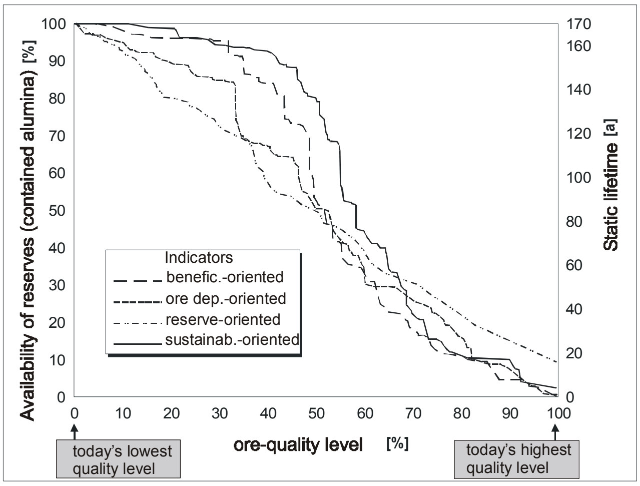

Figure 5: Reserve availability model: Availability of world bauxite reserves and static lifetime of bauxite reserves as function of ore-quality. Environmental indicators used are shown on the graph.

<u>World distribution of bauxite reserves</u>

Model calculations on bauxite availability discussed above are based on world reserves. In the following similar calculations are shown that focus on reserve calculations for 12 bauxite producing countries. Figure 7 compares available bauxite reserves for the 12 countries if – according to the models shown previously – in addition to today's lowest quality-level (i.e. 0%) increases in ore-quality are considered up to 50% and 70%, respectively.

At present, Australia hosts the largest bauxite reserves, followed by Guinea and Brazil. If quality requirements are increased to 50%, Australia's present reserves will be reduced by 25%, while Guinea will not suffer any reserve reduction.

With a further increase of ore-quality to 70%, in terms of reserves, Australia would fall back to rank six among the bauxite producing countries (figure 7).

To what extend demands for higher ore-quality will effect reserve availability of bauxite world-wide are depicted for the sustainability-oriented indicator in a further panel of figures. Figure 8 a) shows the worldwide distribution of bauxite deposits from which ore is extracted that at present fulfils minimum quality requirements (0%, as defined before). In case ore-quality is increased by 50% (relative to the lowest level) the number of producing deposits will be reduced from 134 to 84 (figure 8b). A further increase in ore-quality to 70% will particularly effect all bauxite producers in Europe as well as the majority of the Australian and Asian mines (figure 8c). In that case, main bauxite production will be from mines located in Middle and South America and West Africa.

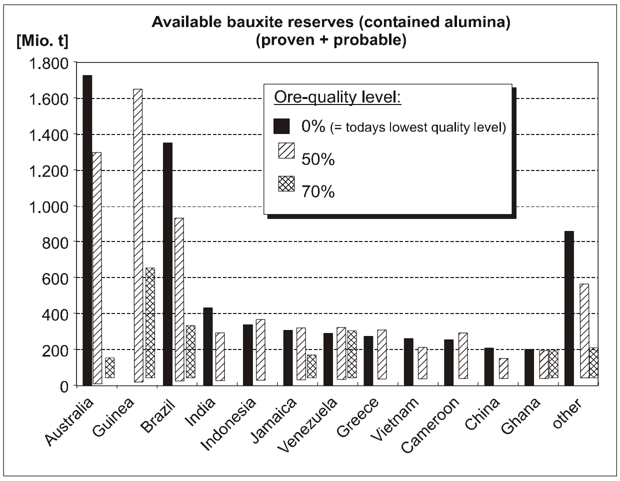

Figure 6: Model calculations demonstrating changes of bauxite reserves in twelve major bauxite producing countries as a function of ore-quality levels (0%, 50% and 70%).

Figure 7: Geographic distribution of bauxite production sites (a, b and c indicate available deposits for 0%, 50% and 70% quality requirements, respectively).

Summary and Conclusions

The present study has investigated geologic and mineralogic characteristics of bauxite deposits that influence their chemical and physical response to subsequent technical processes such as mining, beneficiation and alumina production. In that way, these characteristics control the environmental behavior of bauxite deposits and, thus, are termed environmental signatures. Based on deposit- as well as a global-scale assessment of geologic, mineralogic and geochemical characteristics of bauxite, ten ore parameters were distinguished that serve as environmental signatures. In a further step, these signature were integrated into Environmental indicators. They represent numerical variables that are characterized by a higher level of aggregation. Environmental indicators were used to model generic scenarios that are beneficiation-, ore deposit-, reserve-, and sustainability-oriented. On that basis, scenario-calculations were performed to model the influence of variable quality requirements on the global bauxite availability. In this context, the term quality or ore-quality is used as an environmental indicator that helps to assess, within the concept of sustainable development, the impact extraction and processing of bauxite has on the environment. Scenario-calculations show that increasing quality parameters by 50% result in a significant depletion of available bauxite reserves and thus in a reduction of the static lifetime of bauxite. Similar results were obtained by employing environmental indicators to monitor the effects future substitutions of current producers by new mine developments will have on bauxite availability with respect to increasing demands for higher quality. Given the scenario, only bauxite with an ore-quality 70% better than the current average is to be mined in future, than world demand can only be met by producers in West Africa and Middle and South America. Results presented in this study clearly point to the fact that stringent quality demands for bauxite ore in the environmental category will lead to a significant reduction of available bauxite reserves and will effect the geographic distribution pattern of bauxite producers.

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CONSTRAINTS ON THE GLOBAL AVAILABILITY OF BAUXITE RESERVES*

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ABSTRACT

Bauxite is the principal ore for the production of aluminium metal. The characteristics of 170 bauxite deposits world-wide were evaluated with the aim to identify critical ore parameters that affect both the environment and alumina production. Presently identified world bauxite reserves suggest supply for at least 170 years. However, a review of ore qualities of bauxite deposits to be mined in the future traces a trend that indicates decreasing availability of high quality ore. Assuming future increasing demands for high quality bauxite to reduce environmental impact, the availability of the current bauxite reserves is strongly reduced with a heterogeneous geographical distribution of remaining bauxite reserves. These findings can be applied as sensitive parameters for optimal mine selection.

ABSTRACT

Bauxite, ore deposit, reserves, bauxite availability

*   Source: Applied Mineralogy. Rammlmair et al., (eds), 2000 Balkema, Rotterdam, S. 341 - 344.

1 INTRODUCTION

Bauxite is the principal ore for the production of aluminium metal. The ore is converted to aluminium metal via a two-stage process that firstly involves the refining of bauxite to alumina (the Bayer Process) and secondly the electrolytic reduction of alumina to aluminium metal (the Hall-Heroult Process).

Presently identified world bauxite reserves, based on parameters such as degree of geological assurance and economic feasibility, amount to 21 billion metric tons. If, however, in addition to these factors, environmental considerations are included in the reserve calculations, then the present estimate may be too optimistic.

In the context of the present study, environmental and technical considerations are defined to include specific geologic, mineralogic, and geochemical characteristics of bauxite that affect subsequent alumina production, and in that sense represent critical quality indicators. Based on a deposit-scale as well as a global-scale bauxite supply assessment, a number of such quality indicators were defined and utilized to estimate future availability of bauxite for scenarios that invoke optimization of these parameters, with the aim to minimize adverse impacts on the environment.

In future, the average global bauxite quality will be strongly influenced by deposits for which currently feasibility studies are conducted. Before that background, the concomitant change of quality parameters and the availability of bauxite is modeled to gain insight into the effects that a progressive displacement of present bauxite producers by potential future producer will have on future bauxite supply.

The present study forms part of the Collaborative Research Center 525 "Resource-Oriented Analysis of Metallic Raw Materials Flow" established by the Deutsche Forschungsgemeinschaft (DFG) at the University of Technology Aachen. This research program strives to develop an integrated resources management system that analyses the flow of materials and energy through the entire life cycle and thus provides a scientific base for improving production and resource-use efficiency. The first phase of the program is concerned with the bauxite-alumina-aluminium cycle and related geologic, engineering, environmental, social, and economic aspects.

2 BAUXITE SUPPLY

In 1997, world bauxite output totaled 123 million metric tons. Although 24 countries reported bauxite mining, ca. 80% of the total ore extracted originated from 8 major mining districts (cf. Plunkert 1997).

Presently identified world bauxite reserves amount to nearly 21 billion metric tons (cf. Plunkert 1997, Roullier 1995). Bauxite supply estimates, derived from ratios between present reserves and annual production, indicate adequate bauxite supply for at least 170 years. However, as is the case with other metals, bauxite reserves are rigidly controlled by market price. If, in addition to economic factors, environmental considerations are included in bauxite reserve calculations, then the presently estimated adequacy of supply may be too high.

3 FUTURE TRENDS

Nearly two third of the proven and probable reserves identified to date are contained in deposits that are currently in an exploration stage. Reserves of these deposits are most likely to control future ore quality. Analyses of long and mid term development graphs indicate a highly dynamic behavior of the average global ore quality (Fig. 1). While on a long term basis the ore quality rises, a reverse trend is possible for a mid term period. The trend shown for the alumina content of bauxite in Figure 1 matches trends for other quality indicators. These trends are mainly a result of the limited amount of high quality bauxite that is available at the same point in time. As a consequence, the average ore quality of reserves undergoes a continuous decrease. This trend is most likely to continue in the future.

Due to the fact that heterogeneous ore quality distribution can not only be found on a deposit-scale, but also on a regional or global scale, the trend mentioned above may also cause a geographical diversification of production sites. As an example, Figure 2 portrays regional variations of one critical bauxite parameter, namely digestion temperatures necessary for alumina refining in the Bayer-Process. As process temperature is controlled by the ore mineral assemblage, changes in the preferred technical process-conditions thus have a sensitive effect, both on the amount and the regional distribution of available reserves.

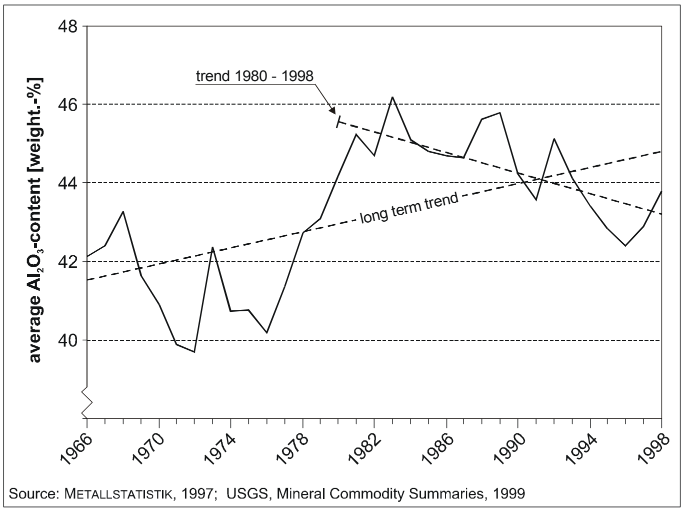

Figure 1. Long and mid term development graph of the global average bauxite quality (Alumina-content).

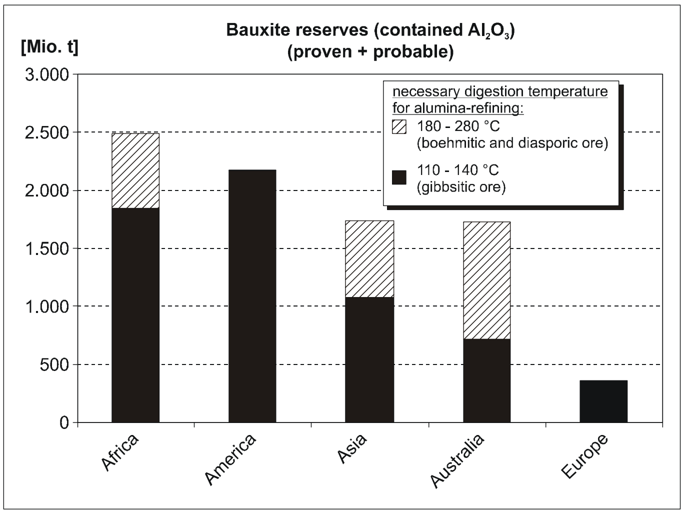

Figure 2. Regional variations in bauxite quality with regards to digestion temperatures necessary for alumina refining by the Bayer-Process.

A decrease of the average global ore quality and amount of available reserves may even be intensified by the following aspects:

- increasing demand for high quality raw materials due to global competition and production-chain optimization,
- introduction of strict legislation in terms of environmental and socio-economic regulations.

This contradictory situation has a critical effect on the availability of adequate reserves and thus may lead to a strong revision of the global supply system. Therefore, the present study firstly defines a set of quality indicators, and secondly analyzes the effect of enhanced quality requirements on the amount of reserves that meet these requirements is analyzed.

4 QUALITY INDICATORS

Due to the heterogeneous ore quality distribution mentioned above, assessment of reserve availability has to be performed through a bottom-to-top approach. This requires a quality assessment of each single ore deposit that forms part of the global reserve figure.

In the case of bauxite as a raw material for alumina and aluminium production, the following quality indicators are applied to acquire environmental and technical effects of an ore deposit:

- *recoverable alumina* (*rec.Al_2O_3*): indicates the alumina-content that can be made available by the Bayer-Process with respect to geochemistry and mineralogy of the ore,
- *reactive silica* (*R.SiO_2*) and *TiO_2-content*: strictly control consumption of energy and flocculants used in the Bayer-Process,
- *bauxite/rec.Al_2O_3 ratio*: amount of bauxite required to produce one ton of alumina,
- *red mud/rec.Al_2O_3 ratio*: amount of red mud (solid residue from the Bayer-Process) per ton alumina produced,
- *moisture content:* has a negative effect on ore processing and transportation,
- *waste/ore ratio*: many bauxite deposits occur as thin and shallow ore-blankets and thus the waste is in many cases equivalent to the overburden
- *land-use/rec.Al_2O_3*: total area occupied by mining per ton of alumina produced; depends on the geometry and thickness of the ore body as well as the alumina content and in-situ density of the ore.

5 AVAILABILITY OF BAUXITE RESERVES

Availability of reserves in the context defined here, represents the effect of an increasing global demand for high quality ore on the amount of deposits or reserves that meet these requirements.

Therefore, a computer-aided calculation routine was applied to examine 170 bauxite deposits in terms of the quality indicators introduced in Chapter 3.

The results of the model calculations are presented in Figure 3. The curves, shown for individual quality parameters, depict the successive substitution of today's lowest level of ore-quality (0 %) by the presently highest available ore-quality (100 %) and resulting variations in the remaining amount of bauxite reserves (contained alumina). It can be seen from Figure 3 that the various parameters used have different effects on the bauxite availability. While a 50 % enhancement of rec.Al_2O_3 means a reduction of the initial bauxite reserves by ca. 50 %, the same requirement applied to the land-use/rec.Al_2O_3 ratio results in ca. 10 % reduction only. In general, the rec.Al_2O_3-content exerts the most critical effect on the availability of bauxite. The waste/ore ratio represents the least sensitive factor. The observed differences in the sensitivities of the variables investigated show that detailed analyses of all quality parameters must be taken into account.

As mentioned earlier, ore grades show a very heterogeneous regional distribution. Thus, changing quality requirements also critically affect the geographical distribution of mining sites. Figure 4 demonstrates variations in the dependence of available bauxite reserves on increasing quality requirements for twelve bauxite producing countries. The availability of reserves (proven + probable) in Figure 4 is given for a 0 % (initial reserves), 50 % and 70 % quality level (including all quality indicators shown in Figure 3) for each country. Australia's bauxite reserves (currently ranked first in the world) are reduced by ca. 90 % at a quality level of 70 %, whereas Guinea's reserves (currently rank 2) are reduced by ca. 65 % only. Such scenarios may thus completely change current bauxite reserve estimations.

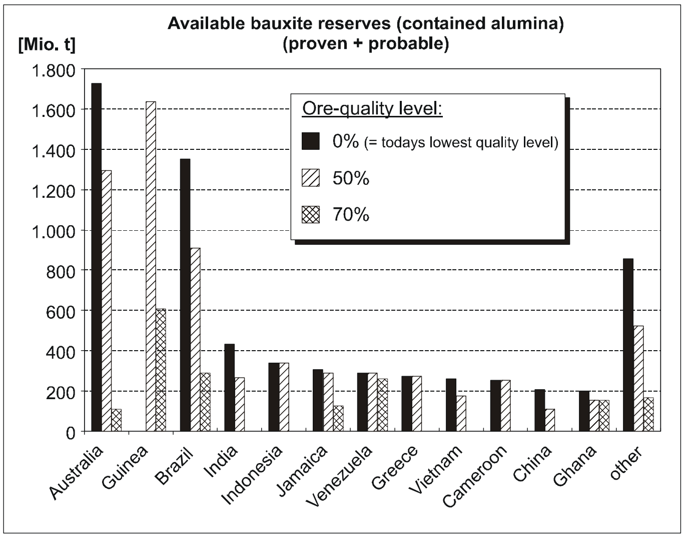

Figure 4. Variations in the dependence of available bauxite reserves on increasing quality requirements for twelve bauxite producing countries. The 0, 50 and 70 % quality levels include eight quality indicators.

6 SUMMARY AND CONCLUSIONS

The study presented here investigates the availability of bauxite reserves associated with changing quality

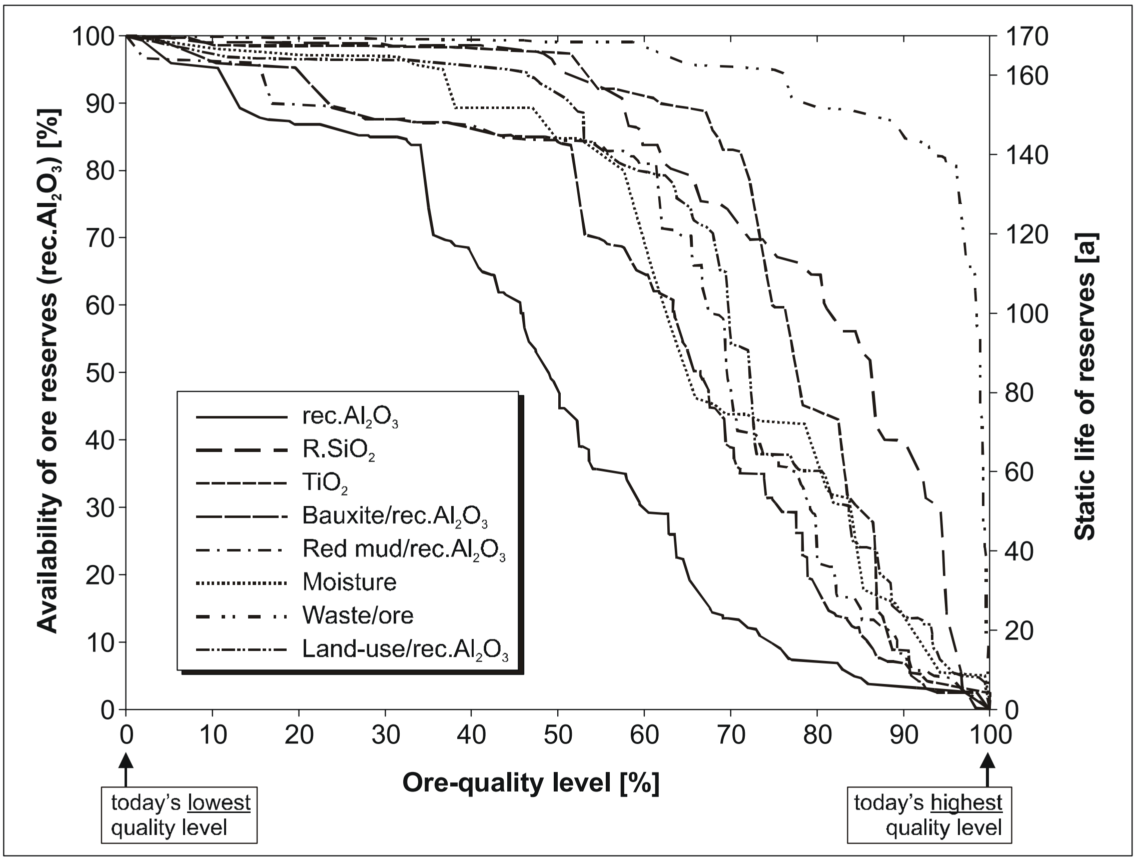

Figure 3. Availability and static life of world bauxite reserves 1997 (contained alumina). Explanations see text.

requirements. Based on a deposit-scale, as well as global-scale, assessment of geologic, mineralogic, and geochemical characteristics of bauxite, a number of ore-parameters were distinguished. It could be shown that these Parameters critically affect subsequent alumina production. Based on these investigations, areas were identified where materials flow and waste at the source of the material, i.e. the bauxite deposit, can be reduced and to trace trends that may have implications on future bauxite supply.

Before the background of a sustainable development, this study represents a further step to provide criteria that can minimize the impact on the environment caused by bauxite mining and processing. It also reveals trends that enhanced quality demands may have on bauxite reserves. Knowledge of the most and least sensitive quality parameters allows for a specific selection of future bauxite deposits and, thus, positively affects global material flows.

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EVALUATION OF BAUXITE AVAILABILITY

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Abstract

Sustainable yields of renewable resources have long been recognized as valuable concepts. Applying the concept of sustainability to nonrenewable mineral resources such as bauxite, however, leads to concern about both depletion of resources and degradation of the environment, and also raises questions about the adequacy of supply to meet future demands. Current bauxite supply estimates, derived from ratios between present reserves and annual production, indicate adequate supply for nearly 200 years. If, in addition to economic factors, environmental considerations are included in bauxite reserve calculations, then the presently estimated adequacy of supply may be too high.
The evaluation of typical ore characteristics of 170 bauxite deposits world-wide let to the identification of ten critical parameters that effect mineral availability in the context of sustainability. Results indicate that future increase in quality requirements in the environmental category by 50% will result in a reduction of presently available resources by 20%, whereby the number of producing bauxite deposits world-wide will decrease to 84. A quality increase by 70% will reduce resources to 21% of the present figure.

Introduction

Analysis of resource scarcity is generally focused on non-renewable commodities such as energy and mineral resources and warnings about shortages of material stocks of natural resources have been recurrent through history. Before that background, major concerns have been expressed about the availability of mineral supplies necessary for the maintenance of economic stability and growth.

The concept of sustainable development brings a further perspective to these concerns, so as to preserve the reproductive capacity of natural resources to provide for the needs of future generations. However, the nature of nonrenewable resources is such that they add another complicating factor to the concept of sustainability and it is debated how this issue can be approached in accordance with sustainability principles. In this context, the issue of mineral resources is generally addressed in the environmental indicator systems by proxy, namely, through measures of the impact that extraction, processing, use, and disposal have on the environment. Therefore, sustainability for a specific mineral resource, such as bauxite, can be examined best in a material flow study that provides the basis for assessing the cumulative effect a particular material use has on the environment.

This approach is currently being taken by the Collaborative Research Center 525 that was established in 1997 by the Deutsche Forschungsgemeinschaft (DFG) at the University of Technology (RWTH) Aachen. The aim is to develop an integrated resources management system that analyses and quantifies the flow of materials and energy through the entire production cycle and thus provides a scientific base for improving production and resource-use efficiency and identifying areas where adverse impacts on the environment can be minimized.

The present paper considers the first stage of materials flow associated with the aluminum production cycle. It focuses, in particular, on the adequacy of bauxite supply and examines the magnitude of the resource stock if in addition to technologic and economic factors environmental considerations are included in bauxite reserve calculations.

Bauxite Supply

Since World War II, world production of bauxite, the principle ore for the production of alumina and aluminum, has risen from less then 5 Mio t per year to 125 Mio t in 1998.

In the same year, mine production was reported in 24 countries, but the 12 largest producing countries accounted for about 97% of the world production. Australia is currently the largest producer with about 40 Mio t of bauxite per year, followed by Guinea (16.5 Mio t), Jamaica (11.9 Mio t), Brazil (11.5 Mio t) and China (7.3 Mio t).

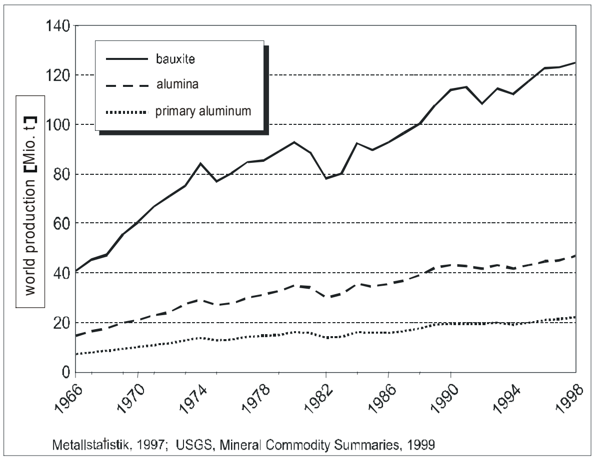

Figure 1: World production of bauxite, alumina, and primary aluminum from 1966 to 1998.

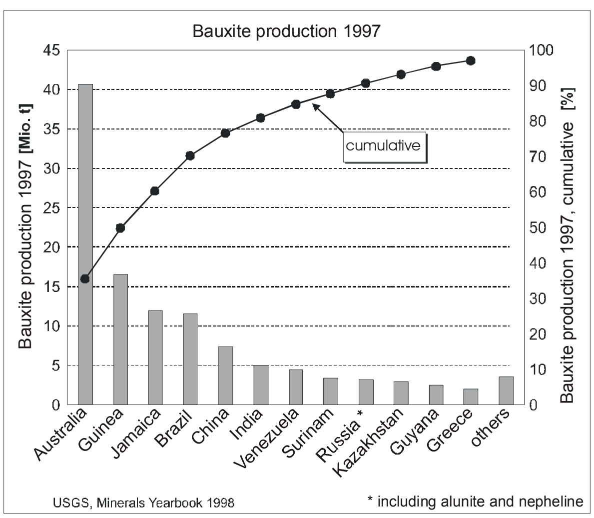

Figure 2: 1997 bauxite production by countries.

In 1997, proven and probable world bauxite reserves were estimated to amount to 23000 Mio t (cf. Plunkert 1997, Roullier 1995). Bauxite reserves are unevenly distributed throughout the world, with the largest reserves being located in Australia (23.7%), Guinea (19.5%) and Brazil (14.4%). Bauxite supply estimates, derived from ratios between present reserves and annual production (i.e. static life time) indicate adequate bauxite supply for at least 170 years.

One third of the current bauxite reserves is contained in deposits that are currently being mined, while the other two thirds are located in deposits that are in exploration state, or where feasibility studies have been completed (Sehnke 1994, Roullier 1995, Plunkert 1997, U.S. Geological Survey, 1997, Carvalho et al. 1997).

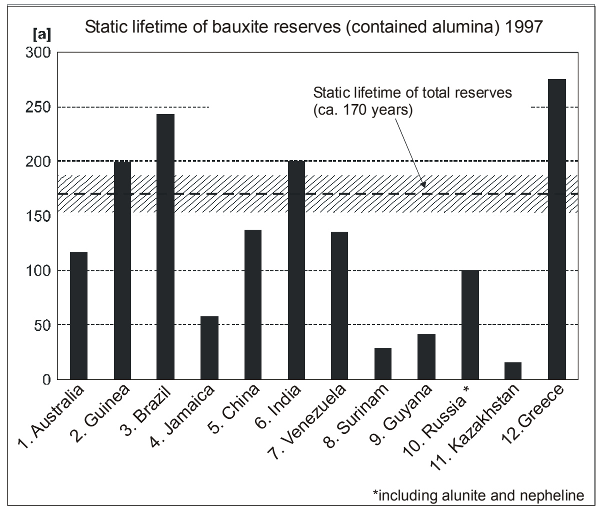

Figure 3: Static life time of bauxite reserves by countries.

Methodology

In a similar way, the environmental indicator system is used for describing the state of the environment in a region or country, environmental signatures of mineral deposits can be used for describing geologic, mining, and processing factors that influence potential environmental effects. In that sense, the impact can be assessed the raw material source, extraction, beneficiation, smelting, or refining of a specific mineral commodity has on the environment. Environmental signatures are defined here to include all ore deposit characteristics that are environmentally important. In addition, environmental indicators are used to demonstrate trends. They are defined here to represent quantitative variables that measure the effect the use of a raw material has on the environment.

For this study, more than 170 bauxite deposits world-wide were evaluated to identify environmentally important geologic characteristics.

The environmental effects resulting from mining and processing of bauxite, i.e. the Bayer-Process, were also analyzed and considered further variables that describe the generic environmental system discussed here. Linkage of geology- and processing-based variables resulted in ten pertinent environmental signatures that together can be integrated into

environmental indicators for monitoring the environmental behavior of the alumina production cycle.
In practice, each of the 10 signatures can be used as a tool to help to assess for individual bauxite deposits, geology-, mining-, and processing-related factors that have a potential impact on the environment. The environmental indicators, on the other hand, comprise the grouped and weighted environmental signatures and, therefore, are characterized by a higher level of aggregation.

The indicators are used as tools to model generic scenarios that can be technology-, site-, supply-, or scarcity-orientated.

Environmental signatures of bauxite deposits

Based on pertinent geologic characteristics of bauxite deposits the following set of environmentally important signatures can be defined.

- recoverable alumina (rec. Al_2O_3)
- reactive silica (= R.SiO_2)
- TiO_2-content
- moisture content
- ore reserves
- annual ore production
- bauxite/Al_2O_3-ratio
- red mud/Al_2O_3-ratio
- waste/ore-ratio
- land use/t rec.Al_2O_3

Recoverable Al_2O_3: The mineralogical composition of the ore, in particular the amount of valuable minerals, controls the energy consumption of the Bayer-process and the yield of Al_2O_3.

Reactive silica and (R.SiO_2) and TiO_2-content: The presence of SiO_2 and TiO_2 has a negative effect on the Bayer-Process, because their concentration in the ore strictly controls the amount of energy and flocculants used in the process.

Bauxite/Al_2O_3-ratio and Red mud/Al_2O_3-ratio: The bauxite/Al_2O_3-ratio as well as the bauxite/rec.Al_2O_3-ratio provide information on the amount of bauxite needed to produce a given amount of aluminum oxide. These figures, therefore, are measures for the amount of bauxite that has to be mined from an ore deposit to produce one ton of rec. Al_2O_3.
The red mud/Al_2O_3-ratio as well as the red mud/rec.Al_2O_3-ratio provide information on the amount of red mud that occurs when a given amount of aluminum oxide is produced.

Ore reserves: This term refers to the economic characteristics of ore deposits and is determined by the geologically proven and economically recoverable amount of ore.

Annual ore production: This relates to annual production figures of individual mines or the accumulated production world-wide. The static lifetime for a mineral commodity is defined by the ratio of world reserves and world production at a given year.

Moisture content and waste/ore-ratio: The moisture content refers to the amount of non mineral-bound water in the ore. A high moisture content has a negative effect on mining and processing and transportation of the ore. The waste/ore-ratio provides a figure for the amount of country rock that has to be moved to produced a given amount of ore. This value also influences the methods employed to mine the ore.

Land use/t rec.Al_2O_3: This ratio considers the amount of land (m²) used for bauxite mining per ton of recoverable alumina extracted. The figure varies with the geometry and thickness of the ore body as well as with the alumina content and in-situ density of the ore.

Environmental Indicators
Factor analysis was used to investigate possible relationships between relevant environmental signatures discussed before. By applying the method the total data set was reduced to seven factors. The resulting factor-loadings were then used as a measure for the significance of this factor (extracted by factor analysis) to contribute to a specific environmental indicator. In that way a total of 5 environmental indicators was defined which help to monitor the environmental behavior of bauxite deposits.

Generic: Equal weighting of all factors

Beneficiation-oriented: Strong weighting of factors that influence the efficiency of alumina production using the Bayer-Process.

Ore deposit-oriented: Strong weighting of factors that influence the environmental signature of bauxite deposits.

Reserve-oriented: Strong weighting of factors that influence bauxite reserves.

Sustainability-oriented: Strong weighting of factors that influence all effects the use of raw materials (i.e. bauxite) has on the environment.

Assessment of bauxite availability

In the following models are shown that employ environmental signatures as well as environmental indicators as limiting conditions for the adequacy of bauxite supply under variable conditions (scenarios). The models are based on the premise that environmental signatures and indicators - in the sense of sustainability - are a reflection of the environmentally important characteristics of a bauxite deposit, and so of the quality of bauxite that is extracted from this deposit. In this context, high bauxite quality relates to positive environmental signatures/indicators while low quality refers to negative signatures/indicators. The scaling of ore-quality levels is such, that today's lowest quality (or negative environmental indicator) encountered in the 170 bauxite deposits studied is taken as zero level, while today's highest quality is set to 100%.

Influence of environmental signatures on bauxite availability

Figure 4 presents results of a model that calculates for a set of environmental signatures adequacy of bauxite supply (availability of ore reserves) as a function of ore-quality. Also given is the static lifetime for bauxite reserves based on constant annual production of 50 Mio t Al_2O_3.
It is obvious from the graph that various environmental signatures have different effects on bauxite availability. For example, an increase by 50% of the rec.Al_2O_3–signature results in a reduction of initial bauxite reserves by ca. 55%, the same increase applied to the land-use/rec.Al_2O_3-signature reduces available reserves by

10% only. An even lower effect on resource reduction is shown for the waste/ore-indicator.

It is clear, however, that application of environmental signatures as a measures of ore-quality can have a strong effect on the adequacy of bauxite supply, if there is a demand in future– in the context of sustainability – for higher ore-quality standards.

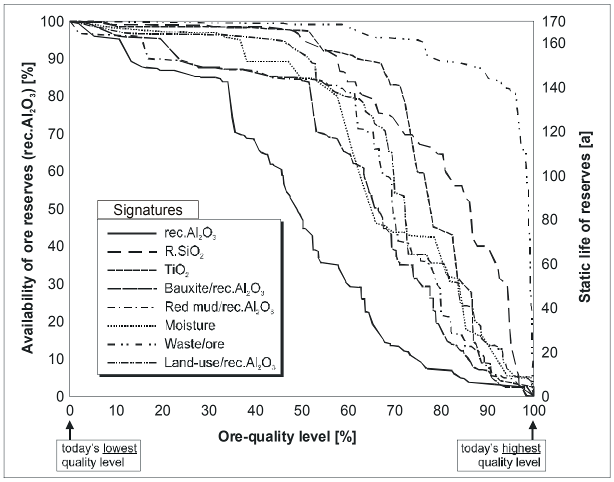

Figure 4: Reserve availability model: Availability of reserves and static lifetime of bauxite reserves as function of ore-quality. Environmental signatures used are shown on the graph.

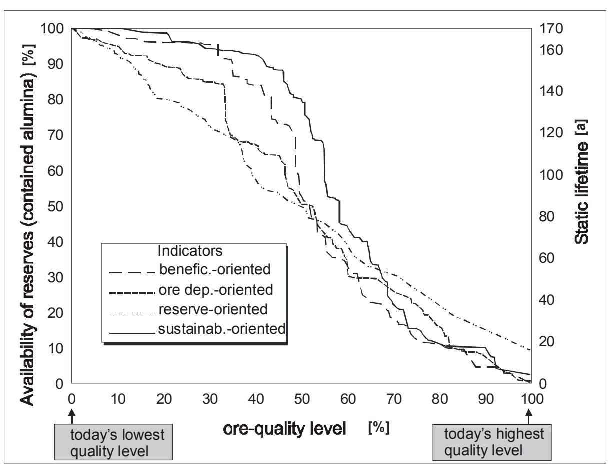

Figure 5: Reserve availability model: Availability of world bauxite reserves and static lifetime of bauxite reserves as function of ore-quality. Environmental indicators used are shown on the graph.

Figure 5 shows model calculations that investigate the influence of environmental indicators - again expressed in terms of ore-quality or the demand for a specific quality level on the availability of bauxite and the static lifetime of bauxite reserves.

If we assume, for example, a demand for increasing the sustainability-oriented indicator (reflected in the ore-quality) by 50%, this would then result in the reduction of bauxite reserves by 20%. Applying the same ore-quality increase for the beneficiation-, ore-deposit-, and reserve-oriented indicators the reserve availability would be decreased by almost 50%. The advantage of employing environmental indicators over environmental signatures is placed on the fact that the former represent a higher level of aggregation and can be used for analyzing specific scenarios by which the impact can be assessed the use of bauxite has on the environment.

Geographic distribution of bauxite reserves

Model calculations on bauxite availability discussed above are based on world reserves. In the following similar calculations are shown that focus on reserve calculations for 12 bauxite producing countries. Figure 6 compares available bauxite reserves for the 12 countries if – according to the models shown previously – in addition to today's lowest quality-level (i.e. 0%) increases in ore-quality are considered up to 50% and 70%, respectively.

At present, Australia hosts the largest bauxite reserves, followed by Guinea and Brazil. If quality requirements are increased to 50%, Australia's present reserves will be reduced by 25%, while Guinea will not suffer any reserve reduction.

With a further increase of ore-quality to 70%, in terms of reserves, Australia would fall back to rank six among the bauxite producing countries (figure 6).

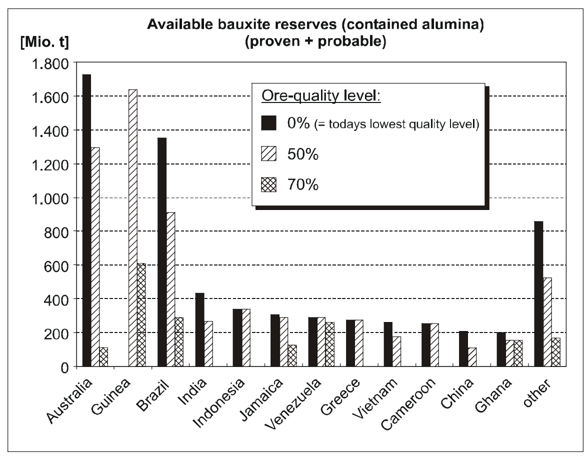

Figure 6: Model calculations demonstrating changes of bauxite reserves in twelve major bauxite producing countries as a function of ore-quality levels (0%, 50% and 70%).

To what extend demands for higher ore-quality will effect reserve availability of bauxite world-wide are depicted for the sustainability-oriented indicator in a further panel of figures. Figure 7 a) shows the world-wide distribution of bauxite deposits from which ore is extracted that at present fulfils minimum quality requirements (0%, as defined before). In case ore-quality is increased by 50% (relative to the lowest level) the number of producing deposits will be reduced from 134 to 84 (figure 7 b). A further increase in ore-quality to 70% will particularly effect all bauxite producers in Europe as well as the majority of the Australian and Asian mines (figure 7c). In that case, main bauxite production will be from mines located in Middle and South America and West Africa.

Figure 7: Geographic distribution of bauxite production sites (a, b and c indicate available deposits for 0%, 50% and 70% quality requirements, respectively).

Summary and Conclusions

This study investigates the adequacy of bauxite supply and its dependence on changing quality requirements. Based on deposit- as well as a global-scale assessment of geologic, mineralogic and geochemical characteristics of bauxite, ten ore parameters were distinguished that serve as environmental signatures which can be used as a tool to assess geology-, mining-, and processing-related factors that influence potential environmental effects. Environmental indicators are characterized by a higher level of aggregation and are used to model generic scenarios that are beneficiation-, ore deposit-, reserve-, and sustainability-oriented. The influence of specific environmental signatures on bauxite availability was assessed by modeling variable quality requirements for bauxite. In this context, the term quality or ore-quality is used as an indicator for the impact extraction and processing of bauxite has on the environment, within the concept of sustainable development. Application of environmental signatures as measures of ore-quality strongly effect the adequacy of bauxite supply. Model calculations show that an increase in these parameters by 50% results in significant depletions of available bauxite reserves and thus in a reduction of the static lifetime. Similar results were obtained by using environmental indicators to monitor changes in bauxite availability with respect to increasing demands for higher quality. In the same way is the global distribution of bauxite suppliers affected. An increase of ore-quality to 70%, for example, would reduce potential bauxite producers to mines in West Africa and Middle and South America. In general, results presented in this study point to the fact that an increase in quality requirements in the environmental category will lead to a significant reduction of available bauxite reserves and will effect the geographic distribution pattern of bauxite producers.

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BAUXITE MINING AND ITS EFFECTS*

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ABSTRACT

The sustainable development challenges facing the bauxite mining industry have become a critical concern for mining companies, governments and NGOs. Considering the scale of bauxite mining activities, it is not surprising that such activities have a wide range of social, economic and environmental impacts. Bauxite is mined at more than 70 sites in 25 countries. Most of the deposits are shallow and the mining methods – open pit mining using scrapers, shovels front-end loaders, trucks, etc. – are all very similar. Differences in the thickness of the topsoil, overburden and bauxite layer lead to varying mass flows and land use. A selection of social, economic and environmental effects associated with open pit mining are presented and discussed. The paper focuses on the quantification of social issues related to employment opportunities and effects on the indigenous population. Further emphasis is placed on the classification of bauxite mining economies in terms of income structure. Finally, descriptive indicators to analyse the environmental effects in the context of land use and diversity of ecosystems are presented and put into concrete terms.

KEYWORDS

Sustainable Development, Bauxite Mining, After Effects, Social Impacts, Economic Impacts, Ecological Impacts, Land Cover

* Source: Singhal, R.K.; Mehrotra A.K. (eds.): Environmental Issues and Management of Waste in Energy and Material Production. Proceedings of SWEMP 2000, Balkema, 2000, pp.49-55

INTRODUCTION

The identification of options for the resource-sensitive supply and processing of metallic raw materials is the long-term goal of the Collaborative Research Center 525 (CRC 525). The research programme was established in 1997 at the Aachen University of Technology and is funded by the Deutsche Forschungsgemeinschaft (DFG). An integrated resource management system for important metallic raw materials is to be developed and tested by the CRC 525 with respect to the applicability of this system as a framework for providing useful and efficient tools for decision makers by considering technical developments and economic and ecological aims. Ten institutions at the Aachen University of Technology and one programme group from the Forschungszentrum Jülich collaborate in nine subprogrammes (SP) within this project.

The initial three-year phase of the programme (1997-1999) focused on the aluminium flow analysis, extending from bauxite deposits through mining to alumina and aluminium processing and also including the process chains of secondary production and waste disposal.

The Institute of Mining Engineering I (SP 2) is analysing, modelling and balancing the demand for resources at bauxite mining. Besides bauxite, further resources such as energy and environmental media as well as human and financial resources are used or stressed in the mining process. The Department of Engineering Geology and Hydrogeology (SP 5) deals with local, regional and global investigations of the environment. The aluminium analysis will be completed during the second three-year phase of the programme, beginning in 2000.

1. BAUXITE PRODUCTION

Bauxite is mined throughout the world at more than 70 sites in 25 countries. Major mining production areas are shown in figure 1.

Figure 1. Bauxite-producing countries and sites. The size of the bullets corresponds to the annual production of the region.

Mining sites in equatorial regions and in the southern hemisphere account for an increasingly large share of production. Major producers are Australia, Guinea, Brazil and Jamaica.

The main purpose of bauxite mining is the production of aluminium. Apart from the aluminium industry, bauxite is also required by the chemical and refractory industry and for the production of abrasives. The demand for aluminium has grown over the last century. Considering the total quantities produced, the increase was quite moderate in the first 40 years. During the following decades, production increased rapidly from less than 1 Mio. tons p.a. to more than 22 Mio. tons p.a.. Since bauxite production is closely linked to the development of the aluminium market, these figures also rose from around 4 Mio. tons in 1940 to 125 Mio. tons in 1998 (Fig. 2).

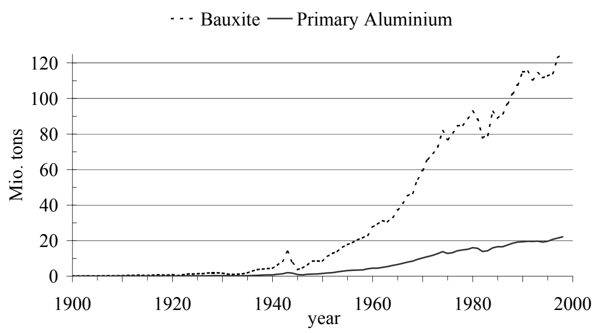

Figure 2. World bauxite and aluminium production since 1900 (Metallgesellschaft 1997; U.S. Geological Survey 2000).

If one relates the overall mining production of bauxite to the estimated world population of 5.8 billion in 1998 (Worldbank 2000), the consumption of bauxite per capita amounts to 21.6 kg per year. Projecting this figure over an expected 60–year lifetime, every human being will roughly consume 1300 kg of bauxite.

2. BAUXITE EXTRACTION

Most of the bauxite deposits are very shallow and are mined in an open pit. There are also a few underground mines which are not taken into account here because of their small share of world bauxite production. Deposits of lateritic bauxite commonly belong to the blanket type, whereas karst bauxites often appear as bauxite pockets. The overlying strata usually consist of loose soil and uncemented or minor consolidated rock. Thus, most operations do not need any explosives to break up the overlying strata. Some operations have to use rippers to loosen overburden or bauxite before extraction.

Topsoil and overlying strata are removed by scrapers, front-end loaders, hydraulic excavators or draglines. Front-end loaders and hydraulic excavators are also used for bauxite extraction. The in-pit-transport is characterised by trucks. Dozers prepare areas for extraction and reclamation. The biggest share of the equipment is driven by diesel engines. Only a small number of mines also use electric equipment. There is a trend towards an increase in the equipment capacities, leading to lower specific fuel consumption.

In order to analyse bauxite mining, data and information are collated, compiled, and generated in a database. Data from numerous bauxite mines - operative and closed down - has been collected during field-trips and extracted from literature. This data forms the basis for estimations of site-specific values which are inadequately documented in literature. Each data-set comprises information on the identification of the site, geological information (e.g. thickness of overburden and bauxite layer, bauxite density, etc.), data on bauxite quality, production, equipment fleet, fuel consumption, and number of employees. Furthermore, the database contains site-specific information on the stages of the bauxite extraction process.

This database is used to calculate values for land use, energy consumption, labour-input as well as associated material flows of overburden and emissions. Table 1 shows selected figures as a result generated by a database-report.

Table 1: World bauxite production in 1998 and selected cumulative parameters for the production of metallurgical bauxite

total mine production	125	Mio. t
metallurgical bauxite	106	Mio. t
land use	13.7	Mio. m²
overburden mass flow	69	Mio. m³
fuel consumption (diesel)	120	Mio. l
labour force (extraction only)	15,000	workers

All of the aforementioned parameters are part of the stress field of economy, ecology and social aspects and have several effects.

3. EFFECTS OF BAUXITE MINING

Considering the scale of mining activities, it is not surprising that they have a wide range of social, environmental and economic impacts. A selection of potential effects associated with the open pit mining of bauxite is shown in Figure 3.

Impacts of open pit mining have been widely discussed in literature. For further information see (Eggert 1994), (Sengupta 1993), (UNEP 1997), and (Martens 1998). We distinguish between four mining life cycle stages with respect to the origin and nature of effects: exploration, mine development, mining, and mine closure.

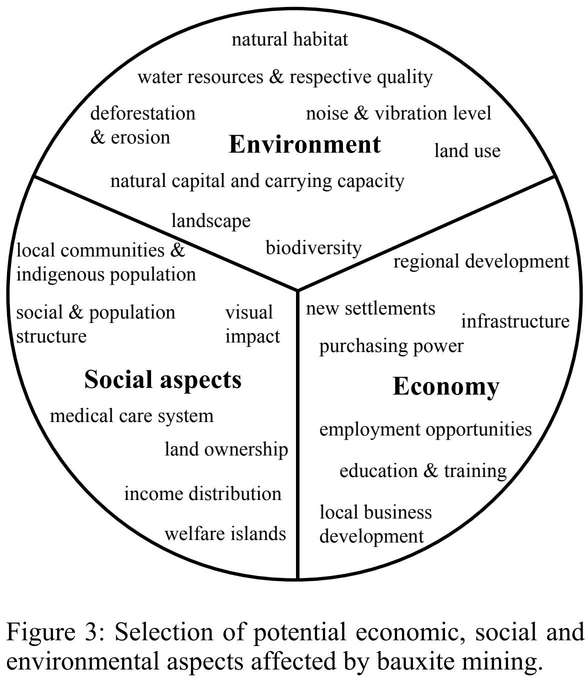

Figure 3: Selection of potential economic, social and environmental aspects affected by bauxite mining.

Before a bauxite deposit can be mined, it has to be identified and its economic and technical viability demonstrated. The exploration phase causes almost negligible environmental damage due to drilling, grab and bulk sampling and pilot plant operation.

Once a workable bauxite deposit has been identified, mining and processing facilities as well as essential supply systems and an infrastructure have to be set up. The mine development phase is characterised by construction activities which usually cause a significant change in the landscape, ranging from a mere visual impact through to severe deforestation and the destruction of natural habitats. The environmental impacts of mine development are more relevant than those arising from the previous life cycle stage but much less than those related to bauxite extraction.

Strictly speaking, activities related to bauxite mining following mine development can affect all three environmental media - land, water and air. In general, "open pit operations produce far more waste per tonne of ore than underground operations, where there is no overburden and where some of the removed material can be used to backfill excavations as work progresses" (UNEP 1997). This does not necessarily hold true for open pit bauxite mining due to the shallowness of ore layers, resulting in less overburden and enabling successive excavation and reclamation sequences. Since neither acid rock drainage or potentially hazardous tailings nor waste material occur, the severest environmental problems related to bauxite mining usually arise from land degradation. Excavation, extraction and waste disposal can lead to substantial soil degradation, deforestation and destruction of wildlife habitats. Fortunately, most ground water levels are below the basic level of superficial bauxite deposits. Consequently, a lowering of the water table is not a major impact question for open pit operations. Water effluents from mine operation include drainage, wastewater from bauxite washing and surface run-off, carrying suspended solids. Significant dust emissions arise from road transport, ore processing, and wind erosion from uncovered top-soils unless appropriate measures are implemented. Gaseous air emissions are mainly caused by fuel combustion.

Due to the non-renewable nature of mineral deposits, mines have a finite life span. The mine closure and decommissioning stage directly follows the cessation of mining. The objective of the rehabilitation and reclamation phase consists in creating a productive and sustainable post-mining land use for the site. Simultaneously, a number of goals related to the protection of public health and safety and to the minimisation of the environmental impact associated with seepage and drainage must be pursued. Pits and waste piles have their slopes stabilised and may be revegetated. In addition, plant growth and water quality have to be monitored. The future land use potential is usually dependent upon topography, drainage, vegetative species mixes and surface texture. Furthermore, the success of the reclamation efforts depends on precipitation patterns and physical and chemical properties of surface and near-surface layers.

Apart from environmental impacts, mining activities also have economic and social effects.

After successful exploration, changes in land use and land ownership may restrict former access to natural resources for local communities. In this context, a participation of all interested parties is desirable during the process of social and environmental compliance prior to mining.

During mine development, the construction of facilities, roads, settlements, and energy and fresh-water supply systems may lead to a noticeable regional development in terms of improved living conditions, including the establishment of medical care and education centres. In some cases, a relocation of indigenous communities will be inevitable. Further economic and social consequences of mining arise from direct employment opportunities and the following stimulation of local business development due to the increased purchasing power of the local population. The distribution of the economic benefits of mining changes the income distribution and social structure of the surrounding settlements. Education and training as well as improved living conditions may contribute to a profound alteration of cultural values and former life styles. Furthermore, indigenous people are very sensitive to any disturbance of their local environment. The migration of workers and others taking advantage employment opportunities directly or indirectly related to mining may significantly affect the former local communities.

When mining ceases, a serious economic decline in the area is inevitable unless alternative employment opportunities are available for the redundant mine workers and the related support services. Otherwise, the site and its surroundings dispose of facilities, buildings and infrastructure that may be useful to other industries or business forms. Alternative investment and re-employment programmes stimulated by the mining companies and government can help create new employment opportunities and thus alleviate the adverse socio-economic impacts of mine closure.

In the following, selected social, economic and environmental impacts will be presented and discussed from a global point of view.

4. DISCUSSION OF SELECTED IMPACTS

Social, economic and environmental effects are strongly interdependent and should not be seen as strictly separate problems.

An environmental information system has been developed by the SP 5 of the CRC 525 to quantify the global effects and impacts of bauxite mining in a global material flow study (Bauer & Sliwka, 1998). Spatial data on environmental properties has been collected from across the globe based on a geographic information system. In combination with the bauxite mining database, site specific indicators are quantified which can be used to discuss selected effects of bauxite mining. Unlike former panel-based studies (Atkins, 1993), which gathered a high information content for a sub-set of sites, this approach enables the consideration of almost all sites. This system had already been used to characterise bauxite deposits on a global scale (Hausberg et al. 1999). Core elements of the spatial database are small scale survey data on soils, land cover characteristics, hydrology, morphology and population densities. These are important key indicators not only for the consideration of social and environmental impacts but also to discuss endpoints for a variety of impact pathways.

5.1 Social Impacts

5.1.1 Employment Opportunities

World-wide bauxite mining operations provide approximately 15,000 direct employment opportunities. In terms of productivity, the average employee produces roughly 4.7 t/h of bauxite. The productivity varies significantly from site to site. Local productivity depends on various site-specific factors, e.g. operating performance, bauxite quality and transport distance between pit and processing plant. Thus, no evaluation of local or regional productivity can be carried out without a further analysis of site-related economic and technological characteristics.

A macroeconomic analysis of the employment structure may be carried out based upon the definition of small and medium-sized enterprises recommended by the European Commission (European Commission 1996):

- small enterprises: <50 employees
- medium enterprises: 50 – 249 employees
- large enterprises: >249 employees

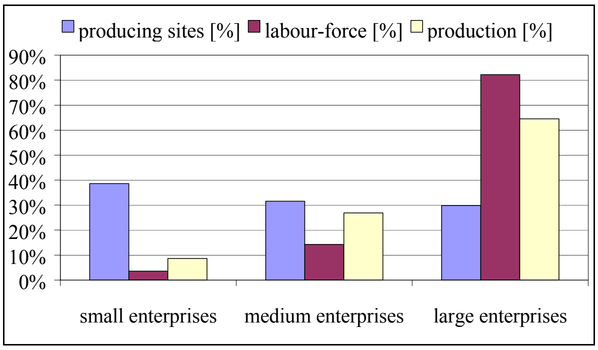

Figure 4: Bauxite mines, production and labour-force classified according to size of enterprise.

More than 80% of employees work in large enterprises which represent two thirds of the total production. 70% of mining sites claim to be small or medium-sized firms employing less than 20% of the total labour-force (Fig. 4).

5.1.2 Population and Indigenous People

Besides the provision of jobs, mining has further social effects on the local population, e.g. through resettlements or changes of land cover. At peripheral sites with low population densities, company towns are built whose inhabitants are unfamiliar with the local environment, living conditions, and cultural structures of the original social community. These sites often attract itinerant workers and others who take advantage of the developed infrastructure and considerably enhance the percentage of foreigners in the vicinity of the site. Indigenous people in particular, e.g. Indians in South America or Aborigines in Australia, whose culture is closely related to the stability of their local environment, are very sensitive to any disturbance. Indigenous people are protected by several international and national conventions which have to be considered in all stages of mining projects.

Sites in more densely populated areas are not likely to interfere with undisturbed ecosystems. In these cases, important effects are resettlements and concurrent utilisation of local resources (roads, land, water).

Available data on population density and distribution on a global scale provide no information on the presence or absence of indigenous people in the vicinity of a particular site, but it is almost certain that the probability of their presence increases with a decrease in population density. This relation was proved in field studies conducted by the CRC 525 at bauxite mines in Australia, Brazil and Venezuela.

Population density is hereby used as a key indicator to differentiate between social effects of bauxite mining. In Figure 5, production sites and the proportion of the worlds annual production are according to population density, quoted in inhabitants per km² [I/km²].

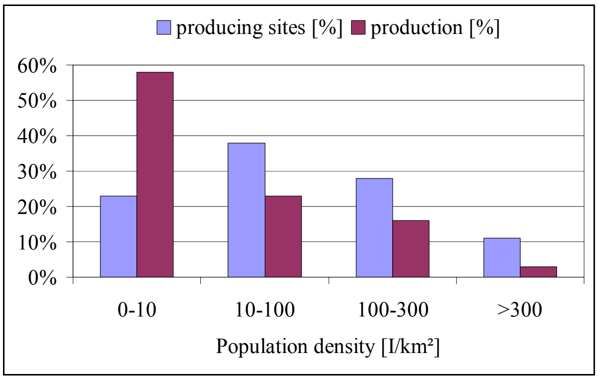

Figure 5: Bauxite mines and production according to population density.

Population densities of 0 to 10 inhabitants per km² were chosen to indicate social effects on indigenous people. Population densities of more than 300 inhabitants per km² indicate social effects by concurrent utilisation of local resources. Although 58% of the world's bauxite production takes place at peripheral sites, at only 23% of the current mining enterprises is an interference with indigenous people probable. Higher population densities (>100 I/km²) indicate the presence of established rural or urban structures at the majority of producing sites. Their contribution to the global bauxite market amounts to around 20%.

5.2 Economic Impacts

A significant, country-related economic impact of mining may result from the export of bauxite to other economies. The value added by alumina and aluminium production in almost every bauxite mining country normally has to be considered. However, in order to estimate the potential contribution of bauxite, we have related total bauxite production and bauxite price to the total export of commodities. Significantly different shares result for the major producers of bauxite in 1997, e.g. Guinea >47%, Guyana >18%, Jamaica >17%, Australia and Brazil <1%. Note that the price of bauxite varies greatly from region to region, due not least to bauxite quality, ore grade, productivity, transport, and mining technology. The low income economies of Guinea and Guyana in particular are very dependent on bauxite exports and resulting revenues, whereas more developed and diversified economies such as Australia and Brazil are expected to be less vulnerable to changes in market structure.

For operational and analytical purposes, the World Bank's main criterion for classifying economies is gross national product (GNP) per capita. “GNP is the sum of gross value added by all resident producers plus any taxes (less subsidies) that are not included in the valuation of output plus net receipts of income from abroad” (Worldbank 2000). GNP per capita is gross national product divided by midyear population and is converted using the World Bank Atlas Method. Every economy is classified as low income (GNP $760 or less), lower middle income (GNP $761- $3,030), upper middle income (GNP $3,031- $9,360), and high income (GNP $9,361 or more) (Worldbank 2000).

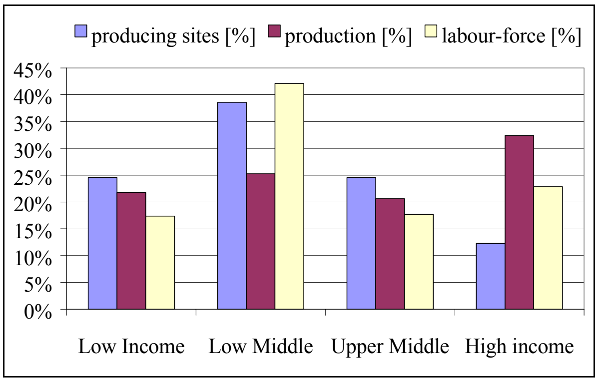

Figure 6: Bauxite mines, production and labour-force according to income structure of economies (GNP per capita).

A classification of producing sites, production and workforce is shown in Figure 6. One third of bauxite production takes place at 12% of mining sites in high income economies, providing employment opportunities for almost a quarter of the total labourforce.

Two thirds of sites operate in low and low middle income economies and account for less than 50% of total bauxite production. Less than 20% of the total bauxite-related labour-force is employed at mining sites in low income economies. In terms of production bauxite mining claims equal importance in all kinds of economies.

5.3 Environmental Impacts

The main environmental effects of bauxite open pit mining relate to the use of land. Not only the cleaning of the surface in the pit but also the construction of roads and stockpiles constitute disruptions to the local ecosystem. The restructuring of drainage systems or fragmentation of ecosystems by transportation networks may cause negative effects far beyond the mining site. The extent of these impacts depends on the land cover characteristics on the site and its vicinity which are altered by the mining process.

5.3.1 Dominant Land Cover Characteristics

Land cover types in the vicinity of each mining activity have been collected and grouped within the environmental information system to identify dominant land cover characteristics affected by bauxite mining. Several environmental effects are being discussed with respect to the kind of land cover. In this discussion, the world's forest is associated with the global warming and air quality. Tropical rain forests and wetlands are specially associated with high biodiversity. Agricultural land was classified because of a potential concurrent use of the surrounding population for a limited period of time. The group "others" is used to summarise remaining land cover types such as tundra, deserts, grassland, etc (figure 7). The specific percentages of each group at all sites were summed up. Figure 7 shows the overall percentage of each group scaled by site and land use. The relations between site percentages and land use percentages within each group can be explained by large differences in the operation size. Considering that a single site can be surrounded by different land cover types, at 50% of the sites mining takes place on agricultural affected land. In terms of the total annual land use of 13.7 km² (calculated by geometric deposit properties and annual production), agriculture accounts for only 25%. These are mostly small mines in arable areas (e.g. China, India).

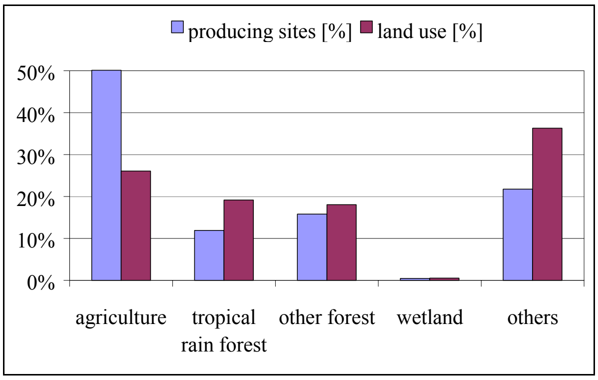

Figure 7: Bauxite mines and production according to affected ecosystem.

If one now considers forest cover, and especially tropical rain forest, it can be seen that only a few sites with a greater share of annual land use are dominated by this ecosystem. Wetlands are, as expected, marginal in this discussion.

5.3.2 Naturalness Indicator

In order to analyse the diversity of ecosystems affected by mining operations, an indicator was developed to measure the naturalness in the vicinity of each site.

The naturalness indicator [N_g = 0-1] is based on the ratio between the area of land cover characteristics unaffected by humans and total area in a unit circle with a 50 km radius of the location. A naturalness indicator level of 1 for a location means that the vicinity has not been affected by human activities so far. A value of 0 indicates a strong manmade alteration.

Figure 8 shows the percentage of current mining sites and their shares of world production according to the naturalness indicator. Approximately 30% of the sites are situated in peripheral regions with very low previous human impact (N_g = 0.8-1). These sites produce 58% of the total annual bauxite production.

The application of this indicator is manifold for any discussion of the effects related to bauxite mining. On the one hand, it can be seen that small mines are generally situated in regions where human activities have already altered the environment. These areas are not supposed to be specially sensitive towards additional impacts atttributed to the mining activity. On the other hand, nearly 80% of bauxite mined in natural and as yet undisturbed ecosystems (N_g > 0.6) by 43% of the mines. These predominantly major producers are expected to have sufficient human and financial resources as well as organisational structures and technical equipment at their disposal to cope with the environmental, economic, and social challenges related to bauxite mining.

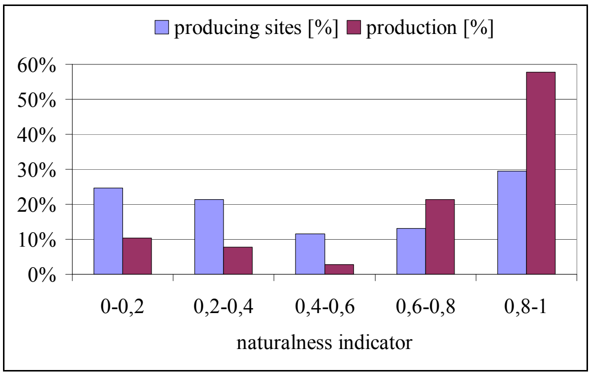

Figure 8: Bauxite mines and production according to naturalness indicator.

5. CONCLUSION

The effects of bauxite mining have become a critical concern for mining companies, governments and other stakeholders. Environmental permits and regulations as well as social commitment are important to bauxite mining companies because they increase time, costs, and risks associated with bringing a mine into production. There is growing evidence of the further need to study and disseminate the positive and negative effects of bauxite mining. Apart from a mere compilation of more relevant data, existing concepts and indicators will have to be improved and new approaches and strategies developed in order to promote technical change and foster economic and environmental efficiency.

There is still considerable research to be undertaken to quantify the nature and extent of external effects of bauxite mining. However, as a general trend changes in industrial and governmental policy can already be observed towards more environmentally and socially sound mining operations.

As shown above, bauxite mining activities in socially and environmentally sensitive areas are mostly carried out by large companies due to the complex and challenging character of mining operations in remote and less developed areas. Many of the potentially negative impacts can be prevented or diminished by adopting appropriate measures and management systems. Others, such as habitat destruction or land degradation, can only be dealt with after exploitation by means of rehabilitation and reclamation.

Most of the global players in bauxite and aluminium are committed to meeting the challenges of continual environmental improvement and have already introduced environmental management systems. Moreover, there is a shift towards the adoption and compliance of uniform international technical and environmental standards for production sites all over the world. It is, however, inevitable that further policy and science directions be specified to address the concerns through partnerships with companies, governments and stakeholders.

"One of the most powerful ways mining companies and their associations can contribute to environmental performance is to assist in the development of more effective technologies" (Miller 1997). Technological and organisational innovation offers a potential escape from the oft-presumed trade-off between economic growth and environmental quality.

The sustainable development challenges facing the minerals and metals industry require a comprehensive, integrated and multidisciplinary approach based on shared decision-making and a reliable information base, as well as close co-ordination and co-operation of all interested parties. The integrated approach of the CRC 525 may offer an opportunity to address and cope with some of these challenges by supporting sustainable development-based decision-making.

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ANALYZING RAW MATERIAL FLOWS
– BAUXITE AS AN EXAMPLE–*

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ABSTRACT

The Collaborative Research Center "Resource-Orientated Analysis of Metallic Raw Material Flows" at Aachen University of Technology (RWTH) aims to develop tools and methods for resource-friendly provision of metallic raw materials within the context of an economic, ecological and social framework. The Deutsche Forschungsgemeinschaft (DFG) – a national research foundation – has been supporting this Center since 1997.
Using the example of bauxite, the project outlines a number of trends, in particular with reference to material flows that will be caused in the future as a result of the change in mining conditions. Based on the data acquired and elaborated by the Collaborative Research Center, it can be shown that material flows are expected to increase by virtue of the forecast increase in the specific demand for primary aluminum. In addition, material flows will increase disproportionately, due to the expected reduction in the alumina content of deposits that are currently being explored and will be mined in future. This also means that a higher level of red mud, specifically, is to be expected, compared to present levels.

KEYWORDS

Raw material flows, bauxite, mining conditions, alumina content, future demand, red mud

* Source: Proceedings of Int. Symp. On Mine Environmental and Economical Issues, Dnjepropetrowsk, Ukraine, 1999

1 INTRODUCTION

In the past 50 years, economies have developed into consumer societies at a breathtaking pace. In this context, the mining industry has the task of ensuring a safe supply base through mineral raw materials and semi-finished goods as a prerequisite of steady growth. The use of energetic and mineral raw materials therefore constitutes a key basis of our civilization. In this context, material flows moved by humans, i.e. materials on their way from extraction through the level of the usable finished product right to their disposal as waste, have reached proportions - both in terms of volume and quality - which have an impact on the global balance of resources as a whole. For example, in order to gain one kilogram of gold, approx. 350,000 kilograms of rock have to be moved and processed [4]. Annual production worldwide of approx. 2,300 tons of gold produces approx. 800 million tons of moved and processed rock. If it was loaded onto trucks lined up one behind the other, they would stretch from the Earth to the moon. For aluminum, with an annual production of 21 million tons of primary aluminum, the ratio is much more favorable [3]. In the case of current bauxite extraction, this only results in approx. 250 million tons.

2 MATERIAL FLOWS

The economic, ecological and social effects of material flows play a crucial role for the generations of the present and the future. On account of the limited availability of resources, for example labor, capital, energy, land, water and air, an arrangement of these material flows – or in other words, optimization of their application – with an eye to saving resources is of great social significance. Such material flows are of outstanding importance as regards the basic supply of man with mineral raw materials, including associated processing, recycling and waste products.
In order to be able to assess the significance of material flows of mineral and energetic raw materials, we must see their past, present and future development in connection with global population growth. This is particularly clear in the case of the "metal of the future", aluminum. While demand increased, the annual production of primary aluminum increased more than tenfold between 1950 and 1997. In the future too, an increase in annual production is assumed (Fig 1).

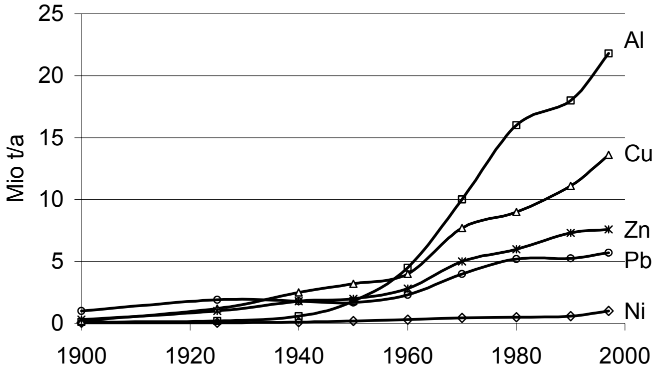

Figure 1: Global production of selected nonferrous metals.

In spite of a few slumps, comparatively strong economic growth in the Asiatic countries and the associated rise in the standard of living in this region will further contribute to increased demand for raw materials – primary and secondary. The link between economic growth and the use of raw materials means that it may be assumed that demand for raw materials will also increase in future. Incidentally, the amount of waste accumulated will also increase as a result.
Increased demand for mineral raw materials can in principle be covered by the following sources: firstly, a reduction in the specific use of raw materials, secondly, increased recycling and thirdly, mining.
The specific use of raw materials and energy with reference to the population is currently only being reduced in some

industrial nations. In developing countries, on the other hand, an opposing trend is discernible. Opportunities for recycling are primarily dependent on the raw material concerned and accordingly, developed to different extents. In addition, recycling has ecological and economic limits because as a rule with repeated reuse, impurities build up in the secondary products, which in turn leads to increased energy consumption and other associated factors of production. Recycling should therefore not always be regarded as the most expedient solution. As a result, the mining of mineral raw materials will also play a crucial role in supply in the future.

If the consequences associated with the production of commodities are considered, studies to date have for the most part been from a purely technical and economic perspective. The actual, much wider range of causes and effects was not taken into account. However, it is increasingly necessary to examine all the relevant material flows associated with the production, use and disposal of commodities "from the cradle to the grave" (Figure 2).

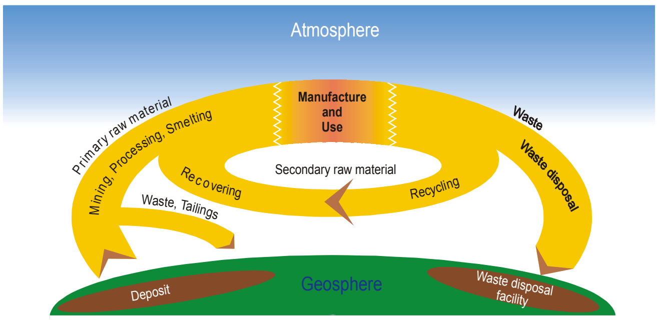

Figure 2: Raw material flows from the "cradle to the grave"

If material flows of non-reproductive energy and production raw materials flow from the geosphere into the anthroposphere and back again, not only considerable mass, volume and energy flows must be optimized from an operational perspective. Furthermore, processes should be considered alongside raw material flows while taking into account other influential parameters, such as ecology and society.

3 METHODICAL APPROACH

The Collaborative Research Center 525 “Resource-Orientated Analysis of Metallic Raw Material Flows“ supported by the Deutsche Forschungsgemeinschaft (DFG) has set as its goal the consideration of raw material flows as a whole. Nine institutes of the RWTH Aachen and of the Jülich Research Center from the fields of engineering sciences, natural sciences, economics, mathematics and system analysis are involved. The Collaborative Research Center is approaching the examination of metallic raw material flows as comprehensively as possible, going beyond the purely technical, economic dimension, with regard to ecological and social questions as well. Aluminum is used as an example in the initial phase of the project. Other metals will follow later.

The interaction of the scientific disciplines, divided into nine sub-programs, is depicted in Figure 3.

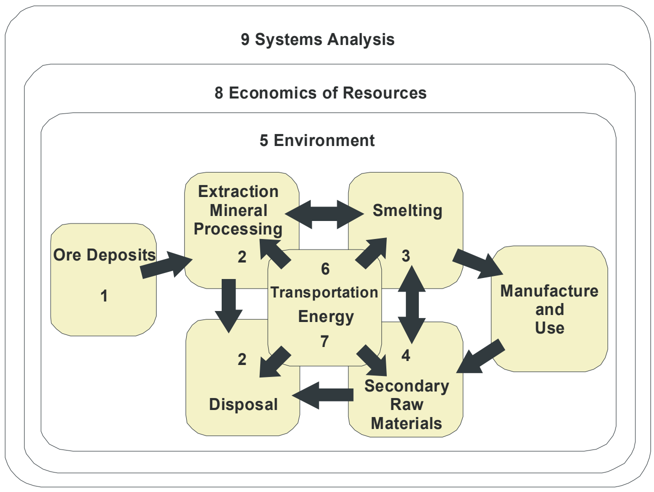

Figure 3: Linkage of sub-programs

Sub-program 1 examines the ore deposits of the raw materials for metal production and deals with the effects of different ore deposit and raw material parameters. Sub-programs 2, 3, 4, 6 and 7 consider the technical fields of raw material extraction, preparation, primary and secondary metal production, processing, waste disposal, transport and energy supply. Bilateral or multilateral co-operation between linked sub-programs is necessary for this. Economic, ecological and social aspects are analyzed by sub-programs 5, 8 and 9 in collaboration with those sub-programs affected. In this context, sub-program 9 considers the raw material flow within the framework of a system analysis and develops computer-aided tools together with the other sub-programs for an integral description and analysis of the material flow. The consequent tool kit (Figure 4) comprises an information system, a model for analyzing the global aluminum economy and selected national aluminum economies. A process chain model and sub-program-specific models complete this tool kit, creating a basis for simulating material flows and their effects.

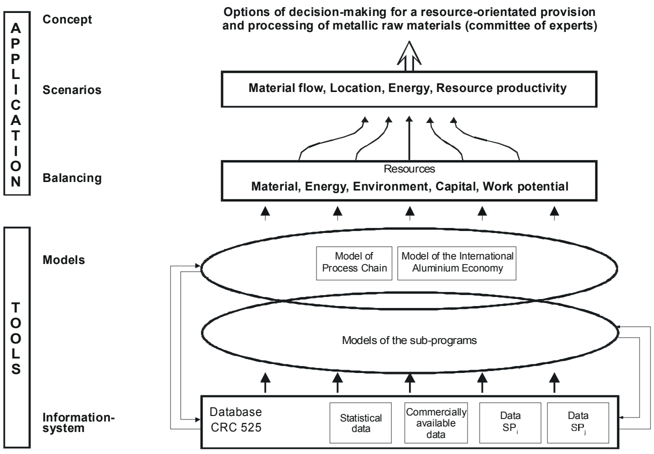

Figure 4: Design and application of the tool kit

Taking the balancing of resources as a basis, these instruments can be used to depict various scenarios. The aim of the Collaborative Research Center is to point out options for preparing and processing metallic raw materials while saving resources. A discussion with experts is essential and must form a part of both the development of scenarios and the evaluation of results.

The results obtained and the options for action which can be deduced from them can serve interested parties from many fields in pointing out ways of arranging material flows as efficiently as possible while taking all resources into consideration.

Below, bauxite is used as an example to show how a quantitative analysis of material flows can be performed and which conclusions can be drawn from it.

4 BAUXITE

On the basis of a database created by the sub-programs “ore deposits“ and “extraction and disposal“, qualitative and quantitative statements can be made about the mass flow of the bauxite through to the first stage of utilization. This database contains information concerning a total of 165 bauxite deposits, with approx. 140 property fields each. In addition to deposit-related parameters, such as geology, mineralogy and geochemistry, mining information is also filed. Including the production stage with the attributes “in operation“, “feasibility study / exploration“ and “closed“, by means of which statements about past, present and future conditions can be made. The material flow of the bauxite is analyzed quantitatively on the basis of the data available.

In 1996 approx. 123 million t of bauxite was mined in 82 locations worldwide. The main producing countries are Australia (35.3%), Guinea (14.5%), Jamaica (9.7%) and Brazil (9%) (Figure 5) [3].

The bauxite is in part processed to alumina in alumina plants situated next to the mines, but in part also first transported to further afield locations and processed there[1][5]. On account of the geochemical composition of bauxite, approx. 70 million t of red mud are produced worldwide during the digestion process.

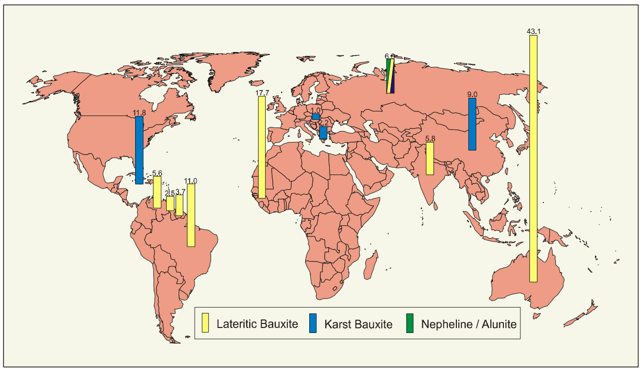

Figure 5: Bauxite extraction worldwide

In order to be able to make statements about future developments with regard to accruing global material flows, data from the database concerning the bauxite to alumina ratio and the red mud to alumina ratio of currently operating mines and with exploratory or feasibility status is used.

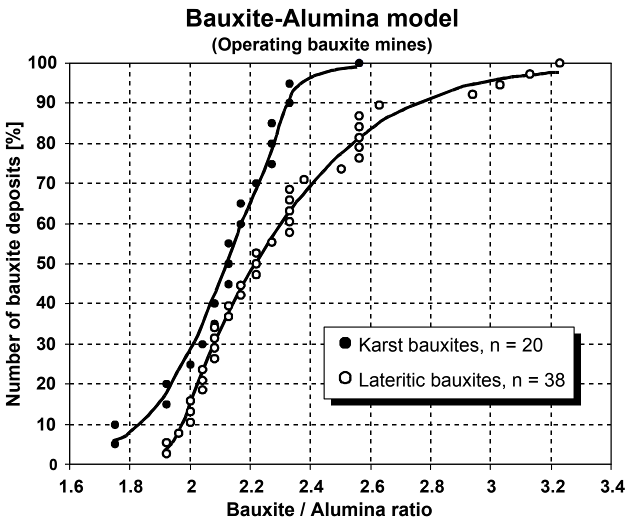

Figure 6: Bauxite-alumina model (operating bauxite mines) [2]

Figure 6 shows the bauxite to alumina ratio of 58 currently operating bauxite mines. The deposits are classified as karst and lateritic bauxite. It is shown here that the bauxite to alumina ratio of lateritic mines is on average higher than for karst bauxite. Furthermore, in the case of lateritic mines, the interval between the values (from 1.9 to 3.2 t bauxite/ t Al_2O_3) is significantly greater. This trend can be explained by the small alumina content available.

Analogous to the previous graph, Figure 7 shows the red mud to alumina ratio of currently producing ore mines.

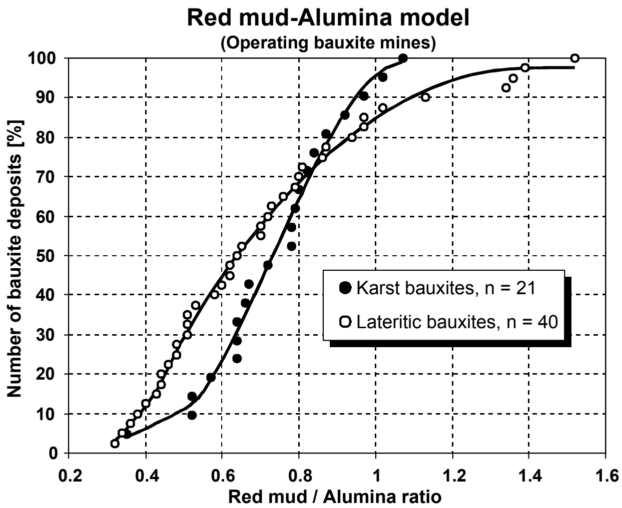

Figure 7: Red mud-alumina model (operating bauxite mines) [2]

Here it is shown that the red mud to alumina ratio of lateritic bauxite is smaller for approx. 70% of the ore mines, but then intersects the curve of karst bauxite and can increase very sharply for the remaining 30%. The reason for this sharp increase is the fact that in some districts lateritic bauxite with a very low aluminum content is mined and this distorts the statistics.
In order to make statements about possible changes in material flows and ore qualities in the future, the two production stages (in operation and feasibility study or exploration) of mines must be compared with each other.
This comparison can be carried out most transparently again using the indicators bauxite to alumina, red mud to alumina and overburden to bauxite.
In the following diagram, the bauxite to alumina ratio for mines in operation and at the exploratory stage or with feasibility status are compared (Figure 8).

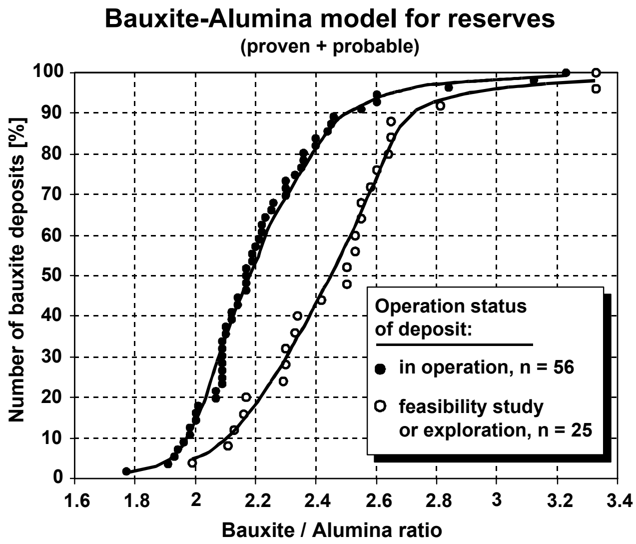

Figure 8: Bauxite-alumina model (proven and probable reserves) [2]

Here it is shown that the bauxite to alumina ratio of mines at the exploratory stage or with feasibility status is significantly higher than that of currently operating mines. This will result in significantly increased mine production even in order to be able to meet a stationary demand for aluminum.

The red mud to alumina ratio demonstrates a similar trend to the previous graph (Figure 9).

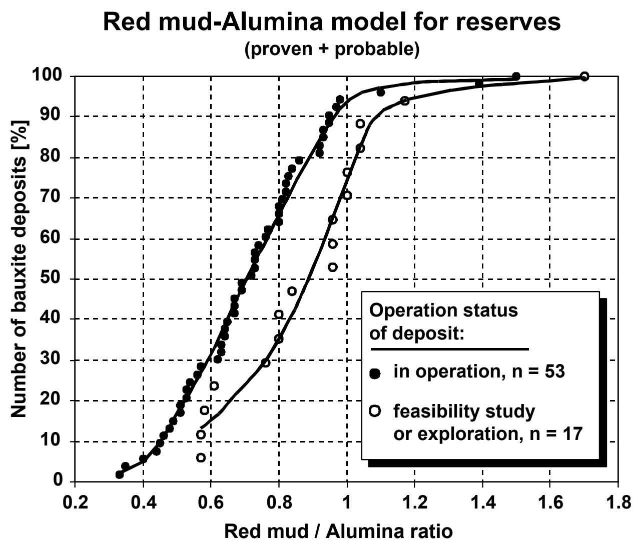

Figure 9: Red mud-alumina model (proven and probable reserves) [2]

The consequence of this global trend is that in the future, ore qualities can be expected to decline and as a result, an increase in the amount of red mud and energy expended can be expected. However, the statistical trend shown in figures 8 and 9 also suggests that an optimization potential exists for future material flows if a careful selection of future mine sites is conducted. Thus bauxite qualities might be kept constant or even increase. The global trends in bauxite quality presented in this paper are obviously not the only criteria that have to be taken into consideration for a complete assessment of a deposits feasibility [2].

In the following graph, in addition to the previous considerations, the overburden to bauxite ratio of the open-pit mines in operation to those at the exploratory stage or with feasibility status is shown (Figure 10).

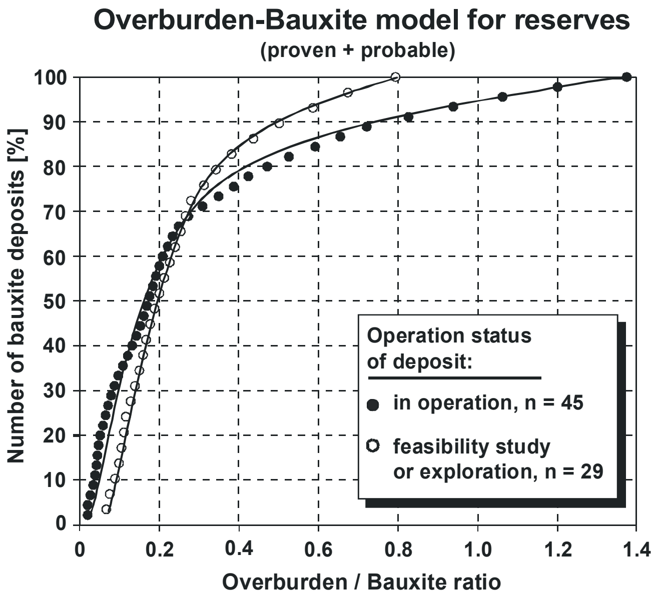

Figure 10: Overburden-Bauxite model (proven and probable reserves)

This shows that the overburden to bauxite ratio in the mines currently in operation is higher than that of those at the exploratory stage or with feasibility status. As a result, a slight trend towards less overburden removal is revealed.

To sum up, it can be ascertained that the material flows released by bauxite will tend to grow even while primary aluminum production in a first step is assumend to remain constant. While there is a slight decline in the amount of overburden to be removed during

extraction, the material flows triggered as a result of falling alumina contents and increasing specific quantities of red mud will grow. If consideration is now given to the worldwide trend towards increased specific use of aluminum, which cannot be completely covered by recycling, a superproportional increase in the material flows released by bauxite can be predicted.
These purely quantitative considerations of material flows formed the basis of other qualitative considerations. These were carried out by other subprograms within the Collaborative Research Center. Initial results are expected at the end of this year and will then be published.

5 SUMMARY

Material flows brought about by man, have acquired a dimension with regard to volume and their quality which influences the global balance of resources as a whole. Previous approaches, which have only analyzed material flows from a technical and economic view point, are no longer adequate for making comprehensive statements about the consequences of the production of metallic raw materials. What is really needed are additional considerations and analyses of their ecological and social consequences. The entire life cycle of a commodity is full of a multitude of positive but also negative economic, ecological and social interactions requiring evaluation. A group of scientists of different background jointly work in a Collaborative Research Center supported by the Deutsche Forschungsgemeinschaft has set itself this task. On the basis of analysis of various metals, a tool kit is being developed and validated which makes it possible to point to options for action in the conflict area of economy, ecology and society. The results may serve interested parties from many fields in finding ways to organize material flows in the most efficient manner while taking all resources into consideration.

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BETRACHTUNG DER BAUXITGEWINNUNG IM TAGEBAU WEIPA, AUSTRALIEN, UNTER BESONDERER BERÜCKSICHTIGUNG DER REKULTIVIERUNG*

(EXAMINATION OF THE OPEN PIT BAUXITE MINING IN WEIPA, AUSTRALIA, UNDER SPECIAL CONSIDERATION OF RECULTIVATION)

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ABSTRACT

The Institute of Mining Engineering I and the Department of Geography, Physical Geography and Geoecology, of the University of Technology Aachen are jointly engaged in a special field of research for the purpose of studying and analyzing ecological aspects, inter alia in connection with the mining of bauxite.

In this research work interest is focused above all on investigations related to pedology and plant ecology, from which findings can be obtained as to what material losses occur in the course of bauxite opencast mining and as to the manner in which these losses can be compensated by rehabilitation and recultivation measures.

In the course of a three months' stay the research team studied the Weipa bauxite mine in North Queensland to determine whether there was a relationship between soil replacement techniques and pedological parameters. Investigations in this connection were confined to the content of organic matter in the soil, one of the key factors for the creation of an efficient ecosystem and for the nitrogen content of the soil, as a standard for the possible mineralization of forms of nitrogen available to plants.

The investigations clearly showed that the applied soil replacement technique has a considerable influence on the quality of the indicators that were examined. Of the four processes that were examined, the biggest success was achieved with the so-called Double Pass method, in which the soil, separated exactly according to A and B horizon, is stripped and then respread. Furthermore, seasonal factors that are interrelated can also be ascertained.

Despite considerable efforts on the part of the mining company as regards regeneration of the ecosystem, it is evident that its complete restoration cannot be achieved in the near future. The reason for this lies in the fact that the original ecosystem is closely and reciprocally interrelated with the lateritic red earths that are removed during mining.

KEYWORDS

Bauxite mining, Weipa, recultivation, soil replacement technique, nitrogen content, organic carbon content, double-pass method

* Source: Braunkohle – Surface Mining 2/99, pp 257-264

1. EINLEITUNG

Metallische Rohstoffe stellen neben den energetischen eine wesentliche Entwicklungsgrundlage heutiger und kommender Generationen dar. Sie haben einen erheblichen Anteil an der Gesamtheit anthropogener Stoffströme, welche stetig wachsen und die Umwelt in vielfältiger Weise beeinflussen. Aus diesem Sachverhalt erwächst die Forderung nach einer dauerhaften und nachhaltigen Entwicklung. Diese beinhaltet Strategien und Maßnahmen für eine ganzheitliche, lebenszyklusweite Betrachtung von Stoffströmen. Dabei steht die Betrachtung metallischer Rohstoffströme, für die noch keine vollständige Betrachtungs- und Bewertungsmethodik existiert, im Mittelpunkt der Untersuchungen des Sonderforschungsbereiches 525.

Zur Erarbeitung von Lösungen zur Frage, wie Stoffströme metallischer Rohstoffe nachhaltiger gestaltet werden können als bisher, kooperieren neun Teilprojekte der Rheinisch-Westfälischen Technischen Hochschule Aachen (RWTH) und des Forschungszentrums Jülich im Sonderforschungsbereich 525 ”Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe”, der seit dem 1. Januar 1997 von der Deutschen Forschungsgemeinschaft (DFG) gefördert wird (Bild 1). Dabei sollen in einer ersten Phase Stoffströme, die mit der Erzeugung von Aluminium im Zusammenhang stehen, untersucht werden.

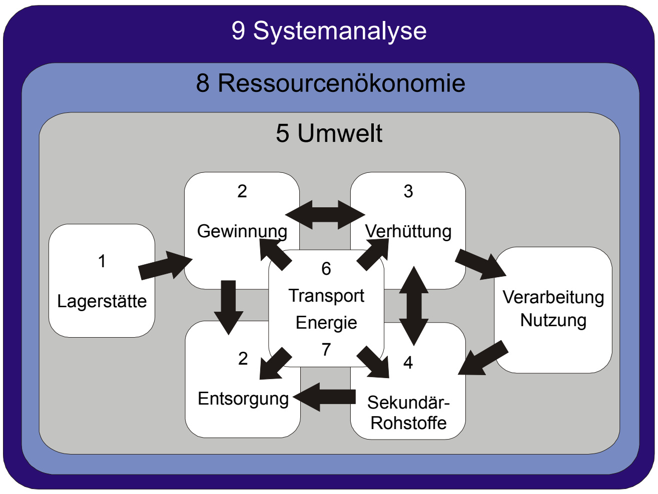


Bild 1: Verknüpfung der Teilprojekte (TP)

Gegenstand der Untersuchung sind zum einen der primäre Bereitstellungsprozeß metallischer Rohstoffe, der von der Genese über die Gewinnung und Aufbereitung bis zur Verhüttung einschließlich der ersten Verarbeitungsstufe reicht und der nachfolgenden zweiten Verarbei-

tungsstufe Metall zur Verfügung stellt. Zum anderen werden die Prozesse der sekundären Bereitstellung, also des Recyclings und der Entsorgung untersucht. Die dazwischen liegende Phase der Nutzung wird in Teilbereichen ebenfalls betrachtet.
Das Institut für Bergbaukunde I (TP 2) und das Geographische Institut, Physische Geographie, insbesondere Geoökologie (TP5) arbeiten in diesem Zusammenhang zusammen, um ökologische Belange u.a. bei der Gewinnung von Bauxit zu betrachten und zu analysieren.
Im folgenden sollen die Ergebnisse eines Aufenthalts auf dem Bergwerk Weipa dargestellt werden. Im Mittelpunkt stehen die von Mitarbeitern des Geographischen Instituts der RWTH Aachen durchgeführten Untersuchungen im Bereich der Rekultivierung.

2. Allgemeines und Geographische Lage

Der Tagebau Weipa der Comalco Pty. Ltd. befindet sich an der Westküste der Cape York Halbinsel im nördlichen Queensland, Australien. Die gleichnamige Stadt Weipa mit ca. 2400 Einwohnern verdankt ihre heutige Existenz ausschließlich dem Bauxitbergbau. Neben einer Vielzahl von Freizeiteinrichtungen verfügt der Ort über alle wesentlichen infrastrukturellen Einrichtungen einer Kleinstadt wie z.B. Krankenhaus, Bücherei, Sportvereine, Lichtspielhaus etc. In unmittelbarer Nachbarschaft befindet sich die Aboriginal Gemeinde Napranum, die Heimat von ca. 750 Ureinwohnern ist. Es existiert keine Bahnverbindung, und eine nur in der Trockenzeit befahrbare Schotterpiste verbindet Weipa mit Cairns (850 km). Sowohl der Tagebau als auch die Ortschaft werden fast ausschließlich über den Seeweg bzw. mit dem Flugzeug versorgt.

Es herrscht ein sommerfeucht-tropisches Klima mit monsunalen Einflüssen. Die jährliche Niederschlagsmenge beträgt durchschnittlich 1890 mm, wovon ca. 96% in den Sommermonaten zwischen November und April fallen. Der relativ ausgeglichene jährliche Temperaturgang weist Maxima von 30°C im Juli und 35°C im November auf. Die niedrigsten Monatsmittel liegen bei 19°C im Winter und bei 24°C in den Sommermonaten. [2]

Nach dem Bodenklassifikationssystem der FAO-UNESCO dominieren in der Umgebung von Weipa Acrisole, die auch als ”bauxitic/lateritic red earths” bezeichnet werden [4]. Das typische Profil dieser Böden besteht aus einem ca. 10 cm mächtigen, durch organische Substanzen dunkel gefärbten A-Horizont und aus einem durchschnittlich 50 cm mächtigen B-Horizont. Im Gegensatz zum lehmigen A-Horizont ist der B-Horizont kiesiger und enthält mit zunehmender Tiefe einen ansteigenden Anteil an Bauxit-Pisolithen. Die durch intensive chemische Verwitterung gekennzeichneten Böden sind an austauschbaren Nährionen verarmt. Verschlechtert wird die natürliche Bodenfruchtbarkeit zudem durch die hohen Anteile an sorptionsschwachen Zweischicht (1:1-)Tonmineralen und Sesquioxiden[1]. Besonders hervorzuheben ist das Problem der Phosphatfixierung infolge des sesquioxidreichen und sauren Bodens. Bei pH-Werten zwischen 5,2 und 6,2 ist die Gefahr der Aluminiumtoxizität für Pflanzen allerdings nicht gegeben.

Wie der größte Teil der westlichen Cape York Halbinsel ist auch die Vegetation in der Umgebung von Weipa durch relativ einförmige, halboffene und etwa 25 - 30 m hohe Eukalyptuswälder gekennzeichnet. Neben den vorherrschenden Baumarten *Eukalyptus tetrodonta* (Darwin stringy bark) und *E. polycarpa* (long-fruited bloodwood) finden sich noch Arten wie *E. nesophila* (Melville Island bloodwood), *E. dichromophloia* (gum-topped bloodwood) und *Erythrophloem chlorostachys* (Cooktown Ironwood). Weitere wichtige Gehölze sind *Acacia rothii*, *Grevillea parallela*, *Parinari nonda* und *Planchonia careya*. Im Unterwuchs dominieren die beiden tropischen Gräser *Sorghum pulmosum* (native sorghum) und *Heteropogon triticeus* (giant spear grass).

3. Die Lagerstätte

Obwohl ein vom Staat Queensland angestellter Geologe bereits 1888 das Vorhandensein von Massen an "brown pisolitic ironstone" bemerkte, dauerte es bis zum Jahre 1955, ehe man auf der Suche nach Öllagerstätten den Wert des anstehenden Erzes erkannte. Nach weiteren Explorations- und ersten Aufschlußarbeiten wurden die ersten Tonnen Bauxit im Jahre 1961 nach Japan verschifft.

Die ursprünglich zugesprochene Berechtsame umfaßte eine Fläche von 6162 km² und wurde laut vertraglicher Vereinbarung im Jahre 1977 auf 2590 km² reduziert. Im Jahre 1993 betrugen die sicheren Reserven 210 Mt. Hinzu kommen wahrscheinliche Reserven in Höhe von

[1] Vor allem bei den Sauerstoffverbindungen der Alkali- und Erdalkalimetalle gibt es zusätzlich zu den Oxiden mit isolierten O_2^--Anionen auch Oxide mit komplexen Anionen. Hierzu zählen die Sesquioxide, mit O_2^{2-}- neben O_2^--Ionen

500 Mt sowie mögliche Reserven von 3.600 Mt. In der 10 - 25 m über dem Meeresspiegel gelegenen Plateau-Lagerstätte steht der Bauxit als flach gelagerte bis leicht einfallende 1-10 m mächtige Schicht an (Bild 2) und weist eine durchschnittliche Zusammensetzung von 54 - 57 % Al_2O_3, 4 - 7 % SiO_2, 5 - 6 % Fe_2O_3 und
2 - 3 % TiO_2 auf.

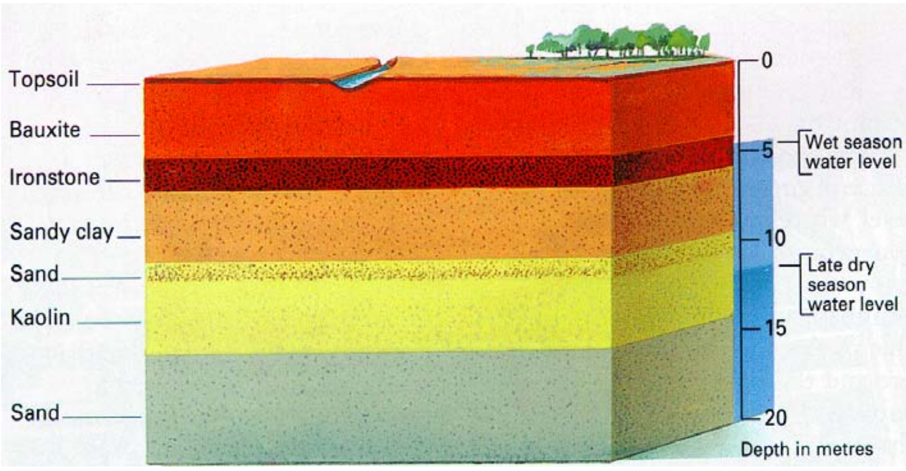


Bild 2: Schnitt durch die Lagerstätte

Das im Durchschnitt 3,5 m mächtige Erz steht zu 80 % in pisolithischer Form mit einem Korndurchmesser von 1 - 16 mm an. Andoom und der ebenfalls schon verritzte Lagerstättenteil Weipa, nach dem der gesamte Bergwerksbetrieb benannt ist, sind zwei von insgesamt acht Lagerstättenteilen, die innerhalb der Berechtsame unterschieden werden. Unterlagert wird das Wertmineral von Schichten aus Laterit (ironstone), Ton, Sand und Kaolin (Bild 2). Der anstehende Kaolin wurde bis 1996 ebenfalls bergmännisch hereingewonnen, dann wurde die Gewinnung jedoch aus wirtschaftlichen Gründen aufgegeben. Jährlich werden etwa 14,5 Mt Rohbauxit abgebaut.

4. Der Abbau

Zum Zeitpunkt der Datenerhebung ging der Bergbau auf Bauxit auf dem Erzkörper Andoom um. Der Bergbauprozeß stellt sich folgendermaßen dar:
Zunächst werden etwa 300 ha/a der Oberfläche vorbereitet, indem der vorhandene Bewuchs mittels Bulldozern abgeschoben wird. Daran anschließend wird der anstehende Oberboden (0,5 - 0,6 m) mit Hilfe von Scrapern (Erdhobeln) gelöst, geladen, transportiert und soweit

vorhanden auf bereits abgebaute Lagerstättenteile aufgetragen oder vorübergehend aufgehaldet (s. Kap. Rekultivierung/Renaturierung).

Etwa 60 % des so freigelegten Wertminerals werden mittels Reißhaken mit einer Eindringtiefe von 1 m aus dem Gebirgsverband gelöst, bevor es mit Hilfe von Radladern auf 150 t SLKW geladen wird (Bilder 3 und 4).

Bild 3: Laden des Wertminerals mittels Radlader auf 150 t SLKW [5]

Während der Gewinnung sind stets drei Radlader und zehn SLKW (Bodenentleerer) an bis zu drei Abbaufronten im Einsatz. Das geladene Wertmineral wird durchschnittlich fünf Kilometer weit zur zentralen Kippstation gefördert, dort abgekippt und anschließend einer ersten Grobklassierung und einem Vorbrecher zugeführt. Der Trennschnitt des eingesetzten Schüttelrosts liegt bei 150 mm. Während die -150 mm Fraktion direkt dem Vorratsbunker der Bahnverladung in Andoom zugeführt wird, wird die +150 mm Fraktion in einer Hammermühle vorzerkleinert, um anschließend ebenfalls der Bahnverladung zugeführt zu werden.

Der Bauxit wird in Andoom auf Züge verladen, die aus je 33 Waggons à 100 t Zuladung bestehen und von einer diesel-elektrischen Lok gezogen werden. Der Bahntransport von Andoom zur 19 km entfernten Aufbereitung in Lorim Point dauert ca. 30 min. Im Gewinnungsbetrieb wird 365 Tage im Jahr rund um die Uhr zweischichtig gearbeitet.

Bild 4: Tagebau nach Durchgang des Abbaus [5]

5. Die Aufbereitung

Bei der Aufbereitung des Bauxits handelt es sich um eine einfache Naßklassierung, die in Lorim Point stattfindet. Hier befindet sich auch die Verladeanlage. Von dort aus wird das Produkt verschifft.

Der aus Andoom geförderte Bauxit wird aus den Waggons abgezogen und entweder mittels Gurtbandförderer und Absetzer einer Halde (40.000 t) oder direkt einem, der Klassierung vorgeschalteten, 5.000 t fassenden Bunker zugeführt. Von dort wird der Bauxit abgezogen und vier identischen, parallel angeordneten 3-Deck-Naßklassieren mit einer Gesamtkapazität von 2.000 t/h aufgegeben. Die erste Trennung erfolgt bei 1,7 mm. Das Überkorn wird nachgebrochen und erneut der Klassierung zugeführt. Das Unterkorn (-1,7 mm) wird auf dem zweiten Deck bei 1,25 mm getrennt. Das Überkorn wird auf die Produktenhalde gefördert, während das Unterkorn nochmals bei 0,3 mm getrennt wird. Die 0,3 - 1,25 mm Fraktion wird der Feinkornaufbereitung (Hydrozyklone) zugeführt und das Unterkorn in Absetzbecken (East Weipa Dam) gepumpt, da es zu hohe Siliziumgehalte aufweist.

Der so aufbereitete Bauxit wird mittels Gurtbandförderer und Absetzer auf zwei Produktenhalden á 400.000 t aufgegeben. Allein durch die Schwerkraft wird der Bauxit entwässert und erlangt so einen Feuchtigkeitsgehalt von 12 %. Der Abzug des Bauxits erfolgt über unterirdische Gurtbandförderer, auf die der Bauxit von den überlagernden Halden über Rollöcher aufgegeben wird. Die geforderte Produktqualität wird zum einen durch kontrollierten Aufbau der Produktenhalde, zum anderen durch gezieltes Ansteuern bzw. Öffnen der Abzüge gewährleistet.

Neben der Produktion von ca. 10 Mdmt[2] metallurgischen Bauxits besteht die Möglichkeit (nur aus Weipa Bauxit), kalzinierten Bauxit zur Schleifmittelherstellung zu produzieren. Die Produktion beträgt maximal 150.000 dmt/a.

85 % des metallurgischen Bauxits werden mittels vier firmeneigener Frachter (70.000 t) zur 2.000 km entfernten Tonerdefabrik der Queensland Alumina Ltd. in Gladstone transportiert; der Rest der Produktion wird an die Euraluminia in Sardinien und weitere Abnehmer verkauft.

6. Die Rekultivierung/Renaturierung

Bereits 1966 begannen die ersten Rekultivierungsarbeiten mit dem erklärten Ziel, eine lebensfähige wirtschaftliche Basis für die Grundversorgung der dort ansässigen Bevölkerung nach Beendigung des Bergbaus zu schaffen. Anfängliche Versuche, Weideflächen zur Rindfleischproduktion einzurichten, wurden wegen mangelndem Lebendgewichtszuwachs schnell wieder aufgegeben. Ebenso wurden schon 1976 Aufforstungen mit Nutzholzarten wie *Khaya senegalensis* (African mahogany), *Tectonia grandis* (teak), *Pinus caribbea* (Caribbean pine), *Swietenia macrophylla* (Honduras mahogany) und *Araucaria cunninghamii* (hoop pine) wegen der zu stark schwankenden Holzerträge und der sehr großen Marktferne aufgegeben. Verschiedene Marktfrüchte (cash crops) wie Mangos, Limonen, Kokosnüsse und andere Früchte wurden im Laufe der Zeit getestet, wobei nur die beiden Baumfrüchte *Anarcardium occidentale* (cashew) und *Azadirachta indica* (neem) erfolgversprechende Ergebnisse lieferten. Die genannten und wenig profitablen Folgenutzungen führten dazu, daß man schon früh eine Renaturierung, das heißt die Rückführung in einen naturnahen Zustand, auf den abgebauten Flächen anstrebte. Bis 1996 wurden 6290 ha (ca. 80%) der gesamten Tagebaufläche rekultiviert bzw. renaturiert, wovon 75 % der Fläche mit einheimischen Gehölzen bepflanzt wurden. Auf die restliche Fläche entfallen 14,5 % Weideland, 5,9 % Aufforstungen und 4,6 % sonstige Flächen [1].

[2] Dry metric tons

Die gesetzliche Grundlage für die Rekultivierungsaktivitäten bildet der „Commonwealth Aluminium Corporation Agreement Act“ von 1957, welcher im wesentlichen fordert, daß die rekultivierten Flächen keine unnatürlichen Hangneigungen aufweisen dürfen und daß der Eingriff in das natürliche Entwässerungsnetz zu minimieren ist.
Comalco betrachtet die Renaturierung ausdrücklich als integralen Bestandteil des Bergbaus und nicht als eine nachgeordnete Notwendigkeit. Schon beim Abtrag des Bodens müssen wesentliche Aspekte der Renaturierung beachtet werden. Wie später anhand eigener Erhebungen kurz dargelegt wird, spielt die angewandte Technik der Bodenumbettung eine entscheidende Rolle für den Renaturierungserfolg.
Nach Festlegung der Abbauflächen muß zuerst der natürliche *Eukalyptus tetrodonta*-Wald entfernt werden. Diese Arbeiten finden hauptsächlich während der Regenzeit statt, da der Boden zu dieser Zeit weich genug ist, um die Baumstümpfe und Wurzeln mit Bulldozern herauszureißen (stripping). Aufgrund des hohen Termitenbefalls sind die Bäume von sehr geringem kommerziellen Wert und werden daher verbrannt.

Bild 5: Für den Abbau vorbereitete Fläche (Boden links bereits abgetragen) [5]

Zwischen April und Dezember während der Trockenzeit wird die kulturfähige Schicht mit zwei „open-bowl scrapers” (Caterpillar 657) im „push-and-pull“ Betrieb gelöst und zumeist auf angrenzenden, abgebauten Flächen wieder aufgetragen (Bild 5). Durch dieses besondere Verfahren kann der durchschnittlich 60 cm mächtige Mutterboden in zwei gleichmächtigen Schichten abgetragen und in der gleichen Abfolge wieder aufgebracht werden. Diese auch als

„Dual Strip" (siehe Kap. Geländeuntersuchungen) bezeichnete Technik erlaubt es, die obere Bodenschicht, die eine wesentlich höhere mikrobielle Aktivität aufweist und reicher an Nährelementen sowie organischer Substanz ist, wieder oberflächlich aufzubringen. Berücksichtigt man allerdings die natürliche Horizontmächtigkeit (im Mittel 10 cm A-Horizont und 50 cm B-Horizont), so wird deutlich, daß bei dieser Technik der A-Horizont mit ca. 20 cm B-Horizont „verdünnt" wird. Das nahezu streng horizontbezogene Bodenumbettungsverfahren „Double Pass" (siehe Kap. Geländeuntersuchungen) hat sich als zu zeit- und kostenintensiv erwiesen.

Nicht immer kann der abgetragene Boden sofort wieder auf bereits abgebaute Flächen aufgetragen werden. In diesem Fall muß der Boden auf Halde gelegt werden und kann erst zu einem späteren Zeitpunkt wieder aufgebracht werden (Bild 6). Da durch die Abbauaktivitäten die freigelegte Oberfläche zum Teil sehr verfestigt ist, wird unmittelbar vor dem Aufbringen des Bodens mit einem Caterpillar(D9)-Bulldozer der Untergrund in 3 m Abständen aufgebrochen (ripping), um eine bessere Durchwurzelbarkeit zu ermöglichen.

Bild 6: Aufgehaldeter Boden [5]

6.1 An-/Bepflanzen

In den letzten Jahrzehnten ist es durch Forschung und ständige Erfolgskontrolle gelungen, geeignete Saatmischungen zusammenzustellen, die trotz der extremen Umweltbedingungen wie Wechsel von Trockenheit und Überflutung, unfruchtbare Böden, Feuer und Termiten zumeist das gewünschte Ergebnis, nämlich die bestmögliche Wiederherstellung der ursprünglichen Vegetation, erzielen. In der Regel verwendet man eine bewährte Standardsaatmischung mit den vorherrschenden Gattungen *Acacia*, *Eukalyptus*, *Dodonea*, *Grevillea* und *Melaleuca* für die meisten Flächen; allerdings wird topographischen Besonderheiten insofern Rechnung getragen, daß z.B. in Landsenken überwiegend überflutungstolerante Arten wie beispielsweise Melaleucaarten ausgesät werden. Trotz der manchmal bis zu 40 in der Standardsaatmischung enthaltenen Arten, wird die Zusammenstellung der Mischung ständig neu überdacht, da sich häufig erst nach längerer Zeit herausstellt, welche Arten sich durchsetzen. Nicht zuletzt hängt die Auswahl der Arten auch davon ab, wie leicht bzw. schwierig das Saatgut zu erhalten ist.

Seit 1982 wird der größte Teil des Saatgutes von Einheimischen aus den nahegelegenen Aboriginal Communities Napranum und Mapoon hauptsächlich zwischen Mai und November gesammelt und anschließend nach Gewicht an Comalco verkauft. Im Jahre 1996 wurden 1056 kg Samen verwendet, wovon der weitaus größte Teil von Aboriginals gesammelt wurde. Allein die Kosten für das sehr zeitaufwendige Sammeln der Samen können bis zu 15% der gesamten Renaturierungskosten betragen [1].

Bevor man mit der Aussaat beginnt, muß der Samen in vitro auf seine Keimungsfähigkeit hin geprüft werden, wobei von jeder Art unter genau festgesetzten Bedingungen im Gewächshaus die Keimungsrate bestimmt wird. Die Resultate dieser zum Teil recht aufwendigen Tests bestimmen, wieviel an Samen von jeder Art in die Saatmischung kommen. Es wird eine Bestandesdichte von 1500 Stämmen pro Hektar, wie sie auch im Durchschnitt im natürlichen Eukalyptuswald besteht, angestrebt. Um die unvermeidlich auftretenden Verluste im Gelände zu kompensieren, wird so viel ausgesät, daß eine theoretische Bestandesdichte von 2500 Stämmen pro Hektar erreicht werden könnte.

6.2 Pflügen und Aussaat

Nach Einsetzen der ersten heftigen Regenfälle beginnt die Saat- und Pflügesaison. Das Pflügen verringert die Konkurrenz der durch den Regen in den Boden gebrachten Grassamen und verbessert gleichzeitig die physikalischen Eigenschaften des Keimungssubstrates. Ein „grizzly disc plough” arbeitet 24 Stunden am Tag bis die komplette „gerippte“ Fläche gepflügt ist. Direkt im Anschluß wird mit Hilfe eines sogenannten „Marshall spreaders” ausgesät. Der Saatmischung sind in der Regel 100 kg Superphosphat pro Hektar beigemengt. Im Januar werden die bepflanzten Flächen noch einmal mit ca. 250 kg/ha Superphosphat oder CK5 aus der Luft gedüngt.

Um eine geschlossene Vegetationsdecke auf den renaturierten Flächen sicherzustellen, werden im Februar Setzlinge mit der Hand ausgepflanzt. Im Jahre 1995 wurden 29648 Setzlinge ausgepflanzt, wovon 93 % Eukalyptussetzlinge waren [1]. Dieser hohe Anteil resultiert aus der im Vergleich zu anderen Arten schlechten Keimfähigkeit der Eukalyptusarten im Gelände. Die Gründe hierfür sind noch nicht eindeutig geklärt.
Seit 1997 ist man dazu übergegangen, einen „one row seeder" für die zusätzliche Aussaat zu verwenden, da sich das Auspflanzen per Hand als zu kosten- und zeitintensiv erwiesen hat.

7. GEOÖKOLOGISCHE UNTERSUCHUNGEN

Sehr große Bedeutung wird von Comalco der Forschung, insbesondere auf dem Gebiet der Renaturierung, beigemessen. In Zusammenarbeit mit Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) werden eine Reihe von vegetationskundlichen, bodenkundlichen und tierökologischen Untersuchungen durchgeführt. Gegenwärtig besteht eines der Hauptziele dieser Arbeiten darin, geeignete ökologische Parameter zu finden und wenn möglich zu quantifizieren, die als Indikatoren für eine erfolgreiche Renaturierung benutzt werden können.
Besonders der Gehalt an organischer Substanz im Boden (ausgedrückt in % organischer Kohlenstoff) ist einer der Schlüsselfaktoren für die Schaffung eines funktionierenden Ökosystems, denn er beeinflußt nicht nur bodenphysikalische und bodenchemische Prozesse, sondern ist auch für die mikrobielle Aktivität im Boden und den Versorgungszustand mit Nährelementen von entscheidender Bedeutung. Der prozentuale Anteil von Gesamt-Stickstoff im Boden ist ein Maß dafür, wieviel Sticktsoff unter bestimmten Bedingungen zu pflanzenverfügbaren Stickstofformen (Nitrat, Ammonium) mineralisiert werden kann.
Die Geländearbeiten in Weipa fanden von Oktober 1997 bis Januar 1998 statt. Unterstützt wurden die Arbeiten vom Superintendent des Comalco Regeneration Centres, Neile Dahl. Es wurden Bodenproben gesammelt, die im bodenchemischen Labor der University of Queensland vorrangig auf ihren Kohlenstoff- und Stickstoffgehalt hin untersucht wurden.
Um den Einfluß der verschiedenen Bodenumbettungsverfahren zu untersuchen, wurde ein Teil der Proben auf einer Versuchsfläche (Soil Replacement Trial) der University of Queensland genommen. Diese etwa 6,4 ha große Fläche wurde 1990 angelegt (stripping, replace-

ment, ripping), 1991 bepflanzt und teilweise gepflügt. Auf der Versuchsfläche wurden verschiedene Renaturierungstechniken getestet.

Bei den im folgenden verwandten Abkürzungen handelt es sich um feststehende Begriffe, die nicht ohne weiteres ins Deutsche übersetzt werden können.

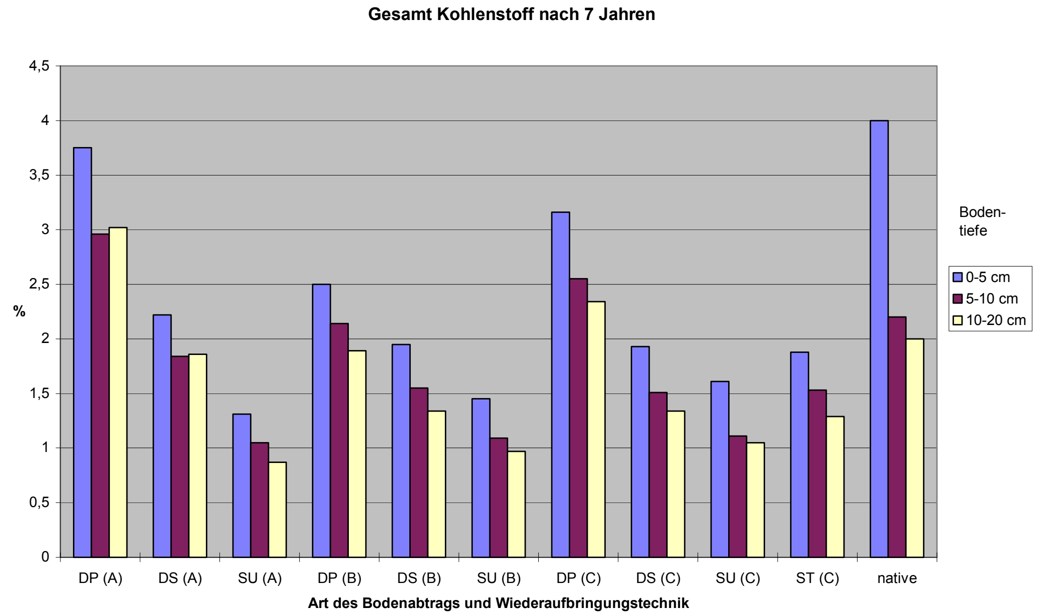
- Mit stripping time (A, B, C) ist der Zeitpunkt der Bodenumbettung gemeint: A = May stripped, B = September stripped, C = December stripped
- Double Pass (DP) bedeutet, daß der Boden exakt getrennt nach A- und B-Horizont ab- und wieder aufgetragen wird.
- Bei der Dual strip Technik (DS) wird der Boden in zwei gleichmächtigen Schichten von ca. 30 cm umgebettet.
- Subsoil only (SU) bedeutet, daß kein Oberboden aufgetragen wird.
- Mit stockpiled (ST) ist das Auftragen von zuvor auf Halde gelagertem Boden gemeint.

Die Bedeutung der unterschiedlichen Umbettungsverfahren für die Errichtung eines stabilen Ökosystems wird anhand der beiden bodenkundlichen Parameter (organischer Kohlenstoff und Gesamt-Stickstoff) dargestellt.

7.1 Ergebnisse

Der Gehalt an organischer Bodensubstanz und der Stickstoffgehalt in den drei angegebenen Bodentiefen stehen in enger Abhängigkeit zu den angewandten Bodenumbettungsverfahren. Die Bilder 7 und 8 zeigen die ausgewerteten Analyseergebnisse, die auf der Versuchsfläche und auf einer benachbarten natürlichen Waldfläche (native) ermittelt wurden. Bei einem Vergleich zwischen natürlicher Waldfläche und den renaturierten Flächen ergeben sich sowohl beim organischen Kohlenstoff als auch beim Gesamt-Stickstoff signifikante Unterschiede ($p<0{,}05$) zu den Umbettungsverfahren DS, SU und ST. Nur mit der „Double Pass“-Technik werden ähnliche Werte, wie sie im natürlichen Ökosystem auftreten, erreicht.

Ausgehend von einem an der University of Queensland empirisch gewonnenen Schwellenwert von mindestens 1,5% organischem Kohlenstoff in den obersten 0-5 cm Bodenschicht ist deutlich zu erkennen, daß mit der „Double Pass”-Technik zu allen Zeiten die für das Pflanzenwachstum günstigsten Gehalte an organischer Substanz erzielt werden. Auch beim Gesamtstickstoff sind die höchsten prozentualen Anteile bei der „Double Pass”-Technik zu beobachten. Auffällig sind die durchweg niedrigen Werte beim „Subsoil only“. Offensichtlich ist eine horizontbezogene Umbettung des Oberbodens eine grundlegende Voraussetzung für eine ausreichende Versorgung des Bodens mit organischer Substanz und mit Stickstoff. Ein Einfluß des Zeitpunktes des Bodenabtrags läßt sich aus den bisher gewonnenen Daten nicht



ohne weiteres ableiten, wenngleich erwähnt werden sollte, daß sich der Zeitpunkt der Bodenabtragung beispielsweise auf den Gehalt an unerwünschten Grassamen auswirkt [3].

Die relativ niedrigen Stickstoff-Werte im September sind dadurch zu erklären, daß in der Trockenzeit das Gefüge des umgelagerten Bodens stark gestört wird, so daß hier bei allen Techniken die ungünstigsten Werte für das Pflanzenwachstum auftreten.

Bild 7: Gehalt an organischem Kohlenstoff in Abhängigkeit von Bodentiefe und Rekultivierungstechnik

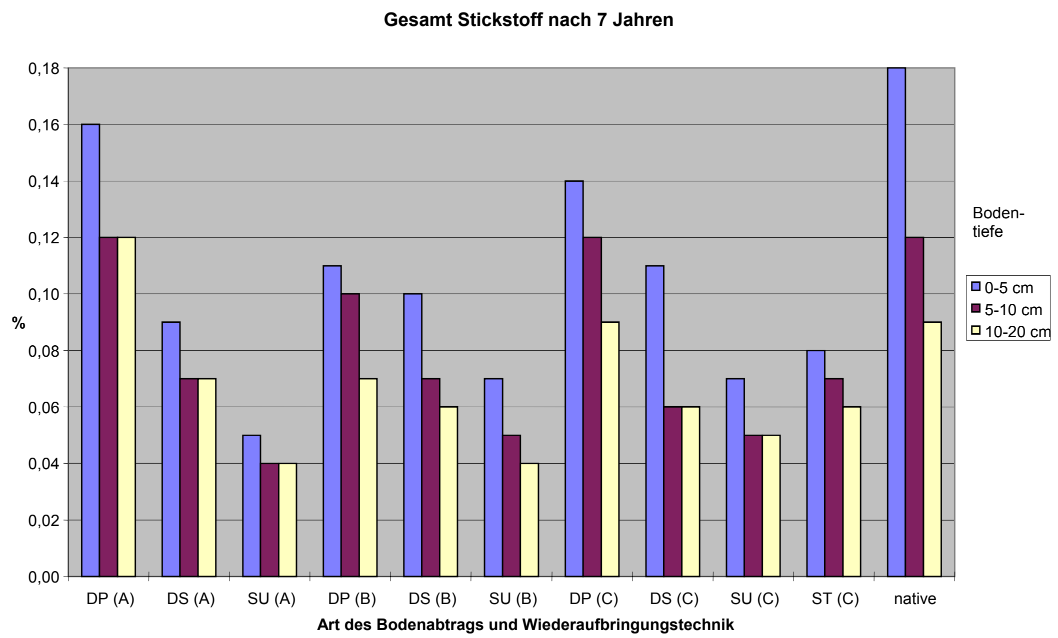


Bild 8: Gehalt an Gesamtstickstoff in Abhängigkeit von Bodentiefe und Rekultivierungstechnik

8. Fazit

Abschließend sollte betont werden, daß eine Regeneration, das heißt die vollständige Wiederherstellung des ursprünglichen Ökosystems, in absehbarer Zeit nicht erreichbar ist (Bilder 9 und 10). Die Gründe hierfür liegen darin, daß sich der Eukalyptus tetrodonta Urwald über einen sehr langen Zeitraum entwickelt hat und in enger Beziehung zu dem lateritischen Bauxitprofil steht. Durch die Entfernung der Bauxitschicht muß sich die neue Vegetation unmittelbar über der näher am Grundwasserspiegel gelegenen „ironstone“-Schicht entwickeln. Das derzeitige, erfolgversprechendste Renaturierungsziel besteht darin, ein sich selbsttragendes Ökosystem (self-sustainable and maintenance-free ecosystem) zu schaffen, dessen Struktur und Funktion nicht unbedingt mit der des ursprünglichen Waldes übereinstimmen muß.

Bild 9: 7 Jahre alte rekultivierte Fläche [5]

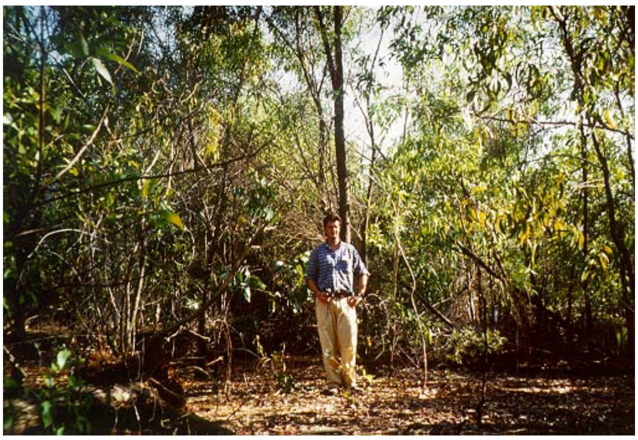


Bild 10: Naturnaher Standort [5]

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TRANSPORT AND PRODUCTION PLANNING IN THE LOS PIJIGUAOS BAUXITE DEPOSIT, VENEZUELA*

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ABSTRACT

The Los Pijiguaos bauxite deposit is dissected by deep erosion valleys resulting in a discontinuous bauxite blanket with the orebody being dismembered into nine isolated blocks. Production planning is further hampered by both vertical and lateral heterogeneity in ore-grade distribution. A computer-based evaluation of four different ore extraction and hauling models shows that inpit ore transportation by trucks is by far the most economic solution. Alternative models employing conveyor belts of various lengths and the installation of a second crusher result in lower operating and personnel costs but in much higher total costs. Comparison of environmental parameters such as atmospheric emissions from fuel combustion reveals that emissions are reduced by about 35 % when using the alternative transport models.

KEYWORDS

Bauxite, deposit, Los Pijiguaos, orebody, transport, production planning, emissions

* Source: Erzmetall 52 (1999), 2, S. 107-114

1. Introduction

In 1997 the German Research Foundation (DFG) has established at the University of Technology Aachen (RWTH) the Collaborative Research Center 525, entitled „Resource-Oriented Analysis of Metallic Raw Material Flows". Main objective of research is the development of recommendations for a resource-sensitive utilization of metallic raw materials within the framework of economic, environmental and social constraints.

In an initial phase, the program focuses on the analysis of material flow associated with bauxite and aluminium production. The evaluation of geologic characteristics of bauxite deposits and their effects on subsequent technical processes represents the first step in this analysis.

The present study is concerned with the investigation of the influence of geologic factors on long-term production planning of a lateritic bauxite deposit. The mine concerned is the Los Pijiguaos bauxite deposit in the Bolivar State of Venezuela, some 500 km south of Caracas and 520 km south west of Cuidad Guayana (Fig. 1). The deposit was discovered in 1976, a feasibility was conducted by Alusuisse in 1979, and mining commenced was in 1987. The mine is operated by the state owned C.V.G.-BAUXILUM-Operadore de Bauxita (Corporation Venezolana de Guayana).

Figure 1: *Location of the Los Pijiguaos bauxite mine.*

2. Regional setting

The Los Pijiguaos bauxite deposit is situated at the northwestern margin of the Proterozoic Guayana Shield. Geologically, the area is underlain mainly by the Parguaza Granite of the Suapure Group. The Rapativi-type granite also represents the parental rock to the „plateau-type" bauxite horizon that is developed on an erosional surface at an altitude between 600 and 700 m. At present, the planation surface is deeply dissected by fluvial erosion channels. A large proportion of the mine site is occupied by deep valleys resulting in a discontinuous bauxite blanket with the orebody being dismembered into nine isolated blocks [1].

3. Bauxite profile

At Los Pijiguaos, the economic bauxite horizon attains an average thickness of 7.6m. The soil cover is rather thin (<1 m) consisting mainly of vegetal matter. A complete gibbsitic bauxite profile typically exhibits an internal stratigraphy characterized by four distinct horizons that include from top to bottom: (a) a hard concretionary layer, (b) an earthy bauxite with partly loose pisolites, (c) a bauxite crust with pisolitic, partly porous to spongy textures, and (d) an earthy bauxite with loose pisolites and loose spongy to cellular concretions [2].

4. Grade Distribution

Grade distribution is rather heterogeneous and varies vertically and laterally within the deposit. To illustrate this fact, Al_2O_3 distributions in block 1 sector 3 and block 2 sector 7 are shown in Figures 2 and 3, respectively. In both figures, plane view representations reveal, for the uppermost portion of the bauxite profile, the distribution of Al_2O_3 contents averaged by the statistical „inverse power of distance" method for each single block volume of 12.5m x 12.5m x 1m and grouped into 6 classes. As can be seen from the maps, there is a marked grade variation within as well as between the two sectors. Corresponding vertical profiles also reveal, besides lateral grade variations, heterogeneous Al_2O_3 distributions with depth. The roughly convex geometry of the bauxite blanket and the corresponding spatial relationship of ore grade distributions suggest that the palaeotopography and thus the palaeodrainage system had an influence on bauxite formation. Proven minable reserves for the entire deposit are currently estimated at 168 million metric tons with an average Al_2O_3-content of 49% and a total SiO_2-content of 10.2%, respectively, and a mean wet density of 1.32 t/m^3 [3, 4].

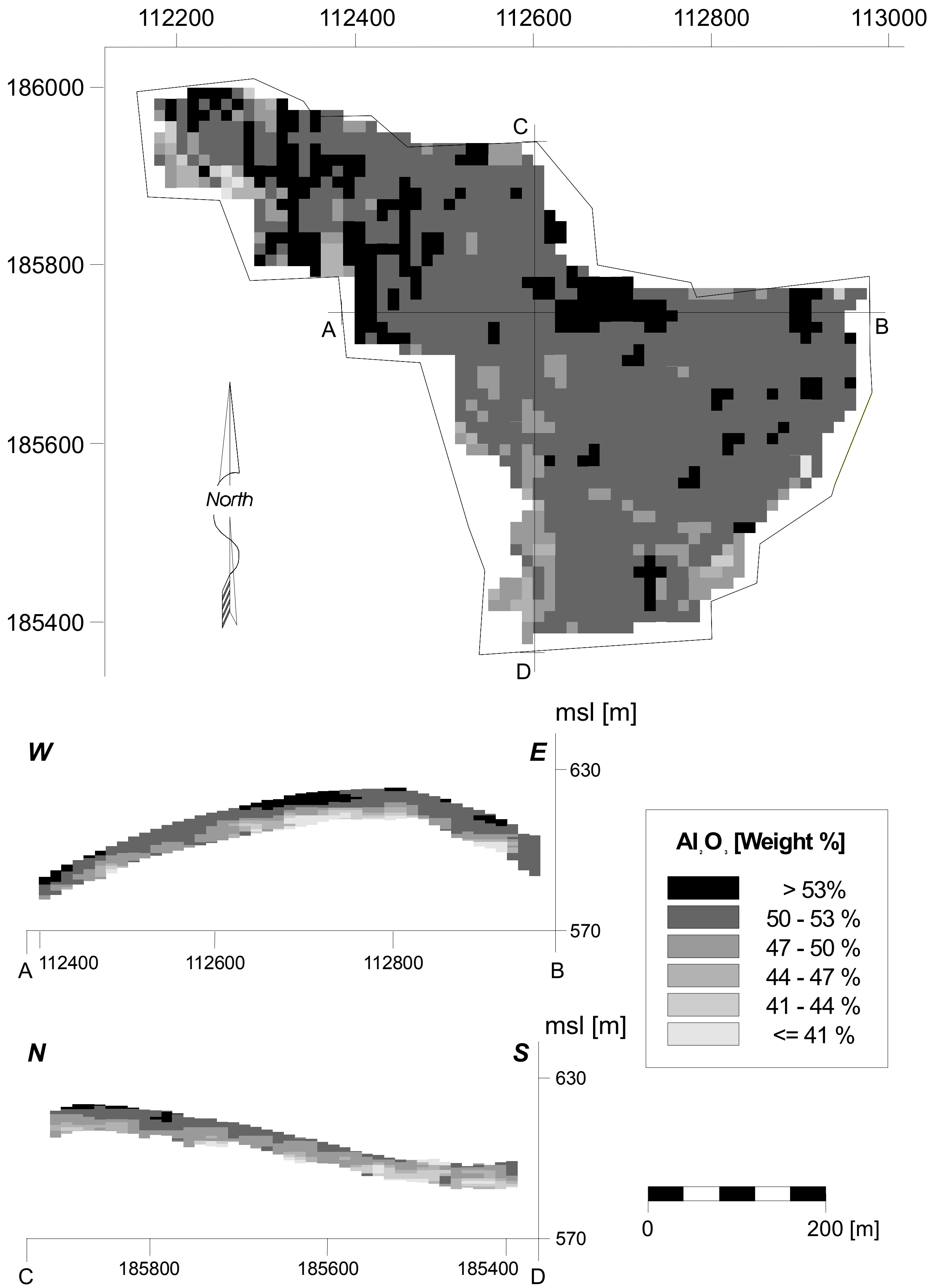

Figure 2: *Illustration of lateral and vertical grade distributions in block 1, sector 3 of the Los Pijiguaos bauxite mine. In Profiles the vertical scale is three times exaggerated.*

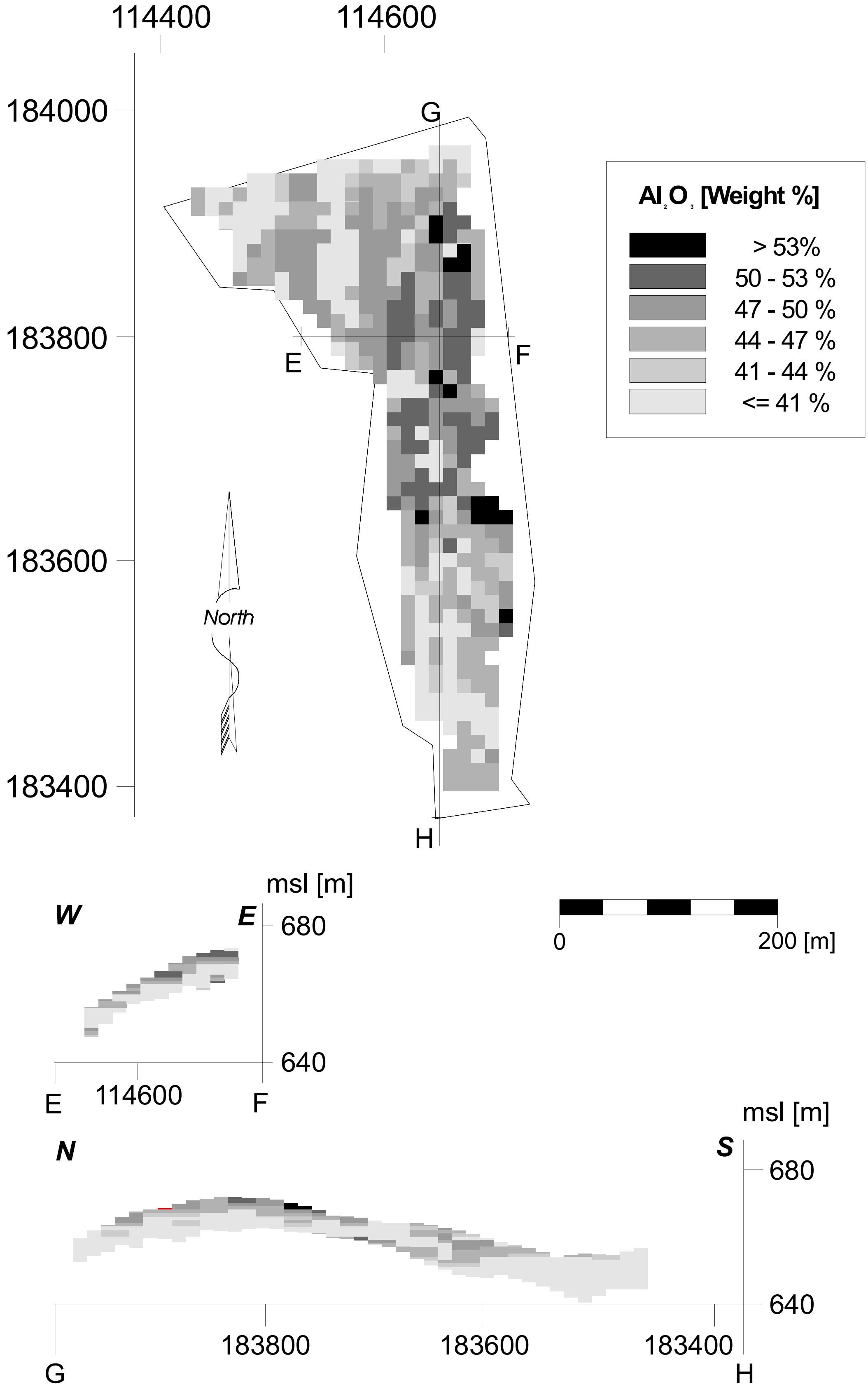

Figure 3: *Illustration of lateral and vertical grade distributions in block 2, sector 7 of the Los Pijiguaos bauxite mine. In Profiles the vertical scale is three times exaggerated.*

5. Mining operations

The shallow bauxite is directly extracted, without blasting, by two hydraulic shovel excavators in a conventional strip mining operation. Overburden is removed by dozers and stockpiled for rehabilitation. The ore is hauled to an inpit crusher by a fleet of 50 and 85 ton trucks. At present mine development the maximum hauling radius is less than 3 km. From the crusher, the bauxite is transported by a conveyer belt over a distance of 4200 m and a drop in elevation of 500 m to the stockpile in the Orinoco valley.
Shipment of bauxite to the alumina refinery near the city of Cuidad Guyana (Fig. 1) requires a two-stage transportation system. Firstly, the ore is transported by train over a distance for 52 km to the Orinoco river port, and subsequently loaded onto barges and shipped for 630 km down the Orinoco River to the alumina plant. Because the Orinoco river is not navigable during the dry season, from November to April bauxite production has to be reduced and stockpiling increased.

6. Production planning

The morphology of the mining area, as mentioned before, separates the bauxite blanket into nine isolated blocks of variable sizes and ore grades (Fig. 4). For mining purposes, the blocks are further subdivided into sectors. Because of the heterogeneous grade distribution illustrated above, and to guarantee constant alumina-, reactive silica-, and quartz contents, selective extraction is required from up to six areas during the course of one year. Therefore, production is controlled by computer-aided mine planning. Short and medium term production planning is based on the evaluation of 10,364 bore hole logs on a 25 m square drilling grid. For the present long term planning to the year 2011, additional 681 bore hole logs on a 100m square drilling grid are included. The long term production planning is based on a presumed annual production of 5.3 million metric tons [5].

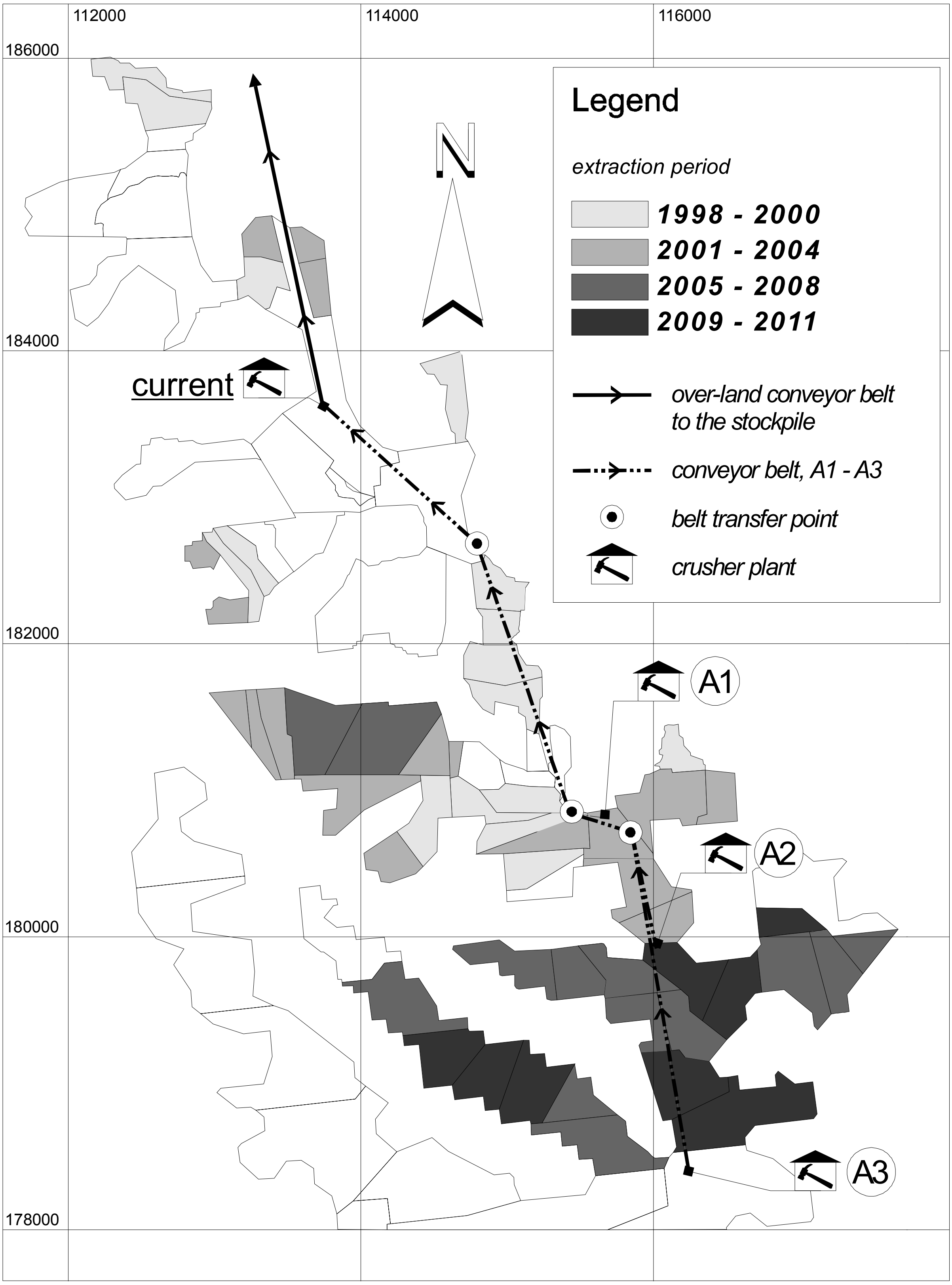

Figure 4: *Schematic long term production plan (1998 - 2011) for the Los Pijiguaos bauxite mine showing the location of the existing over-land conveyor belt to the Orinoco valley as well the inferred location of a second crusher and the inpit conveyor belt extension (A1 - A3, see text).*

7. Transportation

7.1 Present transportation scheme

At present, the ore is hauled by a fleet of trucks to the crusher plant that is located in block 2, in the northern area of the deposit. In future, ore extraction will move gradually further to the south (Fig. 4). As a consequence, the average distance from the excavation front to the crusher plant will rise continuously up to more than 7000 m during the next 13 years, resulting in increased expenditure for trucks, personnel, fuel and maintenance.

7.2 Alternative transportation models

Any long term mine planning requires consideration and optimization of the a number of parameters such as:

1. hauling radius, 2. investment for new mine equipment, 3. costs for fuel, energy, maintenance and other operating costs, 4. costs for personnel, and 5. atmospheric pollution by dust and emissions from fuel combustion. A possible alternative to the present hauling scheme is the extension of the conveyor belt to the southern part of the deposit. Although this will reduce the average hauling radius, it nevertheless requires, in addition to the installation of the conveyor belt, the purchase of further trucks as well as a second crusher. In order to optimize the location of the second crusher and, thus, the length of the conveyor belt, a digital mine model was employed. The distances from the extraction front to the current crusher and/or the second crusher, respectively, were evaluated for the period 1998 to 2011. In addition to the present hauling scheme, calculations were performed for three alternative scenarios taking the length of the conveyor belt as the prime variable. The optimum locations for the second crusher plant considered in the three scenarios (A1, A2, A3) are shown in Figure 4.

8. Database

Parameters used for the hauling models (e.g. investment costs, personnel costs, exchange rates, operating costs, etc.) are taken to maintain constant for the periods considered. Furthermore, changes of inflation rates are also not included in the calculations. Therefore, the models assume a static development of costs.

8.1 Investment costs

Investment costs for the trucks, the conveyor belt and the second crusher are shown in Table 1.

The annuity *a,* or the real annual investment costs, are calculated using the following compound interest equation:

$$a = K \cdot i \frac{(1+i)^n}{(1+i)^n - 1} \quad (1)$$

where K = capital; i = interest rate; and n = number of years for write-off. The interest rate i, used for the modeling is set to 30%, which represents a realistic value for the Los Pijiguaos bauxite project, as experiences with former expenditures have shown.

The annuity calculations of the investments result in the following annual costs [US$]:

- truck CAT 777 C: 289,781
- conveyor belt + second crusher:
  - Model A1: 1,160,201
  - Model A2: 1,396,817
  - Model A3: 1,757,756

8.2 Personnel and operating costs

Current annual wages for an equipment operator at the Los Pijiguaos bauxite mine, including all benefits, amount to 14,862 US$. The number of operators required are shown in Table 1. Operating costs for the trucks include the costs for tires and diesel while lubricant consumption is neglected. Calculations of the operating costs for the conveyor belt and the second crusher are based on electric power consumption.

Table 1: *Costs and technical specifications used for the modeling.*

Truck CAT 777 C	
investment costs *) 1) [US$]	812,000
truck driver per shift	1
tire price 1) [US$]	7708 * 6 = 46,248
life time 1) [h]	3000
diesel price 1) [US$]	0.1184
consumption 2) [l/h]	66.25
capacity 2) [t]	85 (72.1 effective)
velocity, loaded 1) [m/min]	666
velocity, unloaded 1) [m/min]	1000
loading time 2) [min]	2.25

unloading time [1] [min]	1.36
working time per shift [1] [h]	8 * 0.85 = 6.8 (effective)
shifts per day [1]	2 (Feb - May) 3 (Jun - Dec)
working days per year [1]	60 (Jan - May) 173 (Jun - Dec)
equipment availability [1]	0.8
operating time per year [1] [h]	3476.2 (effective)
life time [1] [a]	7 (ca. 24,000 h)
Conveyor belt	
investment costs [*] [2] [US$/m]	771
operator per shift	1
power price [1] [US$/kWh]	0.0631
consumption [3] [MWh]	3888 - 6447
capacity [2] [t/h]	1600
operating time per shift [1] [h]	8
shifts per working day [1]	equivalent to truck
operating days per year [1]	equivalent to truck
life time [1] [a]	15
Second Crusher	
investment costs [*] [2] [US$]	1,000,000
operator per shift	1
power price [1] [US$/kWh]	0.0631
consumption [1]	2086

[*] see equation for annuity calculation (Formulae (1))
Source: [1] company experience value; [2] producer specification; [3] qualified estimation

8.3 Emissions from fuel combustion

Atmospheric emissions produced by haul trucks are calculate from the diesel consumption for the different transportation models. The relevant values used are given in Table 2. Emissions caused by the operation of the conveyor belt and the crushers are negligible because electric power is supplied by hydroelectric power stations.

Table 2: *Emissions produced by haul trucks in kg per kg diesel fuel.*

CO_2	NO_x	CO	HC	SO_2	particle
3.175	0.06	0.035	0.01	0.003	0.003

diesel density [kg/l]: 0.831
Source: German Federal Environmental Agency (UBA), 1995

9. Evaluation of transportation models

In the following, the present hauling scheme that uses trucks only is compared to three alternative scenarios (i.e. A1, A2, A3). As mentioned before, the alternative models represent a combination of ore transportation by truck and by conveyor belt. The comparison evaluates the effects variable hauling distances, investment-, personnel- and operating costs as well as atmospheric emissions have on economic and ecological considerations.

9.1 Average annual hauling distances

Until 1999 bauxite extraction will be mainly from the northern blocks of the mine (see Fig. 4). The three alternative transportation models considered here have in common that during this period all the ore is transported from the extraction front to the current crusher. With the installation of the second crusher, for the period 2000 to 2003 the amount of ore hauled to the present crusher will be reduced accordingly, and from 2004 onwards all of the ore will be transported to the second crusher that is located at the head of the extended conveyor belt. According to that scheme which is based on optimized site selections for the second crusher used in the alternative models, the average annual distance from the excavation fronts to the crusher can be reduced significantly. The variation of hauling radii for the period considered is displayed in Figure 5. Compared to the current hauling scheme, the average distance in the year 2011 can be reduced by 52% using model A1, and up to 82% employing model A3.

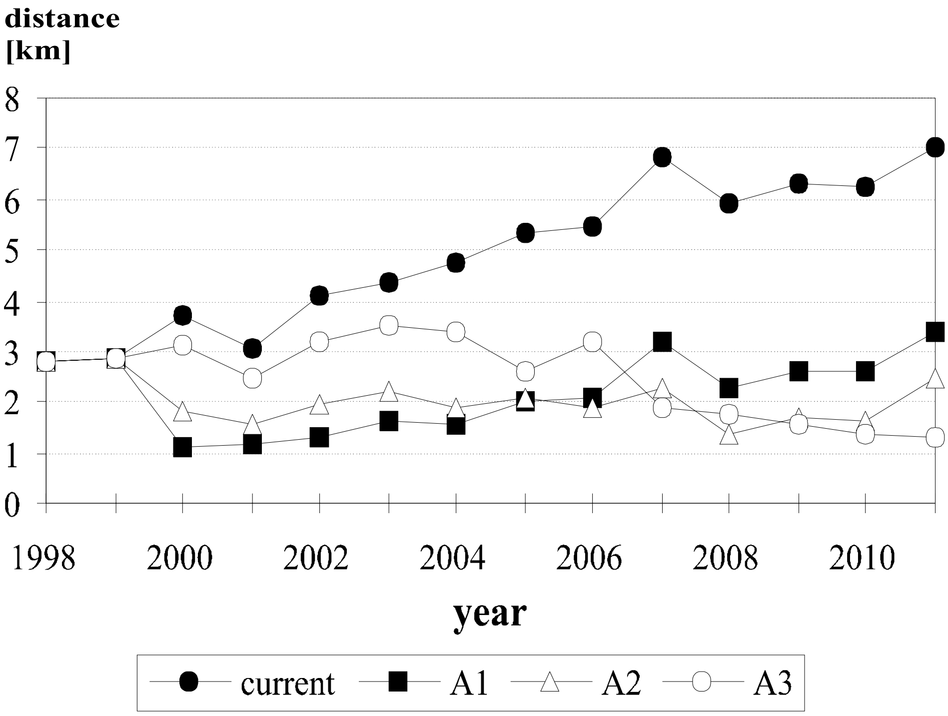

Figure 5: *Calculated average hauling distances for the four transportation models.*

9.2 Cost development

It was mentioned before that the extension of the conveyor belt will not be carried out before 1999, so that the total annual cost development remains identical for all four transportation schemes during the first production period as is illustrated in Figure 6. From the year 2000 onward, cost development for the alternative models differs significantly from the current model. The most dominant parameter causing this deviation is related to the annual investment costs for the conveyor belt extension which is also the reason for the divergence between the three alternative models.

The end of the first write-off period in the year 2004 results in a remarkable reduction of costs for the year 2005. The hauling trucks that had to be bought at the beginning of the period are not all in full operation yet, so that their remaining life time exceeds the 7 years life time limit. The cost development curve for the current transport scheme shows a slight but steady increase over the period considered. Figure 6 clearly demonstrates that the total operating costs, for a projected annual bauxite production of 5.3 million t, using the current model never reaches the costs expected to accrue by implementing one of the three alternative models.

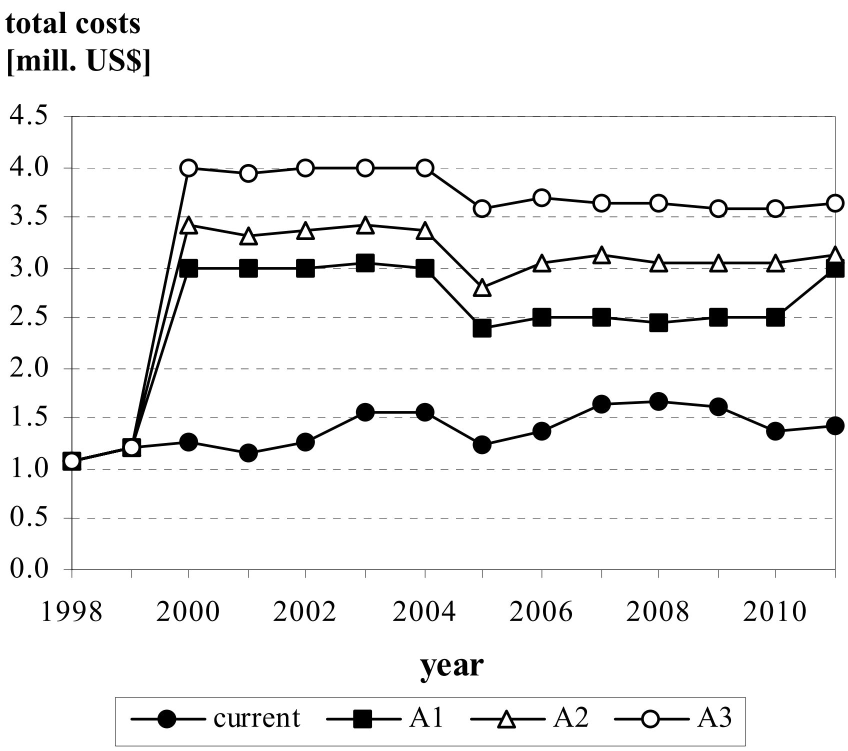

Figure 6: *Total annual cost development for the four transportation models.*

9.3 Development of individual costs

Figures 5 and 6 show the contribution of individual cost factors to the total costs. The graphs are calculated for the current model and, as an example for the alternative models, scenario A1. In both cases personnel- and the operating costs are relatively negligible compared to the investment costs.

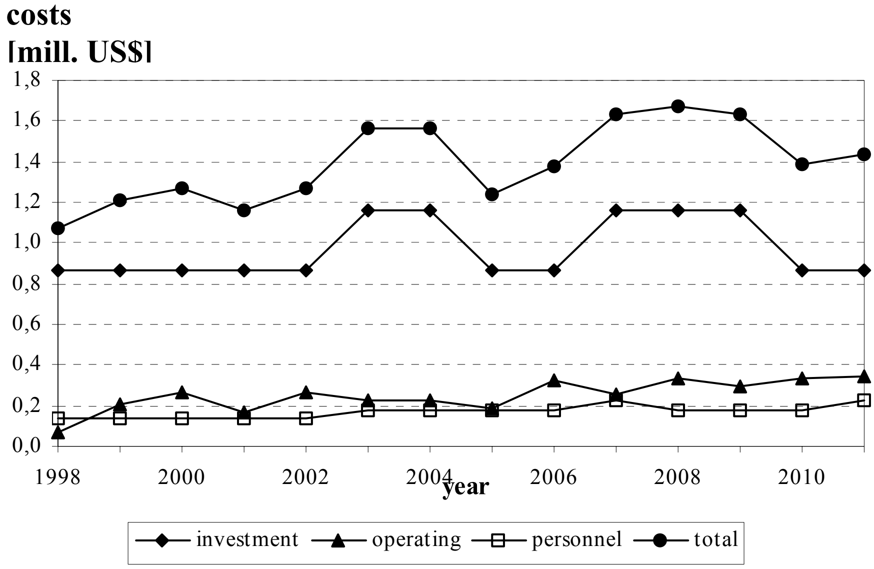

Figure 7: *Cost development for the current transportation model, distinguished by cost factors.*

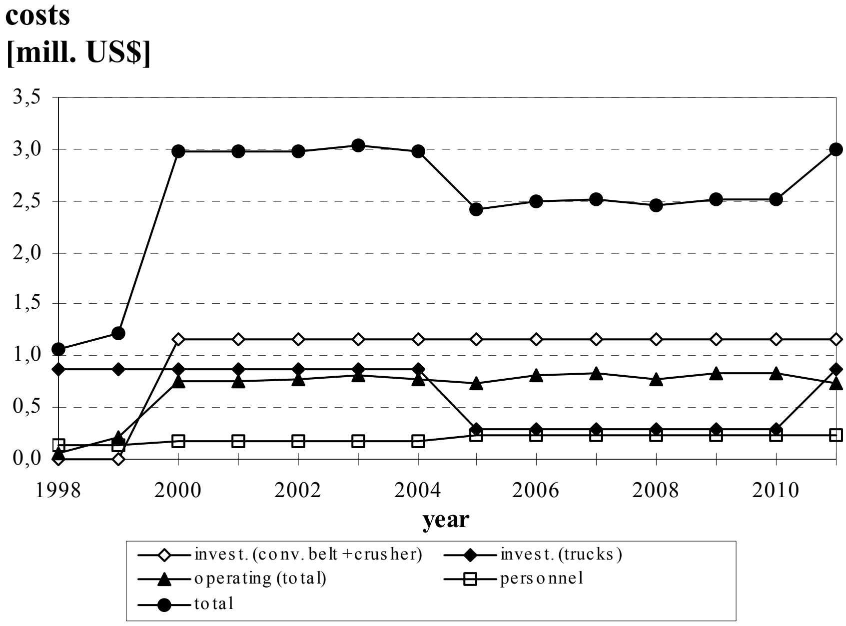

Figure 8: *Cost development for the alternative transportation model A1, distinguished by cost factors.*

9.4 Atmospheric emissions

The amount of gas and particle emissions form combustion was calculated using total operating hours of the hauling trucks, and thus, the diesel consumption per operating hour.

It can be seen from Figure 9 that, as a result of the larger number of trucks and truck cycles employed, the current production and hauling scheme produces a higher amount of emissions compared to the alternative models. The current hauling scheme will produce total emissions of 29.500 t over the period 1088 to 2011 with an annual emission of 2100 t. In contrast, total emissions produced by the alternative transport scenarios are reduced by roughly 35 %. In addition, total emissions will remain relatively constant over the years considered while with the continuation of the current transport scheme emissions will steadily increase. From an ecological point of view, a combination of conveyor belt and truck transportation, i.e. models A1 to A3 are more advantages than truck haulage only. However, when basic economic considerations are taken into account one has to bear in mind that the alternative schemes will result in transport costs that are about 80 to 144% higher.

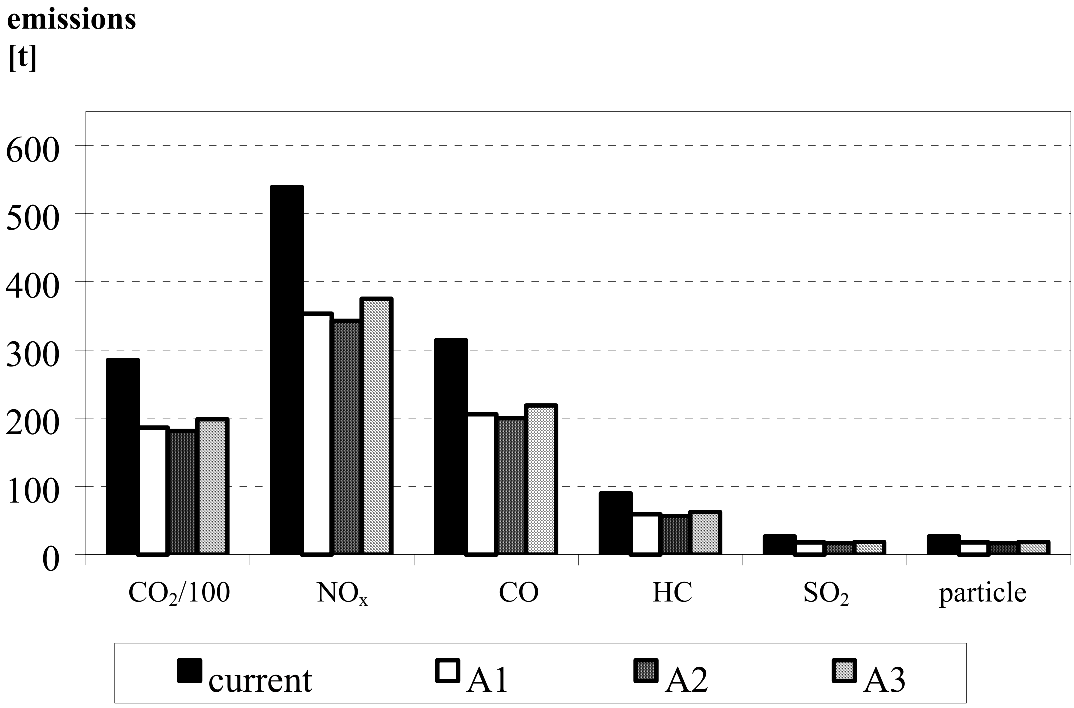

Figure 9: *Comparison of emissions caused by trucks shown for the four transportation schemes over the period 1998 to 2011. Note that CO_2-values are divided by 100.*

10. Conclusions

Computer-based evaluation of four different ore hauling models shows that in case of the Los Pijiguaos bauxite mine, inpit ore transportation by trucks from the extraction site to the crusher is by far the best economic solution. Alternative models employing conveyor belts of various lengths and the installation of a second crusher result in lower operating and personnel costs but in much higher total costs because of increased capital investment. Comparison of environmental parameters such as atmospheric emissions from fuel combustion indicates that by employing alternative transportation schemes (i.e. models A1 to A3) total emissions over the period considered will be reduced by about 35 % compared to truck haulage only.

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BAUXITE MINING IN BRAZIL
-DIFFERENT VIEWPOINTS CONCERNING ENVIRONMENT AND SUSTAINABLE DEVELOPMENT-*

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ABSTRACT

Like surface mining in general bauxite mining always leads to a temporary degradation of environment. Therefore several individual persons and stakeholder groups involved in the business environment of bauxite mining and alumina and aluminum production have given a statement from their points of view.
This paper deals with some basics associated with bauxite deposits and mines in Brazil as well as mining technology and the environment of the deposits. Furthermore effects of bauxite mining are taken in consideration and different viewpoints towards environment, society and Sustainable Development are compared and discussed.

KEYWORDS

Bauxite Mining, Brazil, Sustainable Development, Environment

* Source: VI SMMT / XVIII ENTMH - 2001 - Rio de Janeiro/Brazil

INTRODUCTION

In 1997 the Collaborative Research Center (CRC) 525 firming the title "Resource-Orientated Analysis of Metallic Raw Material Flows" and the sub-title "Development and Application of Methods" was established at the Aachen University of Technology, Germany. The CRC 525 is funded by the Deutsche Forschungsgemeinschaft (DFG), the central public funding organization for academic research in Germany. The long-term goal of the research program is the identification of options for resource-sensitive supplying and processing of metallic raw materials in the area of conflict of technical developments and economic, ecological and also socioeconomic aims. An integrated resource management system for important metallic raw materials is to be designed and tested by the CRC 525 regarding the applicability of this framework in order to provide useful and efficient decision tools. The first phase of the research program (1997 – 1999) was focused on aluminum and aluminum alloys. For the second phase of the research program (2000 – 2002) copper was selected as complementary metal to be examined within the resource-orientated analysis of metallic raw materials. The Institute of Mining Engineering I is involved in the CRC 525 as contractor for studies on extraction of raw materials and waste disposal.

The main raw material for the production of primary aluminum is bauxite. In 1998 aluminum smelters produced 22.1 Mt of primary aluminum worldwide. Therefore, about 104 Mt of bauxite – 85% of the total world bauxite production – were digested to produce alumina (Al_2O_3) which is reduced to aluminum in smelters.

Brazil is an important producer of aluminum accounting for 5.4% of the world primary aluminum production in 1998. In terms of bauxite production the Brazilian share of the world production amounts to 9.6%. Brazil was the fourth largest producer and exporter of bauxite [Punkert-1999, USGS-2000].

BAUXITE IN BRAZIL

There are several major bauxite districts in Brazil containing more than 25 bauxite deposits and projects of which eight are currently mined. Brazilian bauxite is classified as lateritic bauxite which represents the majority of worldwide known deposits. It occurs in shallow seams of 2.5 m to 6 m thickness in average. Figure 1 gives an overview of the distribution of the deposits.

The most important producer of metallurgical grade bauxite is Mineração Rio do Norte S.A. (MRN), mining in the Trombetas region. Other producers of metallurgical grade bauxite are Alcoa Alumínio S.A., Companhia Brasileira de Alumínio (CBA), Alcan Alumínio do Brasil S.A. and Mineração Curimbaba, exploiting bauxite deposits in Poços de Caldas region, Ouro Preto region and Cataguases region. Furthermore two companies – Companhia Brasileira de Bauxita and Mineração Santa Lucrecia (MSL) Minerais S.A. – are mining non-metallurgical grade bauxite at the Rio Jari area and near the Camoai River about 250 km south of Belem.

In 1998, total Brazilian bauxite production amounted to 11.96 Mt including about 0.53 Mt of non-metallurgical grade bauxite. MRN produced 9.32 Mt or 78.3 % of the total metallurgical grade bauxite. The second largest producer was CBA with 1.18 Mt or a share of 9.9 % [ABAL-2000, Ferraz-2000].

Figure 1 - Distribution of bauxite deposits

BAUXITE MINING

Worldwide, all lateritic bauxite mining operations use open pit mining methods. These methods lead to temporary degradation of land due to the necessary removal of vegetation, soil, and overlying strata before mineral extraction. Figure 2 shows an aerial photograph of the Trombetas mine as an example for a huge scale operation.

Depending on mine planning, mining method, and mining equipment the delay between removal of vegetation and start of rehabilitation varies between 1 and 3 years.

The mining method at the Trombetas mine is strip mining. Bulldozers remove vegetation and a thin layer of soil is mined separately for rehabilitation purposes. Afterwards overburden is excavated by draglines and stacked into mined out areas. The bauxite is topped with a lateritic crust which is ripped before backhoes load the bauxite on trucks. Mined out areas are prepared for rehabilitation by bulldozers. Strip mining is the basis for a relatively short period of uncovered surface of one year. Figure 3 shows mining activities at the Trombetas mine.

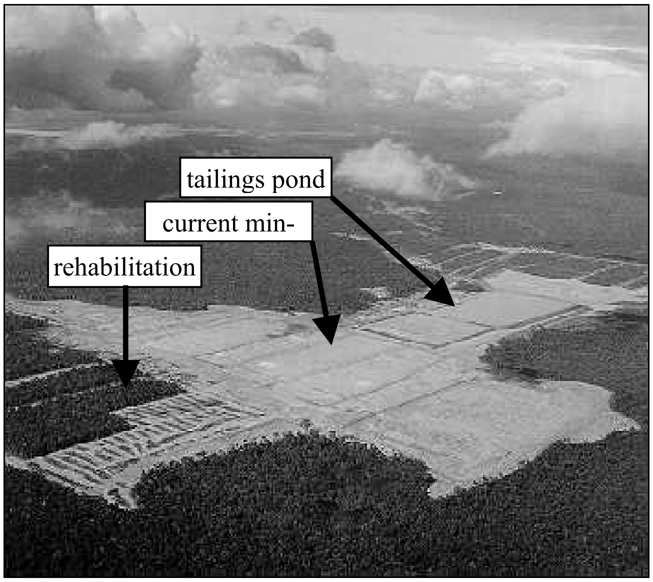

Figure 2: Aerial view of the Trombetas bauxite mine [MRN-2000].

As the crude bauxite from the Trombetas deposit contains impurities a beneficiation is necessary. About 30% of the raw material is rejected in the washing plant. Thus the amount of raw bauxite extracted from the pit is more than 1.4 times the beneficiated product [MRN-2000].

Figure 3: Strip mining at Trombetas mine. Bulldozers ripping lateritic crust [SP2-2000].

Smaller operations often use shovel & truck techniques for transport of overburden as well as bauxite. CBA exploits bauxite deposits in the Cataguases and Poços de Caldas regions. The operations are medium or small scale mines with capacities up to 1 Mt/a. The thickness of bauxite layers in the Cataguases region of the Minas Gerais Forest Zone varies between 0 m and 15 m at an average of 4 m. Subsequent to vegetation removal, soil and unproductive material are deposited aside for use in mine restoration. Bauxite is extracted in a bench system with 3 m high benches and loaded on trucks. As the raw material consists of bauxite and clay, a beneficiation is necessary. The ore recovery after washing is approximately 57 %. This means an additional extraction of 75 % of raw material compared to the beneficiated product.

In the Poços de Caldas region bauxite with an average thickness of 3 m to 5 m is excavated by backhoes and loaded on conventional dump trucks after vegetation is removed. Topsoil is stored for rehabilitation. The raw material is also washed to produce saleable bauxite [CBA-2000]. Figure 4 shows mining activities at the Três Barras Mine, Poços de Caldas region.

Figure 4: Bauxite mining and loading in the Três Barras Mine [CBA-2000]

ENVIRONMENTAL ASPECTS

Impacts of open pit mining have been discussed in a wide range of studies and are documented in a large body of literature (e.g. [Eggert-1994, Martens-1998, Martens-2000, Sengupta-1993, UNEP-1997]). There is no doubt that all environmental impacts can directly or indirectly be linked to the utilization of land. On the one hand this is due to alteration of land cover, e.g. buildings or infrastructure or mined land instead of vegetation, and can be measured by sealed area or soil erosion etc. On the other hand mining activities can also cause emissions like dust, noise, and vibrations. Mineral extraction can affect all three environmental media – land, water, and air (see figure 5).

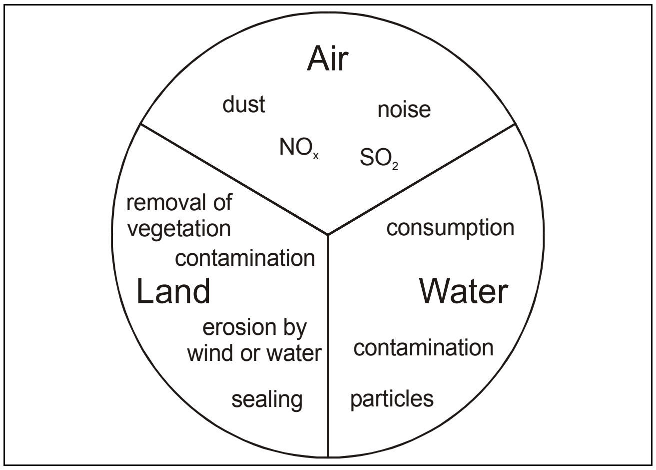

Figure 5: Exemplary impacts on environmental media.

Looking at Brazilian bauxite mines, one has to differentiate between the deposits in prior uninfluenced regions in the north of Brazil, e.g. the Trombetas region, and deposits adjacent to urbanized areas, e.g. south-eastern Brazil. The Trombetas mine is situated in the humid tropics of the rainforest climate, surrounded with undisturbed rainforest. Thus, any activity causes damage to environment (see figures 2 and 3). The annual demand for land amounts to 170 ha. This area is exposed to erosion by wind and water and does not contribute to any of its former functions. Vegetation and buildings in the surroundings are turned red by bauxite dust. Furthermore contamination of the river system with particles resulting in reduction of fish population is stated in literature [Moser-1996].

To meet impacts on the environment the mine operators in Brazil are obliged by law to a natural restoration. MRN has developed an integrated environmental management system to guarantee minimized effects in accordance with legal issues. Bauxite mines, which are not located in rainforest climates are generally confronted with similar environmental impacts. The more urbanized an area is, the more social and local economic impacts are caused by mineral extraction, e.g. resettlements and providing of jobs. Some environmental impacts like deforestation of areas which have already been affected before by men and rehabilitated after mining are not to be seen as critical as activities in formerly uninfluenced areas.

All bauxite mining companies run rehabilitation departments in order to meet legal conditions. Furthermore most deposits are partly owned by global acting aluminum producers and thus are influenced by their environmental policy. Those two factors and global public discussion have already led to efforts resulting in rehabilitation awards, e.g. in Western Australia.

Brazil's most important bauxite producer MRN revegetates mined out parts of the deposit by planting 2.500 plants of more than 80 species per ha after soil is prepared with small boughs and roots from former vegetation cover as longterm fertilizer. The plants are grown in a company owned nursery. Figure 6 shows a rehabilitated area with three year old plants.

Figure 6: Rehabilitation at Trombetas mine [Sliwka-2000]

CBA also reclaims mined area by topographical reshaping and replanting aiming at a recomposition of the native flora and additional measures to attract the regional fauna.

SUSTAINABLE DEVELOPMENT

The roots of Sustainable Development on a global level can be traced back to 1972, when the United Nations Conference on Human Environment took place in Stockholm, Sweden. During this meeting, some principles were stated, which can be seen as basic approaches.

It took twenty years, until in 1992, more than 100 heads of state came together in Rio de Janeiro, Brazil for the first international Earth Summit. This meeting was convened to address urgent problems of environmental protection and socio-economic development. The assembled leaders signed the Convention on Climate Change and the Convention on Biological Diversity, endorsed the Rio Declaration and the Forest Principles, and adopted Agenda 21, a 300 page plan for achieving Sustainable Development in the 21st century.

The Commission on Sustainable Development (CSD) was created to monitor and report on implementation of the Earth Summit agreements. It was agreed that a five year review of Earth Summit progress would be made in 1997 by the United Nations General Assembly meeting in special session. This special session of the UN General Assembly took stock of how well countries, international organizations and sectors of civil society have responded to the challenge of the Earth Summit. Sustainable Development may be explained as "... development that meets the needs of the present without compromising the ability of future generations to meet their own needs ..." [UN-1997].

The consequences for the mineral extracting industry are on the one hand an increased responsibility for environment in order to leave intact ecosystems for future generations. On the other hand, before the background of exhaustible resources and the needs of future generations, mineral deposits have to be exploited in a responsible way. This has to be achieved by improved mining and processing methods.

VIEWPOINTS CONCERNING ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

General

In the majority of the cases, companies taking care for environment in the context of mineral extraction undertake efforts in avoiding contamination and improvements in rehabilitation. Environment is interpreted to consist of flora and environmental media in the surroundings of a specific location. Other impacts, e.g. on fauna or humans, often remain unmentioned. The concept of Sustainable Development is interpreted as leaving a hopefully self-sustaining area after mine closure.

Roderick G. Eggert – Professor and Director of Division of Economics and Business, Colorado School of Mines (USA) – notes that mining, by its nature, poses major environmental challenges and quotes Georgius Agricola to confirm that environmental impacts of mining have already been noted in the 16th century. After years of overexploitation of nature, environmental legislation came into force in industrialized countries beginning in the 1960s. Development of a worldwide concern of environment has led to the sustainability discussion. Environmental protection has become an important concern for mineral extracting industry as well as for governments, designing and implementing new environmental policies [Eggert-1994].

James R. Kahn – professor in the Economics Department at the University of Tennessee (USA) – gives a brief history of the sustainability discussion from an economical point of view. He quotes statements about economic growth before the background of scarcity of resources from the 1960s and thoughts about interchangeability between labor (human capital), artificial capital, and extractable natural resources. In his opinion, artificial capital cannot provide an adequate substitution for environmental resources. Sustainable Development, comprising present and future economic, social, and ecological needs, requires an expansion of stocks of artificial capital, human capital, and natural resources. At the same time he demands maintaining stocks of environmental capital which provide ecological services. Therefore he sees environmental policy as important and critical component of economic development [Kahn-2000].

Werner Schenkel and Karl Otto Henseling – working for the German Federal Environmental Agency – present rules for resource utilization. Concerning exhaustible resources they demand not to exceed a level which can be substituted by equivalent renewable or even higher quality ones. Furthermore, material flows into the environment have to be looked at before the background of load-bearing capacity of environmental media. Nature's ability to react on anthropogenous interventions must not be stressed in terms of time [Schenkel-1998].

In 1996, Werner Gocht – Member of CRC 525 and head of the sub-program "Economics of Resources" – predicted that in the 21st century mining companies have to accept protection and management of resources as essential measures in raw materials extraction [Gocht–1996].

Example of bauxite mining in Brazil

Statements of several scientist, researchers, and stakeholders concerning bauxite mining in Brazil, especially in rainforest climates, can be found in literature. In the following passages, statement from very different points of view might give a general idea of the discussion towards environment and sustainability.

After mentioning facts about the Brazilian aluminum economy, Claudio and Christine Moser – commited to rainforests and environment from a social point of view in dialog with ecclesiastical stakeholder organizations (e.g. the German GKKE) – describe the bauxite mining activities at the Trombetas mine with special emphasis on some negative impacts. Apart from the aforementioned impact on environmental media (contamination of parts of Rio Trombetas with particles), they have a critical opinion about the local community's dependence on the company and the company's influence opportunities. Furthermore a conflict in land use between bauxite extraction and utilization by "Quilombolas" – descandants of escaped slaves, living adapted to natural conditions – are described [Moser-1996].

In contrast to Moser, Hans Plaettner – an individual aluminum user doing statistical research on aluminum production – puts more emphasis on the socio-economic use of aluminum production. He handles the topic if aluminum production is responsible for destruction of rainforests. Comparing the damage caused by small indigenous communities, farming land after clearance by burning for a few years, to benefits resulting from bauxite mining, also considering rehabilitation, he concludes that mining is less harmful to environment than some kinds of farming. One item of his statements is the aspect that land used for bauxite mining means more social and economic benefit than the same amount of land used for few years for farming after clearing by burning [Plaettner-2000].

Sliwka and Bauer – researchers and collaborators of CRC 525 – have visited the Trombetas bauxite mine in 1999. They describe mining activities and point out that the discussion of sustainability has several dimensions: economy, ecology, and social aspects. Within the economic dimension both effects on the domestic economy as well as regional and local economical developments have to be considered. Compared to the national importance as major bauxite producing location and therefore important for a whole branch of industry and international trade the local economic effects are rather low. An economic as well as social aspect is creation of jobs and training of skilled workers. The ecological dimension is composed of degradation of land on the one hand and environmental policy, rehabilitation efforts, and investment into technological improvements which benefit environment on the other hand. As prior to bauxite mining the region was mostly uninhabited, the main social aspect at Trombetas mine is stated as the conflict of mining land use in contrast to former use by "Quilombolas". Additional to the confrontation with the mining industry they were restricted in their normal way of life by environmental laws. Access, hunting, fishing, and collecting fruit in the surroundings of the mine was forbidden in order to protect the environment and to prevent slums. Meanwhile, access and collecting fruit is tolerated but still illegal. Some development programs which are supported by MRN were established to develop self-sustaining structures. One program is planting seedlings for rehabilitation purposes. In their conclusion, Bauer and Sliwka note that MRN identified several problems while operating the mine and started efforts for solutions. In terms of ecology they especially stress success in rehabilitation and reduction of pollution. The social dimension is mentioned in context with improved coexistence with "Quilombolas". The company's ability to recognize ecological effects and willingness to take social responsibility, developed while operating the mine is seen very positively.

DISCUSSION

The general statements on mining, environment and Sustainable Development clearly express the role of mining – especially open pit mining – as destructive to land cover and landscape. Thus, effective measures to protect the environment have to be taken. This is seen as an important task for minerals extraction industry as well as for legislation. Sustainability in mining has derived from ecological discussions and is more and more expanded to social dimensions. Solutions for negative environmental and social impacts have to be developed creating a balance with economic factors.

The example of Brazilian bauxite mining shows that, comparing the statements, results always depend on the observers point of view. The statements of Moser and Moser on the one hand and Sliwka and Bauer on the other hand show a positive trend towards increasing sustainability within less than one decade. Whilst one viewpoint is more social orientated the other is mainly focussed environment. Government and company have been facing problems and developed effective measures. This confirms the general statements about the linkage of effects arising from mining and developing strategies considering all aspects of development towards sustainability.

Progress in the discussion about sustainability is very much dependent on participation of stakeholders. The growing awareness of people of the world concerning impacts of human actions will force international operating companies and thus their suppliers to detailed environmental reporting. In future this might result in "sustainability reports".

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ENERGETISCHE ANALYSE VON TAGEBAUEN MIT HILFE DES KUMULIERTEN ENERGIEAUFWANDS (KEA) AM BEISPIEL BAUXIT*

(ENERGETIC ANALYSIS OF OPEN PIT MINING BY MEANS OF CUMULATED ENERGY DEMAND (CED) CONSIDERING AS EXAMPLE BAUXITE)

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ABSTRACT

In 1997 the Deutsche Forschungsgemeinschaft (DFG) has established at the University of Technology Aachen (RWTH) the Collaborative Research Center 525 entitled „Resource-Orientated Analysis of Metallic Raw Material Flows". The aim of the program is to develop tools for a resource-sensitive utilization of metallic raw materials within the framework of economic, environmental and social constraints. The intention of the paper is to show the development of a methodology to compute a *Cumulative Energy Demand* using a process chain. The *Cumulative Energy Demand* offers an opportunity to calculate the total energy input for the generation of a product, taking into account the pertinent front-end process chains. The case study will limit itself to the extraction of bauxite as the first step of the raw material provision. It will show the direct energy input into extraction and in addition to this the energy necessary to produce the respective equipment and supplies.

KEYWORDS

Cumulative energy demand, process chain, bauxite extraction, energy input, front-end process chains

* Source: Erzmetall 52 (1999), Nr. 6, S. 351-357

1 INTRODUCTION

In der modernen Industriegesellschaft stellen metallische Rohstoffe eine wichtige Entwicklungsgrundlage dar. Quantitativ repräsentieren die mit diesen Rohstoffen in Zusammenhang stehenden, ausgelösten Massenbewegungen einen wesentlichen Anteil an der Gesamtheit anthropogener Stoffströme. Durch den zunehmenden Bedarf an metallischen Rohstoffen und den wachsenden Einfluß der ausgelösten Stoffströme auf die Umwelt stellt sich die Forderung nach einer dauerhaften und nachhaltigen Entwicklung mit dem Stoffstrommanagement als systemkontrollierende Größe. Für metallische Rohstoffe existiert noch keine vollständige Betrachtungs- und Bewertungsmethodik, als Grundlage eines Stoffstrommanagements. Daher arbeiten neun Institute der RWTH Aachen und des Forschungszentrums Jülich im Sonderforschungsbereich 525 „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe" zusammen. Dabei bearbeitet jedes Institut ein Teilprojekt (Bild 1). Ziel dieser Untersuchungen ist das Auffinden von Strategien und Maßnahmen für eine ganzheitliche, lebenszyklusweite Betrachtung von Stoffströmen. In der ersten Phase des von der Deutschen Forschungsgemeinschaft (DFG) seit dem 1. Januar 1997 geförderten Projektes stehen Untersuchungen des Aluminiumstoffstroms. Dabei soll der primäre Bereitstellungsprozeß von der Genese über die Gewinnung, Aufbereitung und Verhüttung einschließlich der ersten Verarbeitungsstufe betrachtet werden. Des weiteren werden Prozesse der sekundären Bereitstellung, also der Verwertung sowie der Beseitigung eingeschlossen.

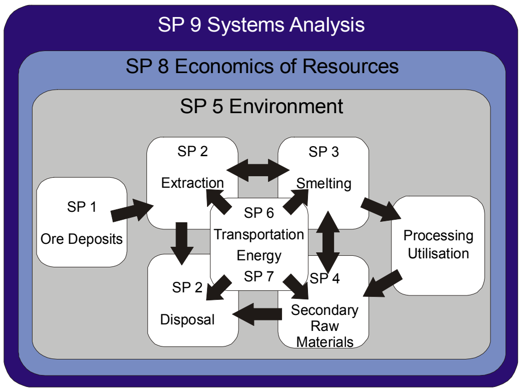

Bild 1: Verknüpfung der Teilprojekte

Das Institut für Bergbaukunde I (SP 2) und der Lehrstuhl für Reaktorsicherheit und Reaktortechnik (SP 7) arbeiten in diesem Projekt zusammen, um energetische Aspekte u.a. bei der Gewinnung von Bauxit zu betrachten und zu analysieren.

2 BAUXITGEWINNUNG

Aluminium ist nach Sauerstoff und Silizium das dritthäufigste Element der Erdkruste. Aufgrund seiner chemischen Reaktivität kommt Aluminium nicht elementar in der Natur vor sondern ausschließlich in Mineralgemengen mit Silikaten und Oxiden auffindbar. Als Rohstoff zur Erzeugung von Primäraluminium werden weltweit fast ausschließlich Bauxite verwendet.

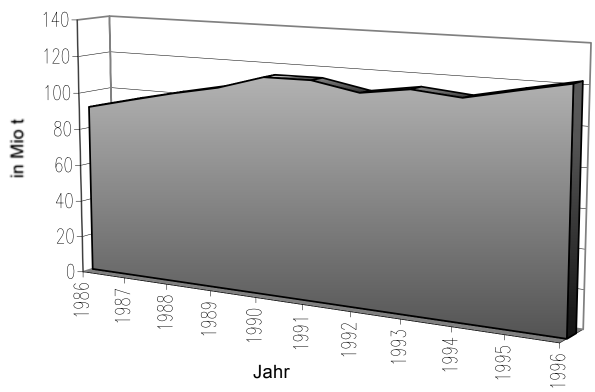

Bild 2: Weltbauxitförderung in den Jahren 1986-1996

Bauxit, das weltweit überwiegend im Tagebau hereingewonnen wird (98%), ist ein inhomogenes Gemenge von hydroxidischen Aluminiummineralen, Eisen- und Titanoxiden. 1996 belief sich die Weltförderung auf rd. 122,7 Mio t (Bild 2).

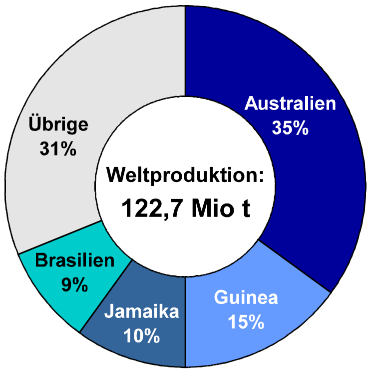

Bild 3: Hauptförderländer für Bauxit in 1996

Die gesamte Weltförderung an Bauxit wird derzeit auf 82 Standorten hereingewonnen [1]. Diese Standorte verteilen sich auf 24 Länder, von denen 16 Entwicklungsländer sind [2]. Hauptförderländer mit einem Anteil von rd. 70% der Weltförderung waren 1996 Australien (35%), Guinea (15%), Jamaika (10%) und Brasilien (9%) (Bild 3).
Aus der Untersuchung aller 82 Standorte nach dem bergtechnischen Kriterium „Betriebsgröße" folgt, daß rund 90% der Betriebe eine jährliche Förderung < 5 Mio t haben. Rund 60% der Betriebe haben eine jährliche Förderung < 1 Mio t (Bild 4).

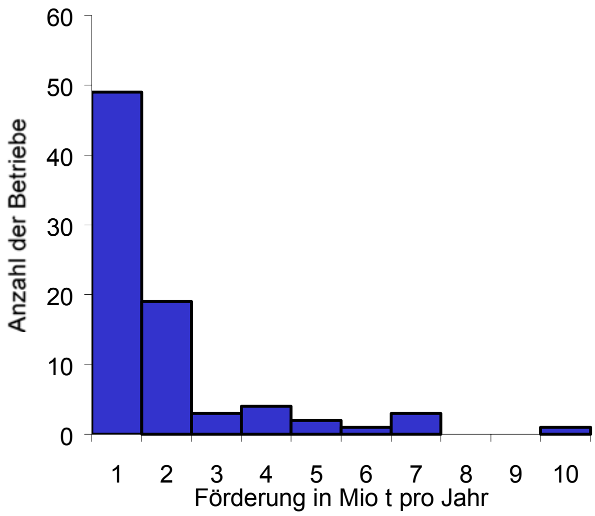

Bild 4: Verteilung der Betriebsgröße bei der Bauxitförderung

In den meisten Fällen handelt es sich um großflächige, oberflächennahe, geringmächtige Lagerstätten, die mittels diskontinuierlicher Gewinnungsverfahren im Tagebau abgebaut werden. Der Großteil der Förderung dient der Herstellung von Primäraluminium.

3 KUMULIERTER ENERGIEAUFWAND

Im Rahmen einer umfassenden und ressourcenorientierten Gesamtbetrachtung stellt der mit der Gewinnung von Bauxit verbundene energetische Aufwand eine wichtige Größe dar.
Neben Treibstoffen und Elektrizität zum Betrieb der Gewinnungsgeräte werden auch Maschinen, Rohstoffe und Hilfsstoffe benötigt, die stets selbst Produkte energieintensiver Herstellungsprozesse sind. Dem Wertmineral Bauxit, für dessen Gewinnung sie gefertigt wurden, müssen ihre energetischen Aufwendungen im Sinne einer Gesamtbetrachtung ebenso zugeschrieben werden wie ihr Bedarf an Elektrizität und Brennstoffen.
Die Erfassung der Energieaufwendungen ausschließlich auf der Ebene von Endenergien (Brennstoffe, Wärme, Strom) ist problematisch, da diese Energieformen aufgrund ihrer physikalisch grundsätzlich unterschiedlichen Eigenschaften kaum vergleichbar sind und die Energieaufwendungen und Verluste für ihre Bereitstellung nicht erfaßt würden.
Die Frage nach dem energetischen Aufwand zur Bereitstellung von Energieträgern kann methodisch eindeutig und sachlich angemessen durch die Ermittlung der hierzu erforderlichen Menge Primärenergie beantwortet werden, also dem Verbrauch von Energie, die in Primärenergieträgern (Rohkohle, Erdöl, Erdgas, Uran, ...) gespeichert ist.
Die Gesamtheit aller auf den Verzehr von Primärenergie bezogenen energetischen Aufwendungen wird daher als kumulierter (primärenergetischer) Energieaufwand *KEA* bezeichnet [3]. Dieser Energieaufwand stellt die Summe der kumulierten Energieaufwendungen für

die Herstellung (KEA_H), Nutzung (KEA_N) und Entsorgung (KEA_E) des ökonomischen Gutes dar:
$KEA = KEA_H + KEA_N + KEA_E$

Herstellungsphase	*Nutzungsphase*	*Entsorgungsphase*
Betriebsmittel Betriebsstoffe Rohstoffe Hilfsstoffe Energien ↓	**Rohstoffe Hilfsstoffe Betriebsstoffe Energien Ersatzteile** ↓	Betriebsmittel Betriebsstoffe Energien ↓
Herstellung der Betriebsmittel →	**Nutzung der Betriebsmittel für den Prozeß** →	Entsorgung der Betriebsmittel
↓ recyclierbare Stoffe Abfälle	↓ **Produkt** Kuppelprodukte recyclierbare Stoffe Abfälle	↓ recyclierbare Stoffe Abfälle

Bild 5: Schema der Bilanzierung eines Prozesses zur Bestimmung des kumulierten Energieaufwandes

Kumulierte Energieaufwendungen können sowohl für Rohstoffe wie z.B. Bauxit als auch für Dienstleistungen und für bereitgestellte Energien und Energieträger bestimmt werden. Das nachfolgende Bild 5 zeigt beispielhaft die Bilanzierung eines Produktionsprozesses zur Ermittlung des kumulierten Energieaufwandes eines Produkts.
Den Zusammenhang zwischen nutzbarer Endenergie und dem kumulierten Energieaufwand zu ihrer Bereitstellung beschreiben die Bereitstellungsnutzungsgrade $\boldsymbol{g_{el}}$ für Elektrizität und $\boldsymbol{g_{fuel}}$ für Brennstoffe

$$g_{el} = \frac{W_{el}}{m_B^{prim} \cdot H_u^{prim} + \sum_i KEA_{Anlage,i}}$$

bzw.

$$g_{fuel} = \frac{m_B \cdot H_u}{m_B^{prim} \cdot H_u^{prim} + \sum_i KEA_{Anlage,i}}$$

Das Produkt $m_B^{prim} \cdot H_u^{prim}$ beschreibt den Energieinhalt des Primärenergieträgers und $\sum_i KEA_{Anlage,i}$ die kumulierten Energieaufwendungen für die Errichtung, den Betrieb und die Entsorgung sämtlicher Anlagen, Maschinen und Betriebsstoffe, die zur Bereitstellung der nutzbar gemachten Energie W_{el} bzw. $m_B \cdot H_u$ benötigt werden. Der dimensionslose Bereitstellungsnutzungsgrad charakterisiert damit ähnlich einem Wirkungsgrad die Effizienz einer Energiebereitstellung unter Berücksichtigung sämtlicher energetischer Aufwendungen. Somit können die Verbräuche von Endenergien, z.B. von Dieseltreibstoff und elektrischem Strom, mit Hilfe der jeweiligen Bereitstellungsnutzungsgrade primärenergetisch bewertet werden.
Die Ermittlung der kumulierten Energieaufwendungen erfolgt am Beispiel der Bauxitgewinnung zweckmäßigerweise durch eine Prozeßkettenanalyse. Hierfür werden zunächst alle im Bergbau relevanten Prozesse als Module dargestellt, deren In- und Outputs in der Nutzungsphase im Rahmen einer Sachbilanz nach Bild 5 erfaßt werden.
Im nächsten Schritt werden die Endenergieeinsätze mit Hilfe der Bereitstellungsnutzungsgrade primärenergetisch bewertet und kumulierte Energieaufwendungen für Herstellung, Nutzung und Entsorgung der eingesetzten Materialien und Betriebsmittel bestimmt. Für die meisten häufig verwendeten Materialien (Metalle, Kunststoffe, Glas, Beton, Sand, ...) sind z.T. detaillierte Untersuchungen zum kumulierten Energieaufwand auf Halbzeugebene durchgeführt worden. Die Energieaufwendungen in der Entsorgungsphase sind aufgrund vielfältiger Entsorgungsmöglichkeiten (Recycling, Deponierung) nur im Einzelfall und mit hohem Zeitaufwand zu bestimmen.

4 PROZEẞKETTE

Mit Hilfe einer für Bauxittagebaue entwickelten, allgemeingültig aufgebauten Prozeßkette (Bild 6) ist es möglich, sämtliche Bauxittagebaue modellhaft darzustellen und den kumulierten Energieaufwand zu berechnen.
Der bergbauliche Prozeß umfaßt alle Vorgänge, um planmäßig Wertmineral aus der Erdkruste zu gewinnen und

dieses zur weiteren Nutzung zur Verfügung zu stellen. Diese Prozesse sind innerhalb der Systemgrenze dargestellt.

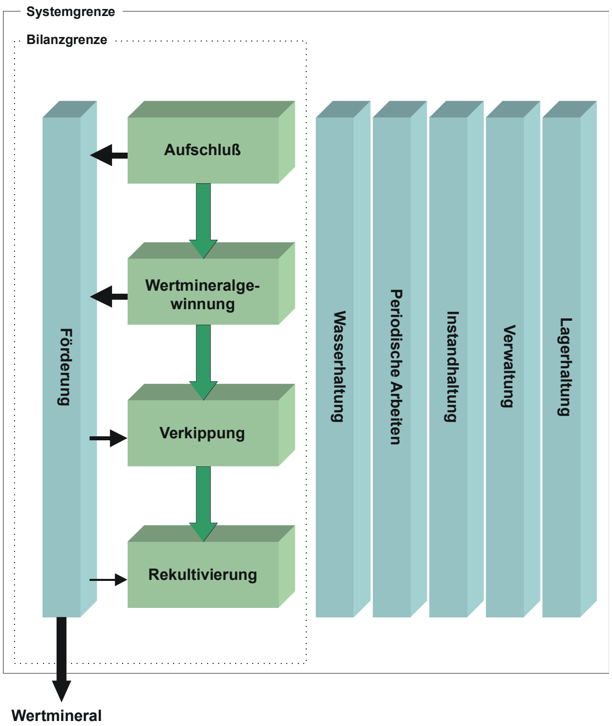

Bild 6: Allgemeingültige Prozeßkette für die Gewinnung im Tagebau

Um einen einheitlichen Betrachtungsraum zu gewährleisten, wurden zunächst horizontale und vertikale Bilanzgrenzen bestimmt. Die horizontalen Bilanzgrenzen engen den Betrachtungsraum zeitlich ein, während die vertikalen die Betrachtungstiefe festlegen. Die in diesen Bilanzgrenzen zu untersuchende Prozeßkette wurde in die Teilprozesse Aufschluß, Wertmineralgewinnung, Verkippung, Rekultivierung und Förderung zergliedert. Die Teilprozesse Wasserhaltung, periodische Arbeiten, Instandhaltung, Verwaltung und Lagerhaltung sind integrative Bestandteile des Bergbauprozesses. Dabei werden jedoch die Teilprozesse Lagerhaltung, Verwaltung und Instandhaltung nicht in die Betrachtung mit aufgenommen, da sie stofflich und energetisch nur von geringer Bedeutung sind.
Betrachtet man einen festen Betriebspunkt innerhalb eines Bergbaubetriebes so laufen die Teilprozesse Aufschluß, Wertmineralgewinnung, Verkippung und Rekultivierung über diesen hinweg. Der Teilprozeß Förderung bildet dabei ein verbindendes Element.
Durch den Tagebauaufschluß wird ein Zugang zur Lagerstätte geschaffen, der eine stete Wertmineralgewinnung ermöglicht. Dieser Prozeßschritt wird in der Ermittlung des KEA nicht berücksichtigt. Berücksichtigung soll der Abschnitt des Aufschlusses finden, der nach der Schaffung eines Zuganges zur Lagerstätte stetig weiter betrieben werden muß, um die Gewinnung zu gewährleisten. Dieser Teilprozeßschritt kann weiter unterteilt werden in Vorbereitung der Oberfläche, Gewinnung von kulturfähigen Bodenschichten und Gewinnung von Deckgebirgsschichten. Die sich anschließenden Teilprozesse Wertmineralgewinnung und Verkippung können wie der Teilprozeß Aufschluß mittels kontinuierlicher oder diskontinuierlicher Techniken durchgeführt werden. Bei Bauxittagebauen herrscht die diskontinuierliche Verfahrensweise vor.
Ziel einer Rekultivierung ist es, die bergbaulich genutzten Flächen wiederherzustellen und somit eine planmäßig erstellte, naturnahe Bergbaufolgelandschaft zu erhalten. Bei allen großen Bauxittagebauen ist dies die Regel.
Der Teilprozeß Förderung umfaßt sowohl die Förderung des Wertminerals als auch die der Abraummassen. Die kulturfähigen Deckgebirgsschichten werden der Rekultivierung, die übrigen Deckgebirgsschichten der Verkippung mittels Fördermitteln zugeführt. Bei Bauxittagebauen herrschen dabei diskontinuierliche Fördermittel vor. Das Wertmineral gelangt durch Fördermittel zum Abnehmer.

5 BEISPIELRECHNUNG

Die Lagerstätte, auf welcher der zu untersuchende Bergbau als Tagebau umgeht, ist flözartig ausgeprägt und von einer 0,5 - 1 m mächtigen, kulturfähigen Schicht überlagert. Das hereingewonnene Bauxit liegt in einer durchschnittlich 3,5 m mächtigen Schicht vor.

Zunächst wird die Oberfläche auf ca. 300 ha/a vorbereitet, indem der vorhandene Bewuchs mittels Bulldozern abgeschoben wird. Die anstehende kulturfähige Schicht wird mit Scrapern im push-and-pull Betrieb gelöst, geladen, transportiert und soweit vorhanden auf ausgeerzte Lagerstättenteile aufgetragen oder vorübergehend aufgehaldet. Im Anschluß werden ca. 60% des freigelegten Wertminerals mit Reißhaken aus dem Gebirgsverband gelöst und mit Radladern auf 150 t-SLKW geladen. Während der Gewinnung sind stets drei Radlader und elf SLKW an drei Abbaufronten zum Laden und Transportieren im Einsatz. Das geladene Wertmineral wird durchschnittlich fünf Kilometer weit zu einer zentralen Kippstation gefördert. Von dieser Kippstation erfolgt ein Zugtransport über rd. 40 km zum Hafen. Eine Wasserhaltung wird nicht betrieben. Die periodischen Arbeiten bestehen im wesentlichen aus Straßenbau und aus Staubbekämpfung.

Zur Berechnung des KEA der Gewinnung von 1 Tonne Bauxit wird zunächst die Energieaufwendung während der Nutzung der eingesetzten Betriebsmittel berechnet (Tabelle 2). Hierbei wurden energetische Aufwendungen für Ersatzteile und Hilfsstoffe nicht berücksichtigt. Ebenso entfällt eine Bilanzierung von elektrischer Energie, da in keinem der untersuchten Teilprozesse Elektrizität benötigt wird.

Teilprozeß	*Betriebsmittel*	*Anzahl*
Gesamt	**Kettendozer**	
	(CAT D7H)	2
	(Komatsu D 375)	2
	Scraper	
	(CAT 657 E)	6
	(CAT 633D)	2
	Reißhakenraupe	
	(CAT D9L)	1
	(CAT D11R)	1
	Radlader	
	(CAT 992C)	4
	Grader	
	(CAT 14G)	1
	(CAT 16G)	2
	(CAT 16H)	1
	Compactor	
	(CAT 825C)	1
	SLKW	
	(CAT 777C)	6
	(Komatsu HD 1400B)	7
	Zug	
	Zug	2
	Waggons	120

Table 1: Vorhandene Betriebsmittel

	Anzahl	**Einsatzzeiten pro Jahr [h/a]**	**Spezifischer Treibstoffverbrauch [l/h]**	**Aufgewendete Energie pro Tonne Rohbauxit [MJ/t]***
CAT D7H	2	1000	29	0,15
Komatsu D375	2	1000	29	0,15
CAT 657E	6	2000	100	3,10
CAT 633D	2	2000	80	0,83
CAT 16H	1	2500	26	0,17
CAT 14G	1	2500	26	0,17
CAT 16G	2	2500	100	1,29
CAT D9L	1	2500	81	0,52
CAT D11R	1	2500	100	0,65
CAT 825C	1	1500	20	0,08
CAT 992C	3	4700	95	3,46
CAT 777C	6	4900	100	7,60
Komatsu HD 1400B	7	4900	165	14,64
Zug	1	8700	370	8,33
Gesamt (KEA_N)				***41,14***

* zugrunde gelegt ist ein Heizwert für Diesel von 37,5 MJ/l [7] und ein Bereitstellungsnutzungsgrad von 0,9.

Table 2: Spezifische Energieaufwendungen bei der Nutzung der eingesetzten Betriebsmittel [4],[5]

Der spezifische Energieaufwand bei der Nutzung der eingesetzten Betriebsmittel beträgt rd. 41 MJ/t (Tabelle 2).

Zu untersuchen ist, wie sich die Energieaufwendungen bei der Nutzung auf die einzelnen Teilprozesse verteilen. Hierzu ist es zunächst notwendig, die eingesetzten Betriebsmittel den einzelnen Teilprozessen zuzuordnen. Die Zuordnung der Betriebsmittel auf die Teilprozesse ist in Tabelle 3 dargestellt.

	Eingesetzte Betriebsmittel	Anzahl*
Aufschluß	**Kettendozer** (CAT D7H) (Komatsu D 375) **Scraper** (CAT 657E) **Grader** (CAT 16H)	 2 2 0,54 1
Wertmineralgewinnung	**Reißhakenraupe** (CAT D9L) (CAT D11R) **Radlader** (CAT 992C)	 0,6 0,6 3
Verkippung	**Scraper** (CAT 657E)	 0,36
Rekultivierung	**Reißhakenraupe** (CAT D9L) (CAT D11R)	 0,4 0,4
Periodische Arbeiten	**Kompaktor** (CAT 825C) **Scraper** (CAT 633D) (CAT 657E) **Grader** (CAT 14G) (CAT 16G) **SLKW** (CAT 777C)	 1 2 2 1 2 2
Förderung	**SLKW** (CAT 777C) (Komatsu HD 1400B) **Scraper** (CAT 657E) **Zug** Zug Waggons	 4 7 3,1 1 120

* einige Betriebsmittel finden Einsatz in mehreren Teilprozessen und müssen bei einer teilprozeßspezifischen Betrachtung anteilsmäßig zugerechnet werden.

Table 3: Verteilung der eingesetzten Betriebsmittel auf die Teilprozesse.

Es zeigt sich, daß rd. 72% der während der Nutzung eingesetzten spezifischen Energieaufwendungen auf den Teilprozeß Förderung entfallen (Bild 7). Der Zugtransport ist dabei lediglich mit rd. 27% an der Förderung beteiligt.

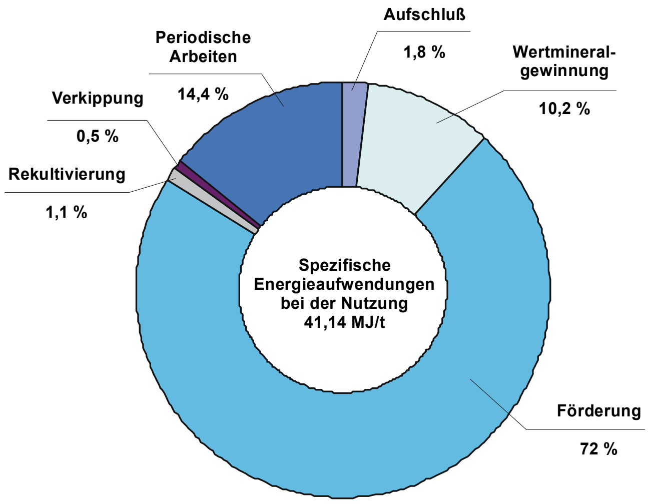

Bild 7: Prozentuale Verteilung der Energieaufwendungen während der Nutzung auf die Teilprozesse

Für die eigentliche Gewinnung werden nur rd. 10,2% verwendet (Bild 7). Auffällig ist auch der hohe Anteil periodischer Arbeiten, der sich aus Straßenbau und Staubbekämpfung zusammensetzt. Die Staubbekämpfung stellt dabei einen Anteil von rd. 60%.

Zu untersuchen bleibt der spezifische Energieaufwand, der für die Herstellung der vorhandenen Betriebsmittel aufgewendet werden mußte. Die Betriebsmittel bestehen zu über 95% aus Stahl. Daher wird vereinfachend angenommen, daß ihr KEA_H aus der Gesamtmasse der Betriebsmittel und dem massenspezifischen KEA von 3 mm dicken Stahlblech berechnet werden kann.

	Anzahl	Geschätzte Nutzungsdauer [a]	Angenommene Masse [t_{Stahl}]	Aufgewendete Energie pro Tonne Bauxit [MJ/t]*
CAT D7H	2	4	26	0,03
Komatsu D375	2	4	60	0,07

CAT 657E	6	8	76	0,13		
CAT 633D	2	8	51	0,03		
CAT 16H	1	4	27	0,02		
CAT 14G	1	4	21	0,01		
CAT 16G	2	4	27	0,03		
CAT D9L	1	7	45	0,01		
CAT D11R	1	7	96	0,03		
CAT 825C	1	6	32	0,01		
CAT 992C	4	3	88	0,27		
CAT 777C	6	8	62	0,11		
Komatsu HD 1400B	7	8	105	0,21		
Zug	2	30	125	0,02		
Waggons	12 0	30	40	0,37		
Schienen**	1	50	456 0	0,16	40	529 0
Gesamt (KEA_H)				***1,51***		

* zugrunde gelegt ist der KEA_H für die Erzeugung von bis zu 3mm dicken Stahlblech (33 GJ/t) [8].
**zugrunde gelegt ist der KEA_H für die Erzeugung von schwerem Stabstahl (26 GJ/t) [8].

Table 4: Spezifische Energieaufwendungen für die Herstellung der Betriebsmittel. [4],[5],[6]

Der spezifische Energieaufwand für die Herstellung der vorhandenen Betriebsmittel beträgt 1,51 MJ/t nur rd. 3,7%. Dies entspricht 3,7% des Energieaufwandes in der Nutzungsphase. Die energetischen Aufwendungen für die Entsorgung der Betriebsmittel konnten im Rahmen der Untersuchungen nicht erfaßt werden. Aus entsprechenden Analysen von Kraftfahrzeugen ist jedoch bekannt, daß KEA_E meist kleiner 10% von KEA_H bleibt [9]. Bezogen auf die Energieaufwendungen der Bauxitgewinnung ist KEA_E damit praktisch bedeutungslos.
Hiermit folgt ein gesamter spezifischer kumulierten Energieaufwand von rd. 42,7 MJ/t. Hiervon entfallen 3,6% auf die Herstellung und insgesamt 96,4% auf die Nutzung der Betriebsmittel (86,8% auf den Energieinhalt des Treibstoffs und 9,6% für seine Bereitstellung).

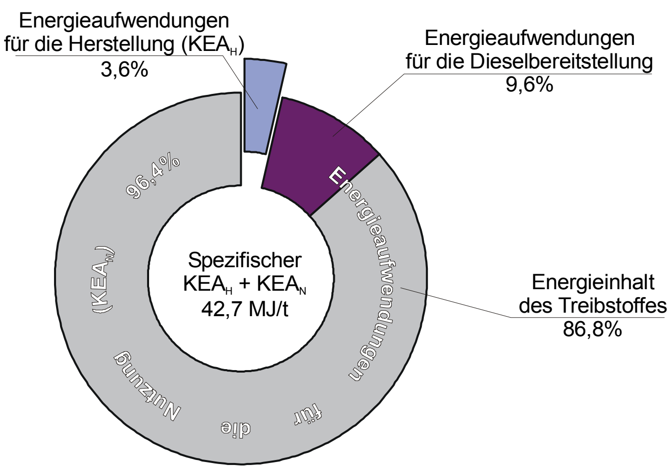

Bild 8: Prozentuale Verteilung des kumulierten Energieaufwandes auf die Herstellung und die Nutzung.

6 ZUSAMMANFASSUNG

Im Rahmen einer ganzheitlichen Betrachtung von Prozessen ist der kumulierte (primärenergetische) Energieaufwand eine wichtige Größe der energetischen Analyse.
Am Beispiel des betrachteten Bauxittagebaus wird deutlich, daß die primärenergetisch bewerteten Aufwendungen von insgesamt 42,7 MJ/ t zu 96,4% durch den Verbrauch und die Bereitstellung von Dieseltreibstoff bestimmt werden, während nur 3,6% auf die Herstellung der Betriebsmittel entfallen. Weiterhin zeigt die Analyse, daß die Bereitstellung des Treibstoffs den Energieaufwand zur Herstellung der Betriebsmittel um den Faktor 2,7 übertrifft. Für eine umfassende Analyse des mit der Gewinnung von Bauxit verbundenen energetischen Aufwands genügt daher nicht die alleinige Erfassung der als Treibstoff und Elektrizität eingesetzten Endenergien. Das Fallbeispiel zeigt darüber hinaus, daß die Energiebereitstellung im Einzelfall einen signifikanten Einfluß auf den kumulierten Energieaufwand des Bauxittagebaus ausüben kann.
Die detailliertere Betrachtung der Prozesse der Bauxitgewinnung zeigt, daß 72% des Dieselverbrauchs auf den Teilprozeß Förderung entfallen. In Hinblick auf eine energetische Optimierung

der Bauxitgewinnung scheinen daher in den Prozessen der Transporte von Wertmineral und Abraum die größten Potentiale zu liegen. Zur Abschätzung der Optimierungspotentiale - z.B. durch Substitution von dieselgetriebenen durch elektrische Maschinen - müssen im Sinne der primärenergetischen Bewertung stets auch die Prozesse der Energiebereitstellung in die Betrachtung mit einbezogen werden.

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BAUXITE QUALITY AND ITS EFFECT ON RED MUD GENERATED DURING ALUMINA PRODUCTION*

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ABSTRACT

Production of aluminium from bauxite comprises a number of phases that can be traced by a materials-flow analysis. The first stage, the Bayer Process, involves refining of bauxite, resulting in the production of alumina (Al_2O_3) and the separation of an insoluble residue from the pregnant solution. On a world-wide scale, this so-called red mud accumulates in enormous amounts and thus represents a major problem, both from an ecological and economical point of view. Depending on the quality of the bauxite and the technical lay-out of the Bayer Process, between 1.1 and 6.2 tons of red mud are generated per 1 ton of alumina produced. According to the materials input into the Bayer Process, i.e. bauxite and chemicals, the resulting red mud comprises a geogenetic and a process-related part. This study, firstly defines and characterises critical bauxite parameters that influence process conditions during digestion, secondly quantifies these parameters, and thirdly identifies optimisation potentials for a reduction of red mud production. Finally, based on these results, model calculations of geological and technical scenarios are presented that trace the flow of raw materials during the production of alumina from bauxite.

KEYWORDS

Bauxite, alumina, red mud

* Source: MEEI 98 - International Symposium on Mine Environmental and Economical Issues, Dnipropetrovsk, Ukraine, Russia, June 1999

1. INTRODUCTION

The Collaborative Research Center (CRC) 'Resource-Oriented Analysis of Metallic Raw Material Flows' was established at the University of Technology Aachen (RWTH) to development methodologies for a resource-sensitive utilisation of metallic raw materials within the framework of economic, environmental and social constraints.

In a first phase, the program focuses on the analysis of materials flow associated with bauxite, alumina, and aluminium production. The evaluation of geologic characteristics of bauxite deposits and their effects on subsequent technical processes represents the first step in this analysis.

Modeling of the bauxite-alumina-aluminum flow is based on the classification and quantification of materials input and resulting output during ore extraction, and processing and manufacturing of goods, to the ultimate disposition of waste.

The present study investigates the first phase of the aluminium production cycle, namely how the quality of input materials, i.e. bauxite, effects the processing of alumina and the resulting generation of red mud.

Bauxite is the most important raw material for the production of alumina and aluminium.
More than 80% of the world's bauxite production is extracted from shallow open-pit mines. In 1996, world-wide bauxite production amounted to about 123 million tons with the leading bauxite producing countries including Australia (35 %), Guinea (15 %), Jamaica (10 %) and Brazil (9 %).

On a world-wide scale, the raw material used for the production of primary aluminium is almost exclusively bauxite. In 1996, the world-wide alumina production was close to 44.5 million tons. The principal alumina producing countries compriese Australia (30 %), U.S.A. (10 %), the former USSR (10 %), Jamaica (7 %) and Brazil (6 %).

The most common digestion process for aluminium oxide production is based on the wet-chemical extraction of alumina (Bayer Process). In this way, the bauxite is digested in a caustic soda solution, with the addition of other chemicals such as CaO and flocculants. About 90-95% of the aluminium contained in the ore dissolves to form the pregnant solution. The insoluble residue, the so-called red mud, consists of iron oxides, silicate-bound Al, quartz, chemicals not used-up during the process, as well as non-recoverable caustic soda. The red mud is separated from the digestion liquor before the precipitation of trihydrate aluminium oxide. To minimise loss of caustic soda the red mud is washed before final disposition.

As was briefly stated before, one of the main aims of this study is the identification and quantification of bauxite characteristics that influence the technical conditions during the Bayer Process. This information is then taken to model geographic and technical scenarios, with the help of which the flow of bauxite and other raw materials during the production of alumina can be traced and whereby waste at the source of the material can be reduced.

2. DATABASE

2.1 *Bauxite quality*

Mineralogic and chemical characteristics of bauxite have a significant effect on the availability of aluminium and the nature and quantity of resulting waste material in the subsequent technical process. Therefore, the development of methods for a mine-scale, regional, and global evaluation of bauxite-quality and related materials flow has to be performed through the investigation of the following steps:

- selection of geologic criteria relevant to alumina production (chemistry and mineralogy of the ore)
- selection of critical indicators for the assessment of bauxite-quality (bauxite-to-alumina ratio and red mud-to-alumina ratio)
- global analysis of bauxite, alumina and red mud flows resulting from bauxite processing
- assessment of possible future material flows

Detailed information on the chemical and mineralogical composition of bauxite from a distinct deposit or district enables calculation of materials flow (i.e. bauxite, alumina, red mud) involved with bauxite processing. As mentioned above, red mud constitutes by far the most voluminous waste generated by that process. The dry, solid portion of red mud that results from bauxite input only, is termed here 'geogenetic red mud'. The annual minimum amount of geogenetic red mud (red mud_{geog}) produced, given in metric tons, is calculated by using the following equation (Hausberg et al., 1998):

$$\text{Red mud}_{geog} = PR - \frac{PR \cdot (LOI + av.Al_2O_3)}{100} \quad [\text{metr. t}]$$

where PR = annual bauxite production in metric tons; LOI = average loss on ignition of the bauxite in weight-%; and av.Al2O3 = average available alumina content of the bauxite in weight-%. The calculation of the potential amount of red mud contained in bauxite deposits world-wide reprsents the basis for the assessment of waste disposal strategies (see Chapter 2.3).

The mineralogical composition of bauxite is a critical parameter for the technical set-up of the Bayer-process (e.g. digestion temperature, NaOH-, CaO-, flocculants input, see also Chapter 2.2). Table 1 provides an estimation of the proportions of bauxite-types mined world-wide, based on the occurrence of principal bauxite minerals.

Table 1. Mineralogical types of bauxite and their proportions of current world production.

Bauxite Type	Proportion of World Production
gibbsitic (< 3% boehmite)	65 %
gibbsitic (> 3% boehmite)	26 %
boehmitic	3 %
diasporic	6 %

Bauxite-quality, as it is understood in the context of the present study, can be defined by two parameters (Tab. 2): firstly, the amount of dry bauxite required to produce a certain amount of alumina (bauxite-to-alumina ratio), and secondly, the amount of red mud resulting from the production of a certain amount of alumina (red mud-to-alumina ratio).

Table 2. Range of mass ratios used for defining bauxite-quality. Data base includes 61 operating mines world-wide.

	Min	Max	∅
bauxite/alumina ratio	1.8	3.2	2.3
red mud/alumina ratio	0.3	1.5	0.7

Bauxite-quality varies considerably for each deposit or district which is an expression of the highly heterogeneous, site-specific chemical and mineralogical characteristics of the ore. Therefore, a global analysis of material flows necessitates the calculation of quality indicators for each deposit first, and following that, the data can be aggregated to a global model.

The additional integration of quality-data from non-operating deposits (i.e. in an exploration or feasibility phase), which are an indication of material flows that can be expected to occur in the next decades, enables prediction of probable changes in bauxite-quality in the future. Figure 1 compares red mud-to-alumina ratios of operating mines with deposits that are currently at a feasibility or exploration status. It can be seen from the model that, on a global scale, red mud-to-alumina ratios of non-operating deposits are significantly higher compared to those of currently operating mines. This suggests a potential reduction of bauxite-quality in the future.

Bauxite supply scenarios, as will be discussed later in chapter 4, are mainly based on the comparison of bauxite reserves from operating and non-operating deposits.

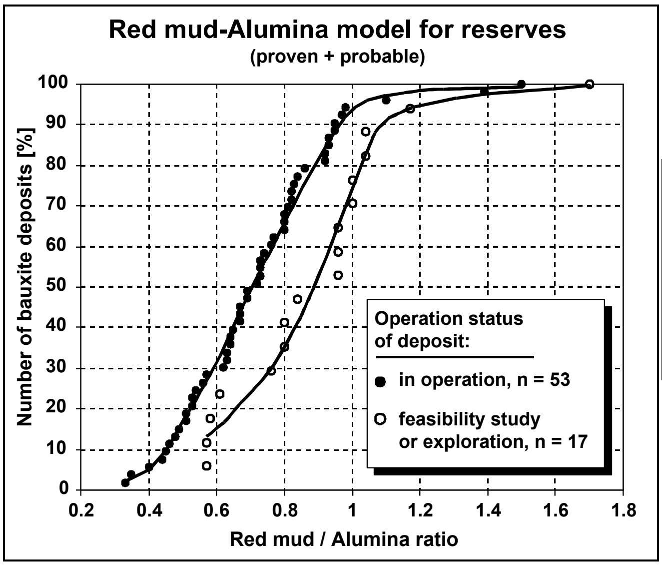

Figure 1. Global quality model (grade model) for bauxite reserves world-wide. Comparison of the Red mud-to-Alumina ratio for operating and non-operating deposits.

2.2 *Alumina production*

Alumina is extracted from bauxite in which aluminium occurs in form of gibbsite [$Al(OH)_3$], boehmite and diaspore [α- and γ-AlOOH] and kaolinite [$Al_2(OH)_4(Si_2O_5)$]. The bauxite is digested in hot caustic soda solution. If the process temperature is too low, the Al-minerals are not dissolved completely and separated with the red mud. Uner certain conditions, already dissolved alumina can recrystallize and will be lost with the red mud, too. These losses can affect up to 3-5 % of already dissolved alumina, but may be even larger if a caustic ratio ? is applied in order to increase the productivity of alumina (Das, 1997; Murgia et al., 1991).

If the digestion process is controlled inefficiently, alumina can be lost as a result of a short retention time and/or insufficient degree of reduction. It can be shown that digestion yields of ≤ 100 % increase the amount of red mud according to the following equation.

$$\text{Mass increase}_{\text{red mud}} = Al_2O_{3\,\text{available}}^{\text{theoretical}} \cdot \left(1 - \frac{\text{yield}}{100}\right)$$

As is shown in Table 3 various types of bauxite differ considerabaly with regard to extraction yields of available alumina (Schepers et al. 1974, Paspaliaris et al., 1996)

Table 3. Alumina extraction yield for different types of bauxite

Bauxite Type	Minimum Yield %	Maximum Yield %
gibbsitic (< 3 % boehmite)	100	95
gibbsitic (> 3% boehmite)	95	90
boehmitic	90	85
diasporic	90	57

New phases are formed during the incongruent dissolution of kaolinite, which precipitate and increase the amount of red mud, too. They also contain caustic soda. The losses of caustic soda can be reduced by adding lime to the liquor during digestion

Reactive silica (as kaolinite):

$$Al_2(OH)_4(Si_2O_5) + 6OH^- + H_2O <=> 2SiO_2(OH)_2^{2-} + 2\,Al(OH)_4^- \quad (1)$$

Sodium aluminium hydro silicate (k=0-2)

$$2SiO_2(OH)_2^{2-} + 2\,Al(OH)_4^- + 2Na^+ <=> Na_2O{*}Al_2O_3{*}2SiO_2{*}(2+k)H_2O + 4OH^- + (2-k)H2O \quad (2)$$

At higher temperature (digestion temperature):

$$3(Na_2O{*}Al_2O_3{*}2SiO_2{*}2H_2O)Na_2X \text{ with X: } 2OH^-, CO_3^{2-}, SO_4^{2-}, 2Cl^-, 2AlO_2^- \quad (3)$$

Na-Ca-cancrinite formation

$$Na_8(Al_6Si_6O_{24})(OH)_2{*}3H_2O + CaO <=> Na_6Al_6Si_6O_{24}{*}CaCO_3{*}3H_2O \quad (4)$$

Hydrogarnet formation:

$$Na_6Al_6Si_6O_{24}{*}CaCO_3{*}3H_2O + CaO + FeOOH <=> Ca_3(Fe_{1-y}Al_{1+y})(SiO_4)_{3-x}(OH)_{4x} \quad (5)$$

The increase of the red mud depends also on the amount of reactive silica in the bauxite. This relationship is shown in Table 4, where according to above chemical reactions the mass gain of red mud is calculated per kg or %, respectively, of reactive SiO_2 present.

Table 4. Mass increase of red mud due to the formation of sodalithe, cancrinite and hydrogarnet (numbers refer to equations shown above)

Equation	Increase of Red Mud	
	kg/kg SiO_2	kg/% SiO_2
(2)	+ 0.513	+ 5.13
(3) with X = OH^-	+ 0.688	+ 6.88
(3) with X = AlO_2^-	+ 0.972	+ 9.72
(4)	+ 0.672	+ 6.72
(5)	+ 2.800	+ 28.00

The calculations assume that the difference in the alumina content of bauxite (i.e. total Al_2O_3 minus theoretically available Al_2O_3) is solely attributable to the presence of kaolinite. Ideally, kaolinite contains 39.5 % Al_2O_3 and 46 % SiO_2. The common reaction that consumes silica is according to equation (5) while reactions following equation (5) do only rarely occur. Thus, the mass gain of red mud can be calculated using following equation:

$$\text{mass increase}_{\text{red mud}} = \left(Al_2O_{3\text{total}} - Al_2O_{3\text{available}}^{\text{theoretical}}\right) \cdot \frac{0{,}46}{0{,}395} \cdot \text{mass increase}_{SiO_2}$$

The content of titanium dioxide in the bauxite ranges from 1-4 %. TiO_2 also reacts with caustic soda during the digestion process to form sodium titanate or sodium metatitanate, in the presence of calcium titanate. The reaction rate of TiO_2 depends on the amount of available lime and the reaction time (Schepers et al. 1974, Shiwen et al.1996).

sodium titanate formation:

$TiO_2 + Na_2O <=> Na_2TiO_3$ (6)

sodium metatitanate fomation:

$2TiO_2 + Na_2O <=> Na_2Ti_2O_5$ (7)

calcium titanate formation :

$TiO_2 + CaO <=> CaTiO_3$ (8)

Consequently, the amount of the red mud increases per kg or % TiO_2 , respectively, according to following equations:

Table 5. Mass increase of red mud due to the by formation of titanate.

equation	increase of red mud mass	
	kg/kg TiO_2	kg/% TiO_2
(6)	+ 0.775	+ 7.75
(7)	+ 0.390	+ 3.90
(8)	+ 0.700	+ 7.00

It is assumed that in a minimum case about 1 % TiO_2 in the bauxite reacts according to equation (7). In other case bauxite may contains as much as 4 % TiO_2, which reacts then according to equation (6). The TiO_2 contribution to the red mud generated can be calculated as follows.

$$\text{Mass increase}_{\text{red mud}} = \text{Bauxite} \cdot \frac{\%TiO2}{100} \cdot \text{mass increase}_{TiO2}$$

In addition, the red mud will also contain some caustic soda and alumina dissolved in the liquor which is impossible to entirely separate from the residue. Depending on the efficiency of washing the residue, the liquor bound to the red mud may consist of 3-12 g Na_2O/l or 3-12 kg Na_2O/m^3, and 3-12 g/l Al_2O_3 or 3-12 kg Al_2O_3/m^3. Obviously, the technique used to dewater the red mud has a considerable influence on the efficacy of the process (Nunn et al. 1998).

Table 6. Alumina extraction yield for different types of bauxite

	Liquor Volume [m^3/t solids in red mud]	Solids in Filter Cake [%]
Conv. thickener	2.2	20-30
Deep thickener	1.1	50
Super-thickener	1.1	50
Vacuum filter	0.8	55-55
Hyperbaric-filter	0.3	70-80

Depending on washing efficiency and dewatering technology the mass increase of red mud can be calculated as follows:

$$\text{Mass increases}_{\text{red mud}} =$$
$$\text{Vol.} \cdot \left(\text{mass}_{Na_2O} + \text{mass}_{Al_2O_3}\right)$$

where Vol is the liquor volume /t solids in red mud and $\text{mass}_{Na2O}/\text{mass}_{Al2O3}$ the amount of free caustic soda/alumina in the liquor

The accumulative mass of red mud is further increased by the loss on ignition (LOI), which is mainly a measure of the amount of crystal-bound water in hydrous silicates but which is also affected by CO_2 in carbonates and SO_2 in sulphides. For the following calculation a minimum of 5 % and a maximum of 10 % LOI was assumed. Accordingly, the mass gain of red mud is:

$$\text{Red mud}\left(\text{including LOI}\right) =$$
$$\text{Red Mud}_{\text{dry basis}}\left(1+\frac{\text{LOI}}{100}\right)$$

2.3 *Waste disposition*

After separation from the pregnant solution, the resulting red mud is commonly stored in tailings ponds or waste dumps because, up to date, there is no way of its economic utilization. At some locations, however, the red mud may not be stored in controlled disposal sites but may be dumped even into the sea.

Focusing on red mud disposition techniques, the industry basically relies on five different methods of red mud disposal, of which 3 are based on wet and two on dry transport conditions for the waste material. Other technical variations include the presence or absence of drainage and sealing devices in the transportation system, and also the geometry of the disposal site. In the following, the five commonly employed disposal practices are explained in more detail.

Shortly after the digestion process was developed it became clear that the losses of caustic soda must be kept to a minimum in order to keep the costs for the production of alumina low. Therefore, parts of the lye with high contents of soda are separated from the red mud by means of thickener, thus increasing the solid content to 20 – 30 %. For that purpose three different methods were developed for subsequent disposal. In the “conventional pond system” method, a pond with simple basis sealing is constructed. Further technical devices such as the installation of a drainage system are not provided. The second method uses a basis drainage system which is installed in a filter sand, thus enhancing a further consolidation of the red mud. With the “solar drying” method layers of red mud are stored on slopes with low inclinations so that intensive irradiation by the sun is used to dry the red mud and reduce the water content to a minimum.

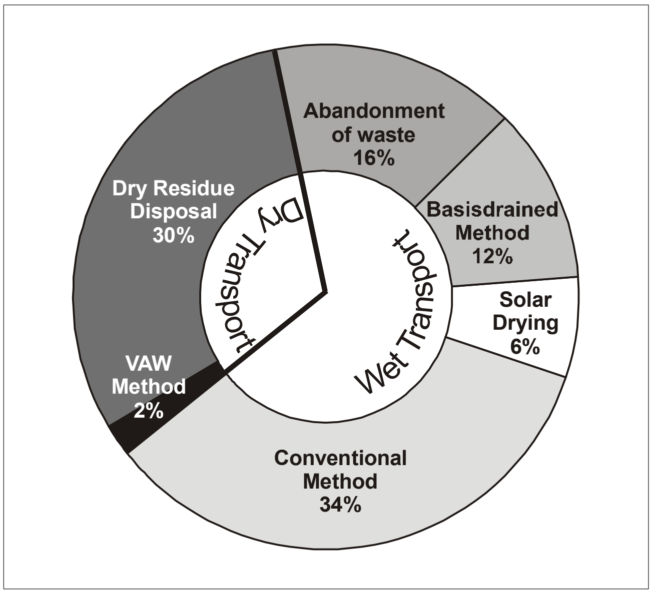

Figure 2. Percentage proportions of various disposal techniques used for the storage of red mud.

Over the past 20 years new techniques have been developed for the conditioning of red mud which allow the discards to be thickened to up to 55 %. These techniques mostly use filters or super-thickeners. The subsequent dispossition takes place either by use of the VAW-method or by use of the dry residue disposal method. By the VAW-method the disposal site is constructed level-wise. Horizontal and vertical drainage as well as sealing is provided for in the individual levels. By the dry residue disposal method the disposal site is divided into several drying segments. The concentrated red mud is put on an a shallow sloping plane where it is left to dry. After one layer has dried, another layer is put on top.

Figure 2 illustrates the percentage proportions of the disposal techniques used world-wide. It is interesting to note that about

16% of the red mud is not stored in proper disposal sites.

The consolidated red mud is composed of a the geogenetic and a process-related portion and water.

$$m_{RMconsol} = m_{RMgeog} + m_{RMprocess} + m_{RMwater}$$

For disposition of red mud the distinction between m_{RMgeog} and $m_{RMprocess}$ is irrelevant and both parameters can be considered constant for a particular technical set-up of the Bayer Process. Significant differences may, however, occur in the water content of the consolidated red mud and this, in turn, has a direct influence of the disposal technique used.

Figure 3 shows the relationship between the water content w' of red mud and the resulting density D_{RM}. It is obvious from the figure, that by using the 'solar drying method' (with a water content w' = 25 %) the density (D) of the consolidated red mud is 2.08 t/m^3, whereas applying the conventional method (with a water content of w' = 45 %) the density is reduced to not more than 1.63 t/m^3.

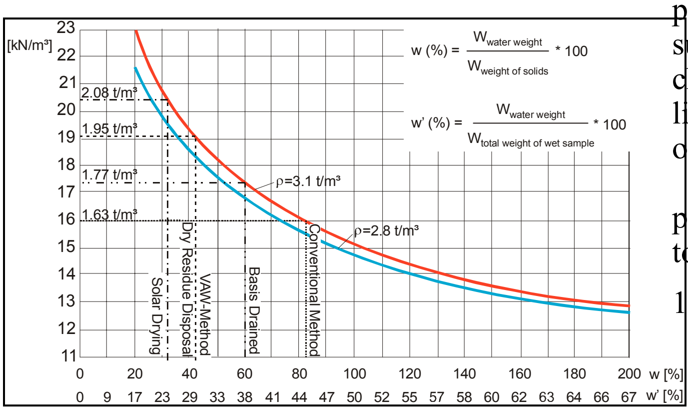

Figure 3. The effect of water contents of red mud on total unit weight (modified after Lotze, 1982)

With the above graph mass and volume of red mud accumulating from the various methods can now be calculated on the basis of density and water content of the consolidated red mud (Fig. 3). This data is expressed as factors that can be allocated to the respective disposal methods.

Table 7. Disposal methods with specific parameters

Disposal Method	Density [t/m^3]	Moisture [%]	m_{consol} [t]	V_{consol} [m^3]
Conventional Method	1.63	45%	1.82* m_{dry}	1.11*m_{dry}
Basisdrained Method	1.77	38%	1.61* m_{dry}	0.91 *m_{dry}
Solar Drying Method	2.08	25%	1.33* m_{dry}	0.64 *m_{dry}
Dry Residue Disposal	1.95	30%	1.43* m_{dry}	0.69 *m_{dry}
VAW – Method	1.95	30%	1.43* m_{dry}	0.69 *m_{dry}

4. SCENARIO EVALUATION

The mass of red mud annually accumulating from bauxite processing is only inadequately known and commonly not considered in mass flow studies. The range of options available for the technical set-up of the Bayer Process, for applying the optimal method for red mud disposition, and for selecting the best suitable bauxite quality provides significant potential for optimization of process and in-put parameters. With the definition of scenarios using bauxite quality and available technology a quantitative assessment of the most critical parameters can be obtained. The evaluation of such scenarios allows comparison of possible changes in red mud quantities, by selecting a limited number of critical variables and keeping other parameters constant.

In the following, two principal options for parameter selection are discussed with the aim to evaluate their effect on red mud quantities:

1. Currently available bauxite quality versus bauxite quality that is expected to be available in the future, whereby technical parameters are kept constant.
2. Best available technology and set-up for the Bayer Process and disposal methods versus worst available technology, whereby bauxite quality is kept constant.

Combination of these principal variables leads to the definition of four scenarios:

1. Bauxite of known quality extracted form currently operating deposits, processed by Bayer plants and disposal sites using best available technology.
2. Bauxite of known quality extracted form currently operating deposits, processed by

Bayer plants and disposal sites using worst available technology.

3. Bauxite of predicted quality to be extracted in future from deposits that are currently in an exploration or feasibility stage, processed by Bayer plants and disposal sites using best available technology.
4. Bauxite of predicted quality to be extracted in future from deposits that are currently in an exploration or feasibility stage, processed by Bayer plants and dispositon sites using worst available technology.

Scenarios 1. and 3. consider future the demand for theoretically available alumina to be constant. Variations in resulting red mud quantities refer exclusively to changes in ore quality of deposits to be mined in future.

The amount of consolidated red mud (after disposal) consists of (see Table 8):

1. the geogenetic portion, that results from bauxite feed only,
2. the process related portion that consists of insoluble Al_2O_3, sodalithe, titanite, free soda and water added in the Bayer Process, and
3. the output of red mud from the Bayer Process modified by subsequent method of disposal

Comparison of operating and non-operating deposits suggests a potential reduction of bauxite-quality in the future (see paragraph 2.1), or in other words, even by keeping current alumina demand constant, the world total bauxite supply has to be increased considerably from 109 to 121 million metric tons. Consequently, this results in an increase of the total amount of red mud from currently 60 to 71 million metric tons in the future (Figure 4).

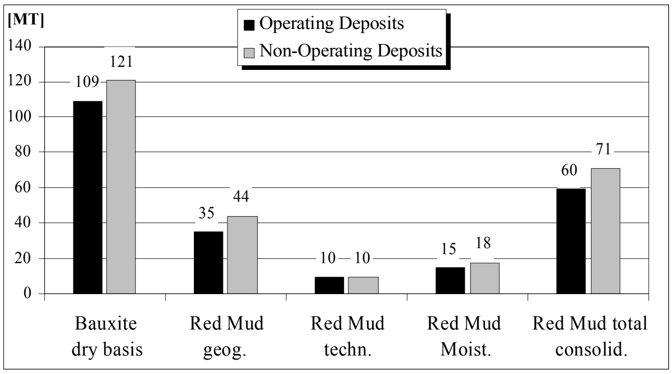

Figure 4. Comparison of current and future bauxite quality and resulting output of alumina and red mud. Note that the technical set-up of the Bayer Process and disposal technique as well as future demand for alumina are taken to remain constant.

If we considering worst case scenarios, both for the Bayer Process as well as for the disposition techniques (i.e. examples 2 and 4), the calculations indicate that the amount of available alumina may be reduced by up to 10% (Figure 5). Furthermore, the world total amount of red mud increases dramatically from 60 to 131 million metric tons.

Table 8. Variation in bauxite, alumina and red mud quantities resulting from different bauxite supply- and technical sceanrios (see text).

	TECHNICAL SETTINGS	BAUXITE Dry Basis Metallurgical Grade No Substitutes			ALUMINA total theoret.		ALUMINA available theoret.		ALUMINA available effective		RED MUD geogen. dry basis		RED MUD technical NS Al_2O_3	Sodalithe	Titanate	LOI	Soda+Al_2O_3	total dry basis	deposit. moist.	total consolid.
		Min. Type	%	MT	%	MT	%	MT	%	MT	%	MT	MT	MT	MT	MT	MT	MT	MT	MT
OPERATING DEPOSITS	Optimized	1	65	70,9	61	33	61	28,6	62,5	28,6	69	24,2	0,00	3,53	0,28	1,47	0,134	29,61	9,77	39,4
		2	26	28,3	28	15,1	28	13,1	27,2	12,4	23	8,1	0,66	1,60	0,11	0,55	0,050	11,07	3,65	14,7
		3	3	3,3	3	1,6	3	1,4	2,8	1,3	2	0,7	0,14	0,16	0,01	0,05	0,005	1,07	0,35	1,4
		4	6	6,5	8	4,3	8	3,8	7,5	3,4	6	2,1	0,38	0,40	0,03	0,15	0,014	3,07	1,01	4,1
		Total	100	109	100	54	100	46,9	100	45,7	100	35,1	1,18	5,69	0,43	2,23	0,20	44,82	14,79	**59,6**
	Less Optimized	1	65	70,9	61	33	61	28,6	64,2	27,2	69	24,2	1,43	14,35	0,55	4,50	0,892	45,92	37,66	83,6
		2	26	28,3	28	15,1	28	13,1	27,9	11,8	23	8,1	1,31	6,52	0,22	1,79	0,355	18,30	15,01	33,3
		3	3	3,3	3	1,6	3	1,4	2,8	1,2	2	0,7	0,21	0,65	0,03	0,18	0,035	1,80	1,48	3,3
		4	6	6,5	8	4,3	8	3,8	5,1	2,2	6	2,1	1,63	1,63	0,05	0,60	0,119	6,14	5,03	11,2
		Total	100	109	100	54	100	46,9	100,0	42,3	100	35,1	4,58	23,15	0,84	7,08	1,401	72,16	59,17	**131,3**
NON-OPERATING DEPOSITS	Optimized	1	68	77	66	35,4	66	30,9	67,1	30,9	61	26,7	0,00	3,61	0,30	1,61	0,147	32,36	10,68	43,0
		2	30	40	32	17,5	32	15	30,9	14,3	37	16	0,75	2,00	0,16	1,00	0,091	20,00	6,60	26,6
		3	1	2	1	0,6	1	0,5	1,0	0,5	1	0,5	0,05	0,08	0,01	0,03	0,003	0,67	0,22	0,9
		4	1	2	1	0,6	1	0,5	1,0	0,5	1	0,3	0,05	0,08	0,01	0,02	0,002	0,46	0,15	0,6
		Total	100	121	100	54,1	100	46,9	100,0	46,1	100	43,5	0,85	5,77	0,47	2,66	0,243	53,50	17,65	**71,1**
	Less Optimized	1	68	77	66	35,4	66	30,9	67,4	29,4	61	26,7	1,55	14,67	0,60	4,84	1,149	49,50	40,59	90,1
		2	30	40	32	17,5	32	15	31,0	13,5	37	16	1,50	8,15	0,31	2,88	0,685	29,53	24,22	53,7
		3	1	2	1	0,6	1	0,5	1,0	0,4	1	0,5	0,08	0,33	0,02	0,10	0,024	1,04	0,85	1,9
		4	1	2	1	0,6	1	0,5	0,7	0,3	1	0,3	0,22	0,33	0,02	0,10	0,023	0,97	0,80	1,8
		Total	100	121	100	54,1	100	46,9	100	43,6	100	43,5	3,34	23,48	0,94	7,92	1,881	81,05	66,46	**147,5**

Explanations: Min. Type = Mineralogy Type (see Table 1); MT = Million Metric Tons; geogen. = geogenetic portion of red mud; NS Al2O3 = unsolved alumina;
Soda + Al2O3 = free soda and alumina; deposit. moisture = free moisture in consolidated red mud; total consolid. = final (consolidated) amount of red mud after disposal

This significant increase of total red mud is not related to changes in bauxite quality but is mostly due to an increase of process-related insoluble residue and water content, both of which increase by almost 400%.

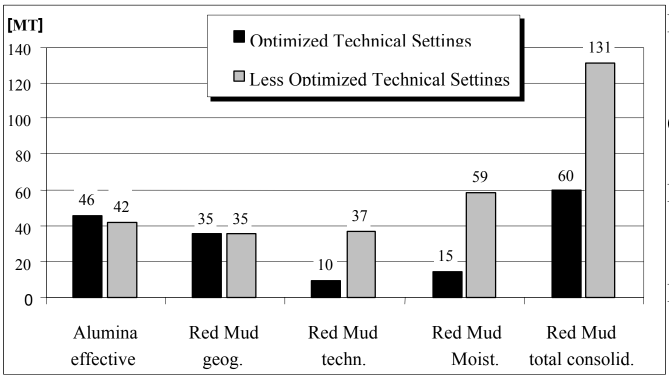

Figure 5. Comparison of optimized and less optimized technical settings of Bayer-process and waste disposal strategies for operating deposits Note that bauxite quality (i.e. chemistry and mineralogy) is assumed to be constant.

5. SUMMARY AND CONCLUSION

The present study uses an interdisciplinary methodical approach for the qualitative assessment of geological and technical effects on red mud generation during alumina production from bauxite.

It can be shown that the optimization of critical technical parameters may result in an considerable reduction of red mud. In particular, the use of lime in the Bayer Process as well as the treatment of red for final disposition indicates significant optimization potentials. In addition, unfavorable mineralogical and chemical properties of bauxite also have a negative influence on resulting red mud quantities. In contrast to the technical parameters, deposit-specific geological constraints are mostly a given fact. Thus, the optimization and integration of geological parameters can only be achieved through a regional or global resource management.

The integrated approach adopted in this study was designed to analyze various stage of materials flow involved in alumina production, from the source of the material to its ultimate disposition. This allows identification of critical input parameters and process stages where material flow and related waste generation can be minimized.

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QUANTIFIZIERUNG EXTERNER EFFEKTE IM BAUXITBERGBAU UND BEI DER TONERDE-HERSTELLUNG*

(QUANTIFICATION OF EXTERNAL EFFECTS OF BAUXITE MINING AND ALUMINA PRODUCTION)

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ABSTRACT

Industrial activities have both positive and negative external impacts . These impacts need to be quantified within the framework of a holistic process analysis. This paper deals with both bauxite mining activities and alumina production in Jamaica. Jamaica is one of the most important producers of these commodities. Currently, four companies are active in this field. The bauxite, which is covered by thin overburden, is extracted in open pit mines and refined to alumina or exported. External impacts caused by such activities can be, for example, income effects, land use or dust emissions. A standardised monetarisation of impacts is possible using two methods: the willingness-to-pay method and the cost-avoidance approach. When the willingness-to-pay method is implemented in Jamaica, the fact that compensation has already been paid out for certain impacts must be taken into consideration because only a selected number of affected people can then be interviewed with regard to their willingness-to-pay. The cost-avoidance approach was based on investments implemented by plant operators or on impact-avoidance measures taken by individuals. Not only the monetarisation of external effects can be tested in Jamaica but also five concepts of their internalisation have been identified. The recent discussion on internalisation of external costs can be stimulated by these five concepts.

KEYWORDS

Bauxite, alumina, externalities, monetarisation, willingness-to-pay-method, cost-avoidance-approach, internalisation

* Source: Erzmetall 54 (2001), Nr. 5, pp 255-263

Vorbemerkungen

Im Jahr 1997 wurde von der Deutschen Forschungsgemeinschaft (DFG) der Sonderforschungsbereich (SFB) 525 mit dem Titel „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe – Entwicklung von Methoden und ihre Anwendung“ an der RWTH Aachen eingerichtet.

Ziel ist die Entwicklung von Entscheidungshilfen für eine ressourcenschonende Nutzung metallischer Rohstoffe im Spannungsfeld ökonomischer, ökologischer und anderer gesellschaftlicher Zielsetzungen. Dazu kooperieren im Sonderforschungsbereich Ingenieure, Naturwissenschaftler und Wirtschaftswissenschaftler aus 12 Lehrstühlen und Instituten der Rheinisch-Westfälischen Technischen Hochschule Aachen (RWTH) und einer Programmgruppe des Forschungszentrums Jülich.

Gegenstand der Untersuchung sind die primären Bereitstellungsprozesse metallischer Rohstoffe, die von der Genese über Gewinnung, Aufbereitung und Verhüttung bis zur Verarbeitung reichen, die sekundären Bereitstellungsprozesse (Recycling) und die Entsorgung. Die Untersuchung erfolgt ganzheitlich und berücksichtigt neben den technischen Aspekten insbesondere auch ökonomische und ökologische sowie soziale Aspekte. Zur Betrachtung von externen Effekten von Prozessen, dadurch verursachten Kosten und Möglichkeiten ihrer Internalisierung arbeitet das Teilprojekt 8 „Ressourcenökonomische Bewertung von Stoffströmen“ mit verschiedenen Teilprojekten zusammen. Die vorliegende Arbeit entstand in Kooperation mit dem Teilprojekt 2 (Gewinnung) und befasst sich mit der Quantifizierung externer Effekte der Aluminiumindustrie Jamaikas.

In Jamaika sind derzeit vier Unternehmen im Bauxitbergbau und in der Tonerde-Herstellung aktiv: die ALCAN Jamaika Co. (93 % Alcan/Kanada, 7 % staatlich), die Aluminium Partners of Jamaica (Alpart: 65 % Kaiser/USA, 35 % Hydro Aluminium/Norwegen), Clarendon Alumina Production Ltd. (Jamalco: 50 % Alcoa/USA, 50 % staatlich) und Kaiser Jamaica Bauxite Co. (51 % staatlich, 49 % Kaiser/USA. Die staatlichen Anteile an den Firmen werden von den Jamaica Bauxite Mining Co. vertreten, die dem Ministry of Mines and Energy zugeordnet ist. Die Bauxitproduktion in Jamaika belief sich insgesamt auf 11.988.000 t (1997), 12.674.000 t (1998) und 11.699.000 t (1999). Damit stand Jamaika an zweiter bzw. dritter Stelle der Bauxitproduzenten weltweit.

Die Untersuchungen wurden in den Kirkvine Works (Bauxit-Abbau und Tonerde-Produktion) der Firma ALCAN in der Nähe von Mandeville, Provinz (Parish) Manchester, Jamaika, durchgeführt. Die Auswahl des Standortes wurde getroffen während einer Exkursion im Rahmen des „International Workshop on Rehabilitation of Mined Bauxite Lands and Red Mud Disposal Ponds“, die Anfang Oktober 1998 stattfand und an der eine Reihe von Mitgliedern des SFB 525 teilnahmen.

Beim Stoffstrom Aluminium treten die wesentlichen externen Effekte im Bauxit-Bergbau und bei der Tonerde-Herstellung auf. Jamaika eignet sich für eine Untersuchung dieser Effekte, da beide Prozesskettenbereiche dort vertreten sind.

2. Lagerstätte, Technische Ausstattung und Prozesse

Bei den durch die Kirkvine Works abgebauten Lagerstätten handelt es sich um Karstbauxite, welche geografisch dem Karibischen Bauxitgürtel angehören. Aufgrund ihrer lagerstättenkundlichen Parameter werden sie zu den mediterranen Lagerstättentypen gezählt. Sie sind ausschließlich an die Karstoberflächen der White Limestone Formation gebunden und zeichnen sich durch eine unregelmäßige Kontaktfläche zu dieser aus. Die einzelnen Lagerstätten zeigen eine taschenförmige Ausbildung mit Erzmächtigkeiten zwischen 6 m und 8 m (Abbauwürdigkeit bei ca. 2 m) und variieren stark in ihrer Größe. Die Lagerstätteninhalte belaufen sich auf 30.000 bis 1.000.000 t Bauxit. Aus Gründen der Qualitätssteuerung werden mehrere Lagerstätten gleichzeitig abgebaut. Abbildung 1 zeigt einige Einzellagerstätten auf einer Luftaufnahme.

Über dem Bauxit befindet sich in der Regel eine bis zu 0,5 m mächtige Schicht kulturfähigen Bodens. Diese wird, nachdem die Vegetationsdecke entfernt ist, mit Scrapern oder Bulldozern am Rand des Abbaubereiches aufgehaldet. Anschließend wird der Bauxit im Tagebau gewonnen, indem er mit Draglines (Abbildung 2) oder Hydraulikbaggern auf SLKW mit 50 - 110 t Kapazität geladen und durchschnittlich etwa 4,5 km zu einem zentralen Bunker transportiert wird.

Abbildung 1: Luftaufnahme von Bauxitlagerstätten

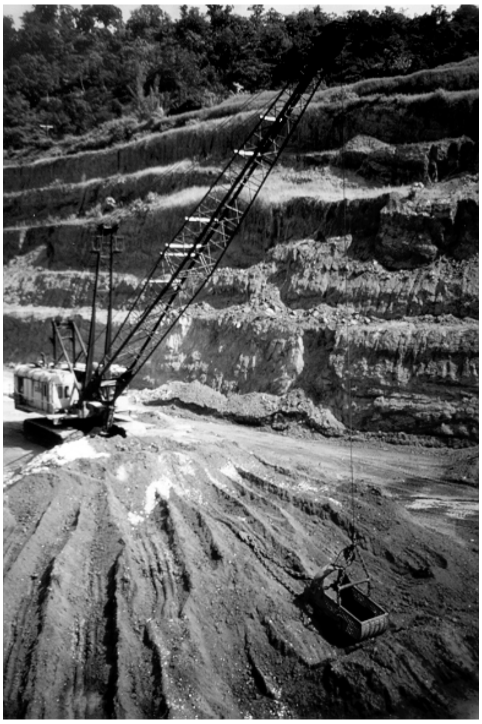


Abbildung 2: Einsatz eines Dragline am Standort Kirkvine

Von diesem wird eine 7,8 km lange Bandanlage beschickt, die den Bauxit zur Tonerde-Fabrik fördert. Seit der Fertigstellung einer Erweiterung von 5,3 auf 7,8 km im Mai 1995 ist diese zur Verminderung von Staubemissionen zu ca. 90 % eingehaust und besitzt eine Förderkapazität von 1.000 t/h. Auf dem Gelände der Tonerdefabrik wird das Erz auf einer Halde zwischengelagert, bevor es nach dem Bayer-Verfahren bei hohem Druck und hohen Temperaturen unter Zugabe von Natronlauge zu Al_2O_3 verarbeitet wird. Der bei diesem Prozess als Abfallprodukt anfallende Rotschlamm wird auf einen Feststoffgehalt von 20 - 30 % eingedickt und nach dem ‚solar drying'-Verfahren deponiert. Dabei wird der Rotschlamm lagenweise auf Hänge mit geringer Neigung in definierten Becken, die mit einer Basisabdichtung aus Lehm oder Kunststofffolie versehen sind, aufgetragen und durch die intensive Sonneneinstrahlung getrocknet. Aus dem Überschusswasser, das sich am Fuß der Deponie sammelt, wird Natronlauge für den Bayer-Prozess zurückgewonnen. Abbildung 3 zeigt eine Rotschlammdeponie.

Abbildung 3: Rotschlammdeponie

3. Identifizierung externer Effekte

Sowohl bei der Gewinnung und der Förderung des Bauxits als auch bei der Tonerde-Produktion treten ein Reihe von externen ökologischen und sozioökonomischen Effekten auf. Dabei sind an wichtigen ökologischen Wirkungen des Erzabbaus zu nennen:

- die Flächeninanspruchnahme durch den Erzabbau: die offene Tagebaufläche in Kirkvine beträgt 40-50 ha, da stets 3-4 Abbaupunkte in der Förderung stehen, um eine Mischung der Erztypen zu ermöglichen. Die Flächeninanspruchnahme ist temporär, da ausgeerzte Flächen nach kurzer Zeit wieder kultiviert werden. Das trifft nicht zu auf die ca. 50 ha, die für Straßen, Förderband und Betriebsanlagen genutzt werden. Die landschaftsorientierten externen Effekte der Flächeninanspruchnahme können also auf Vegetationsverlust bzw. Verlust an landwirtschaftlicher Nutzfläche in der Größenordnung von 100 ha veranschlagt werden. Diese negativen Effekte werden zum großen Teil ausgeglichen durch aufwendige Kultivierungsmaßnahmen, die aus einer eher spärlichen Sekundärvegetation (die natürliche Vegetation ist zerstört) Ackerböden, Obstplantagen oder Weideflächen machen.

  Erwähnt werden müssen noch externe Effekte, die durch Umsiedlung der Bevölkerung entstehen, wenn Dörfer im Lagerstättenbereich liegen (Abbildung 4). Durch großzügige Entschädigungszahlungen der Firma werden diese Nachteile ausgeglichen.

Abbildung 4: Ansiedlungen in direkter Nähe zu Lagerstätten

- Staubemissionen durch Erzabbau, Erzförderung und Straßenverkehr: die stärkste und unangenehmste Staubentwicklung setzt bei stark windigem bis stürmischem Wetter in sehr trockenen Klimaperioden des tropischen Landes ein. Staub, der dann beim Abbau des Erzes mit Ladern oder Baggern, durch Abwehen aus offenstehenden Tagebaubereichen, beim SLKW-Transport zum Bunker, bei der Verkippung in den Bunker und auf den nicht überdeckten Teilstücken der Förderbandstraße entsteht, wird dann bis zu 3 km Entfernung in größeren Mengen verweht. Staub wird aber auch von den nicht befestigten Straßen ab-

geweht, die sich im gesamten Betriebsgelände befinden und teilweise für den öffentlichen Straßenverkehr freigegeben sind.
In Einzelfällen werden Atemwegsbeschwerden geäußert, die auf das Einatmen von Staub zurückgeführt werden. Auch entstehen Verschmutzungen in den Häusern durch Absetzen des feinen, rostroten Staubes. Für die Verschmutzungen werden von der Firma individuelle Kompensationszahlungen geleistet, für die geäußerten gesundheitlichen Beeinträchtigungen werden nach Begutachtung durch den Betriebsarzt (medical director) die Behandlungskosten übernommen.

- Lärm durch Erzabbau und Erztransport: Zeitweilig finden Erzabbau, Laden und SLKW-Transporte in unmittelbarer Nähe von Siedlungen statt. Dann kommt es zur vorübergehenden Lärmbelästigung einzelner Bevökerungsgruppen, die Kompensationsansprüche geltend machen, die nach Überprüfung der Sachlage durch Zahlungen von ALCAN befriedigt werden, also ebenfalls – zumindest zum größeren Teil – internalisiert werden. Firmenangaben zufolge werden regelmäßig Lärmmessungen durchgeführt mit dem Ergebnis, dass die zulässigen Grenzwerte nur in Einzelfällen überschritten werden. Dieser externe Effekt verursacht also nur geringe externe Kosten.

Als ökologische Effekte der Tonerde-Produktion treten vor allem auf:

- Gas- und Staubemissionen des Bayer-Prozesses: vornehmlich schwefelhaltige Gase können gesundheitliche Schäden und Materialzerstörungen an den üblichen Zinkblechdächern der Häuser anrichten (Berlin Guidelines). Außerdem wird bei entsprechender Wetterlage Staub von der Bauxithalde, von den Öfen, von den Natriumoxalat-Absetzbecken und insbesondere von den offenen Rotschlammdeponien abgeweht. Die Gesundheitsschäden und die sichtbaren Gebäudeschäden ziehen Ansprüche der betroffenen Bevölkerung auf Kompensationszahlungen nach sich, die nach Bestätigung durch Gutachter von ALCAN reguliert werden. Von zahlreichen Betroffenen werden die individuellen Kompensationszahlungen allerdings als zu gering angesehen.

- Grundwasserverschmutzung durch undichte Rotschlamm-Deponien: die älteren Rotschlammdeponien sind nicht zuverlässig durch Tonauftrag oder Kunststofffolien nach unten und zu den Seiten abgedichtet, so dass bei kräftigen Regenfällen Teile der Rotschlamm-Ablagerungen in das Grundwasser versickern und dieses mit Natronlauge oder anderen Schadstoffen verunreinigen. Eine nachträgliche Abdichtung dieser Rotschlamm-Deponien aus den 50er und 60er Jahren ist schwierig, weil für die Ablagerungsräume Seen oder alte Tagebaue verwendet wurden. Über schädigende Wirkungen dieser Altlasten sind keine konkreten Informationen zu erhalten. Bei den neueren Rotschlamm-Deponien wurde dem Stand der Technik entsprechend eine befriedigende Abdichtung vorgenommen.

Die externen ökologischen Effekte verursachen die wesentlichen externen Kosten, von denen aber gerade in Jamaika durch die gesetzlichen Auflagen (Mining ACT: insbesondere Section 99 und Mining Regulation 53), durch die Kontrollen des Jamaica Bauxite Institute und durch die global orientierte Umweltpolitik des internationalen Unternehmens ALCAN ein nennenswerter Teil bereits internalisiert wurde.

Die externen sozioökonomischen Effekte sind zwar auch vielfältig, doch sind sie nur bedingt kostenwirksam, denn entweder sind die Wirkungen nur relativ gering oder die Wirkungen sind bereits weitgehend internalisiert. Auch können sich externe Kosten und externe Nutzen sozioökonomischer Effekte annähernd ausgleichen (z.B. soziale Härten bei Umsiedlung durch Nutzen bei Verbesserung der Krankenversorgung und Schulbildung).

Identifiziert wurden in Kirkvine vor allem folgende sozioökonomische Effekte:
Beschäftigungseffekte (direkte und indirekte Schaffung von Arbeitsplätzen), Verstärkung der ungleichen Einkommensverteilung (Wohlstandsinseln), Migration von Arbeitskräften, Umsiedlungen, Verbesserung der Gesundheitsversorgung und Weiterbildung.

4. Ausgewählte Methoden zur Monetarisierung externer Effekte

Die Methodentests zur Quantifizierung und Monetarisierung externer Effekte, die durch das Teilprojekt 8 des SFB 525 in Indonesien durchgeführt wurden, haben eine besondere Eignung der Zahlungsbereitschaftsmethode (ZBM) für die direkte Bewertung von externen Effekten im Bergbau gezeigt (vgl. Kölfen & Sliwka 1998, Kölfen 2000). Da auch der Vermeidungskostenansatz (VKA) nach entsprechendenVoruntersuchungen potentiell geeignet erschien, wurden die beiden Methoden für die Arbeiten in Jamaika ausgewählt.

Die ZBM veranlaßt die Befragten einer Interview-Kampagne, auf der Grundlage persönlicher Einschätzung und Präferenzen einen Preis zu nennen, den sie für ein bestimmtes Umweltgut oder eine soziale Dienstleistung bezahlen würden. Dabei müssen die Befragten durch den Interviewer zunächst in die Lage versetzt werden, ihre subjektive Wertschätzung für das Umweltgut oder die soziale Dienstleistung voll zu erfassen. Dies muß durch eine Veranschaulichung der (hypothetischen) Situation und durch eine strukturierte Befragung erfolgen, um mit den Interviewpartnern den "Kauf" bzw. die Zahlungsbereitschaft für das Umweltgut zu simulieren. Die individuellen Zahlungsbereitschaften werden dann auf die Gesamtzahl der Betroffenen in der Bergbauregion hochgerechnet, um die externen Kosten zu erhalten.

Vermeidungskosten sind hypothetische oder tatsächliche Aufwendungen zur maximal möglichen Verminderung von Schadstoffausstoß bzw. Schadstoffexposition. Es sind zwei sehr unterschiedliche Ansätze denkbar, einerseits ein substitutiv-institutioneller Ansatz, der technologiebezogen ist und kostenwirksam nach dem neuesten Stand der Technik den Schadstoffausstoß vermindern oder sogar vermeiden soll und andererseits ein substitutiv-individueller Ansatz, der kostenwirksame individuelle Maßnahmen der Betroffenen gegen Schadstoffeinwirkungen vorsieht.

Bei dem substitutiv-institutionellen Vermeidungskosten-Ansatz kann noch einmal zwischen der Verbesserung bestehender technologischer Einrichtungen und Prozesse (produktionssystem-immanenter Ansatz) und der Einführung neuer, strukturändernder Technologien zur Schadstoffausstoßminderung unterschieden werden.

Auch beim substitutiv-individuellen Vermeidungskosten-Ansatz sind zwei Varianten möglich, je nach Art der externen Effekte. Bei Wasserverschmutzung ist auch eine alternative Ressourcenbeschaffung und -nutzung (Kauf von sauberem Wasser in Flaschen), bei Luftverschmutzung dagegen nur der Umzug in schadstoffärmere Lebensräume möglich.

5. Test mit der Zahlungsbereitschaftsmethode

Die Voraussetzungen für eine Anwendung der Zahlungsbereitschaftsmethode (willingness-to-pay method) sind nicht günstig. Zum einen sind für die meisten Betroffenen nur die Schäden durch Staub- und Gas-Emissionen bemerkbar, zum anderen werden seit Jahren Kompensationszahlungen für diese Schäden von ALCAN geleistet, so dass eine (fiktive) Zahlungsbereitschaft nur bei einigen Betroffenen abgefragt werden kann. Im Bewußtsein der Befragten war auch fest verankert, dass für Schäden einer ausländischen Gesellschaft nur der Verursacher zahlen muß.

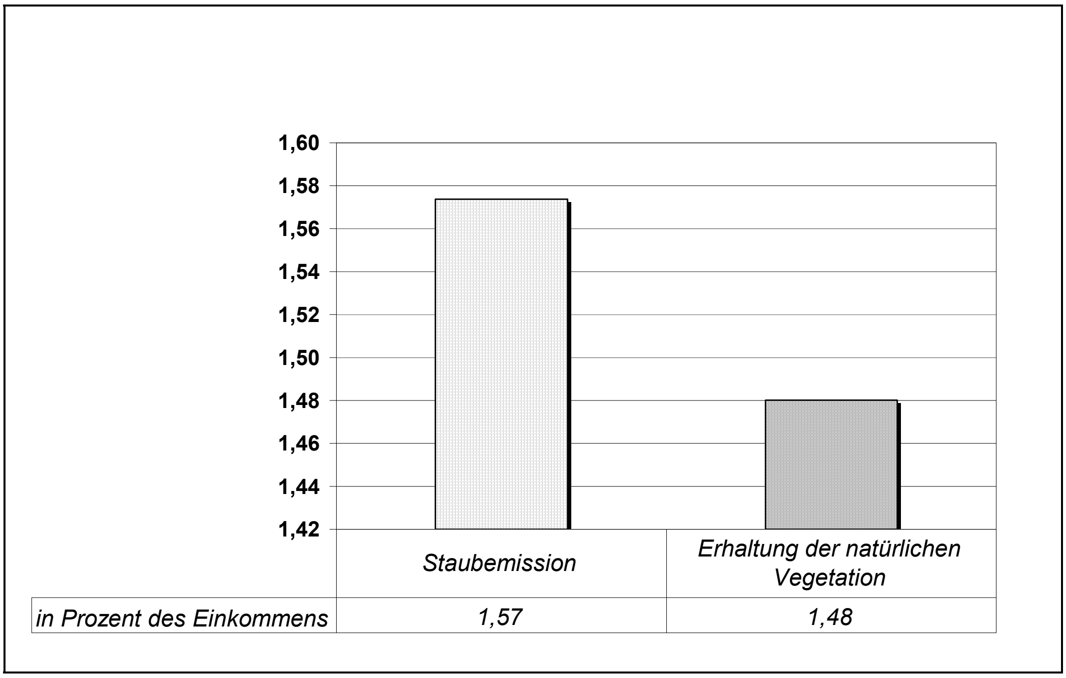
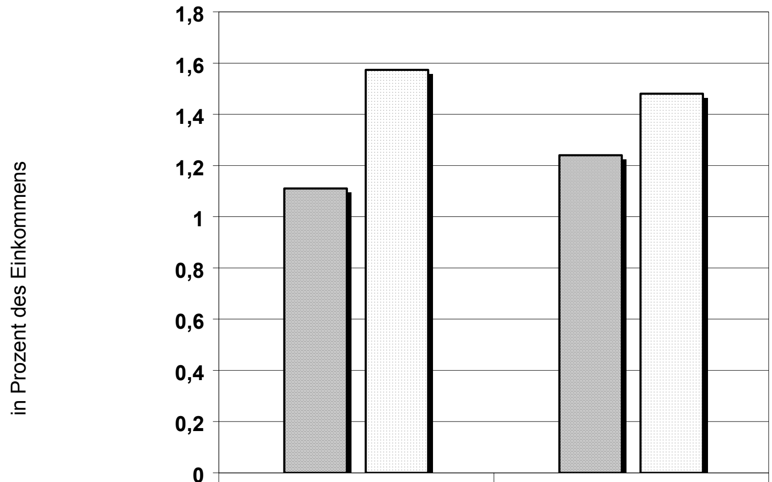


Abbildung 5: Zahlungsbereitschaft in Jamaika für die beiden wichtigen externen Effekte

Trotzdem wurde eine Gruppe von rund 20 Betriebsangehörigen mit einem standardisierten Fragebogen, der auch Vergleiche zu Bintan/Indonesien zuläßt, interviewt, um die individuelle Zahlungsbereitschaft für Vermeidung von Staubemissionen und für Landschaftsschäden zu ermitteln (Abb. 5). Eine ausführliche Diskussion über die Methode war den Interviews vorausgegangen. Bei der Befragung ergab sich, dass die Luftverunreinigungen durch Staub und toxische Gase am deutlichsten als individuelle Umwelteffekte wahrgenommen wurden und dafür auch eine Zahlungsbereitschaft besteht. Es gab bei den Interviews aber auch Hinweise darauf, dass die Zahlungsbereitschaft von der Höhe der Kompensationszahlungen beeinflußt ist, denn die Angaben zur Zahlungsbereitschaft und die Zahlungen der Firma gleichen sich. Eine Zahlungsbereitschaft für eine Wiederherstellung des Vegetationszustandes vor der Tagebau-Erschließung war nur bei wenigen Befragten gegeben, denn die Mehrzahl der Interview-Partner bevorzugten die neuen landwirtschaftlichen Nutzflächen und wollten den ursprünglichen Zustand der artenarmen Sekundärvegetation nicht wieder hergestellt sehen. Da ALCAN in Jamaika den Betriebsangehörigen erheblich höhere Löhne und Gehälter zahlt als dies die staatliche Minengesellschaft in Indonesien tut, ist die Zahlungsbereitschaft in Jamaika als

Prozentsatz vom Einkommen etwas höher. Beim Vergleich der beiden Bergwerke in Bintan (Indonesien) und Kirkvine (Jamaika) fällt zunächst auf, dass sich der Anteil der monetarisierten externen Effekte an den Gesamtkosten in Bintan auf etwa 15 %, in Kirkvine dagegen nur auf ca. 4,2 % beläuft. Dabei ist allerdings zu berücksichtigen, dass in Bintan vier wesentliche Effekte sichtbar für die Betroffenen in Erscheinung traten (Flächeninanspruchnahme, Wasserverschmutzung, Staubemissionen, Änderung des Naturraumes), in Kirkvine dagegen nur zwei (Staub, Flächennutzung), die in Jamaika noch dazu in erheblichem Maße inzwischen internalisiert sind. Diese Internalisierung betrifft die Flächennutzung, denn für Rekultivierungsmaßnahmen werden 5,5 – 6 % der Produktionskosten (1998: rund 32 Mio. US $) aufgewendet (Selbstverpflichtung ALCAN: 0,95 US $/t Bauxit); sie betrifft aber auch die Staubemission, denn die relevanten Kompensationszahlungen summieren sich auf rund 200.000 US $ pro Jahr, was ca. 0,6 % der Produktionskosten entspricht. Damit sind aber die durch Zahlungsbereitschaften ermittelten externen Kosten in beiden Betrieben größenordnungsmäßig gut vergleichbar (Abb. 6).



	Staubemissionen	Erhaltung der natürlichen Vegetation
Bintan / Indonesien	1,11	1,24
Jamaika	1,57	1,48

Abbildung 6: Vergleich der Zahlungsbereitschaft von Firmenbeschäftigten in Jamaika und Bintan (Indonesien)

6. Vermeidungskosten – Ansätze

In Jamaika (Kirkvine Works) konnten Daten für Vermeidungskosten-Ansätze erhoben werden. Die Maßnahmen der Bauxit-Mine zur Verminderung von Staub-Emissionen bestanden vor allem in einer Investition für die Abdeckung der Förderbandstraße und in der regelmäßigen Befeuchtung von Straßen und Haufwerk.

Die zu 90 % überdachte Förderbandstraße wurde im Mai 1995 in Betrieb genommen und stellte eine Investition in Höhe von insgesamt 40 Mio. US $ dar, davon entfielen 4 Mio. US $ auf die Überdachung. Diese zusätzliche Investition für Emissionsminderung belastete die Produktionskosten des Betriebes mit rund 2,2 %.

Für die Befeuchtung sind sechs Wassersprühwagen eingesetzt, die 100.000 Gallonen Wasser pro Tag verbrauchen und Kosten in der Größenordnung von weiteren 1,0 % der gesamten Produktionskosten verursachen. Durch diese kostenwirksamen Maßnahmen der Mine konnten die normalen Staubemissionen deutlich reduziert werden. Eine nennenswerte Vermeidung von starken episodischen Staubemissionen in Perioden extremer Trockenheit gelang dagegen nur unvollständig.

Auch der individuelle Vermeidungskosten-Ansatz wurde in Kirkvine verfolgt. Die Betriebsleitung hat mit dem Jamaica Bauxite Institute einen Einflußbereich der nachweisbar schädlichen Staubemissionen von maximal 3 km um die Betriebsstätten festgelegt. In diesem Gebiet wohnen rund 1.200 Familien mit 7.000 - 8.000 Personen. Die Mieten in diesem betriebsnahen Gebiet liegen niedriger als in vergleichbaren (ländlichen) Wohngebieten außerhalb. Während innerhalb des definierten Gebietes (z.B. in den kleinen Ortschaften) eine Miete für ein durchschnittliches Haus von 18.000,- J $ pro Monat (= 450,- US $/Monat) gezahlt wird, kostet die Miete für ein vergleichbares Haus außerhalb 25.000,- J $/Monat (= 620,- US $). Die individuellen Vermeidungskosten für den Umzug würden für die 1.200 Familien also rund 1,2 Mio. US $ pro Jahr oder rund 3,7 % der Produktionskosten betragen. Dazu müßten noch die erhöhten Fahrtkosten von einigen wenigen Betriebsangehörigen gerechnet werden, die in dem betroffenen Gebiet wohnen.

Die Vermeidungskosten-Ansätze haben im Falle von Kirkvine, Jamaika, etwas geringere externe Kosten ergeben als die Zahlungsbereitschaftsanalyse. Während die institutionellen

Vermeidungskosten bei ca. 3,2 % der Produktionskosten liegen, wurden die individuellen Vermeidungskosten auf 3,7 % der Produktionskosten kalkuliert. Die Zahlungsbereitschaft für Vermeidung von Staubemissionen und Landschaftsschutz lag dagegen bei rund 4,2 % der Produktionskosten.

7. Anspruchsgruppen im Ökologiebereich

Im Bergbausektor können drei hauptsächliche Anspruchsgruppen identifiziert werden: das Unternehmen, der Staat und die benachbarten Kommunen. Die zahlreichen speziellen Anspruchsgruppen (stakeholders) können diesen Hauptgruppen zugeordnet werden.

In Jamaika finden die externen ökologischen Effekte derzeit besondere Aufmerksamkeit. Zuständig für den Umweltschutz sind allerdings eine Reihe von Behörden, die deshalb alle als Anspruchsgruppen für den Bauxitbergbau und die Tonerdeherstellung in Betracht kommen.

Hierzu zählen vor allem:

- das Jamaica Bauxite Institute: die 1976 gegründete staatliche Institution ist dem Ministry of Mines and Energy (bis 1998 Ministry of Agriculture and Mining) zugeordnet und ist zuständig für Regulierungen, Kontrollen und Regierungsberatungen im Bereich Bauxit- und Tonerde-Industrie
- die Natural Resources Conservation Authority: die dem Ministry of Land and Environment zugeordnete Behörde ist für das umweltgerechte Management und für den Schutz der natürlichen Ressourcen des Landes zuständig und kontrolliert beispielsweise die Rekultivierung alter Tagebaubereiche;
- die Water Resources Authority: die dem Ministry of Water and Housing angegliederte Behörde soll insbesondere mit ihrem Department of Underground Water die Verschmutzung von Grundwasser im Einzugsbereich der Rotschlamm-Deponien kontrollieren, wobei ein regelmäßiges Monitoring der Grundwasser-Qualität vor allem die Natriumgehalte betrifft.

8. Ansätze zur Internalisierung externer Kosten

Die betriebswirtschaftlichen Maßnahmen des multinationalen Unternehmens ALCAN Jamaica Co. und die wirtschaftlichen Maßnahmen der Regierung von Jamaika haben zu einer nennenswerten Internalisierung externer Kosten des Bauxitabbaus und der Tonerde-Produktion geführt. Die praktizierten Modelle der Internalisierung lassen sich in fünf Kategorien einordnen:

(a) Investitionen des Betriebes zur Verminderung und wenn möglich zur Vermeidung negativer externer Effekte. Dazu gehören bei ALCAN die deutliche Reduzierung der Staubemissionen beim Bauxittransport durch Investitionen zur Überdachung der Bandanlage.

(b) Individuelle Kompensationszahlungen für sichtbare und nachweisbare Schäden an Eigentum oder Gesundheit von Betroffenen. Hierzu gehören in Jamaika die Zahlungen von ALCAN für die Reinigung von Häusern nach Staubemissionen oder für die Reparatur von Zinkblechdächern, die Entschädigungen bei Umsiedlungsmaßnahmen oder die Behandlungskosten bei betriebsbedingten Krankheiten. Durch diese Kompensationszahlungen wird der größere Teil der individuellen externen Kosten internalisiert.

(c) Steuern und Abgaben zum Ausgleich von gesellschaftlichen Kosten (externe Kosten, die eine Bevölkerungsgruppe des Landes tragen muß). ALCAN zahlt sowohl Royalties (gewinnunabhängige Mengensteuern pro Tonne geförderten Bauxit) als auch eine Bauxitsteuer (seit 1974 indexiert mit Aluminiumpreis) und Körperschaftssteuer.

(d) Direkte und indirekte Subventionen des Staates für das Unternehmen, die als Ausgleich für positive externe Effekte gelten können. Hierzu können in Jamaika die Subventionen (bzw. Verzicht auf übliche Besteuerung) für Energieträger, vor allem Dieselöl, zählen. An den Tankstellen wird Dieselkraftstoff für 33 US cts/l (1999) verkauft (was dem Preisniveau der USA entspricht), die Unternehmen liegen noch darunter.

(e) Investitionen des Betriebes, die zu externen gesellschaftlichen Nutzen führen und damit als Kompensation für (unvermeidbare) externe Kosten gelten können. Das trifft beispielsweise auf die Rekultivierungsmaßnahmen von ALCAN zu, die durch hohen Aufwand landwirtschaftliche Nutzflächen entstehen lassen, deren Nutzen für die Bevölkerung der Region wesentlich größer sind als die der ursprünglichen Sekundärvegetation.

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TECHNISCHE POTENZIALE DER PRIMÄRALUMINIUMPRODUKTION

(TECHNICAL POTENTIALS OF THE PRODUCTION OF PRIMARY ALUMINIUM)

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ABSTRACT[1]

This paper will analyze the current status of aluminum production, and will discuss the potential for sustainable development in this field. The presentation will address the demand for aluminum and bauxite, as well as the different qualities of each substance. It will discuss how aluminum and bauxite impact aluminum and aluminum production conditions. It will also assess the production of alumina using the Bayer process and discuss possible alternative methods (i.e., processes and raw materials) of production. This paper will review the use of salt electrolysis, the current standard operation for production of aluminum, and potential improvement levers and alternative processing routes. This will be followed by a description of the gaseous emissions and appropriate emission control techniques. Finally, an analysis of carbon anode manufacturing will be made.

Worldwide consumption of primary aluminum reached about 23 million metric tones in 1999. Forecasts predict an annual increase of 2.5-3.0% driven mainly by automotive industry applications.

Bauxite comprises 6.4% of aluminum production costs. This amount has been increasing since 1950. Currently known bauxite reserves guarantee a sufficient supply of the aluminum production in the midterm. Alumina constitutes 27% of the production cost of aluminum, which is a decrease of 3.0%. The overall price of aluminum has remained constant since 1960 at approximately US$/mt 2,300.

Bauxite quality is impacted by the content of alumina and alumina-containing minerals, amounts of reactive silica, goethite, and other impurities. These factors define the amount of red mud, the alumina quality, and the processing conditions. Radioactive impurities from bauxite accumulate in the red mud during alumina production. Due to fluctuations in the

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[1] Summary of Ph.D. thesis

amount of radioactive impurities, sometimes in single cases the limit for deposition control is exceeded.

In the last 30 years, no greenfield alumina plants have been constructed. Instead, the increase in world production and capacity has been achieved through brownfield expansions and efficiency improvements. The tube reactor, developed in the late 1960's, could not succeed despite of its economic and energy advantages.

During alumina production, the determining factor for energy consumption is liquor productivity. Today, the highest possible value is 90 g/l Al_2O_3, which is still far from the theoretical maximum of 150 g/l Al_2O_3. At speeds closer to this theoretical maximum, energy consumption in the conventional autoclave system could be decreased. However, this development would be impeded by the low chemical reaction speed.

Alumina calcination has advanced technologically because of the implementation of stationary furnaces and fluidized bed reactors. Though potential for improvement of this process is somewhat limited, two possibilities exist: the application of pressure calcination (though there have been no publications on this topic since 1986) or the precipitation of Boemithe rather than Gibbsite (no known technical application yet).

Numerous alternative routes for alumina production (from bauxite or non bauxitic raw materials) have been proposed. Due to the resulting duplicate products and waste, only two are in use today. The alunite and nepheline processes, currently in use in the CIS, are being used under special conditions and can only be seen as niche processes. Neither these nor any other processes can be considered realistic alternatives to the Bayer process.

Electrolysis technology using carbon anodes has improved and has reached a high technical level today. But the principles are not really different from those described in the 1886 patents of Hall and Heroult. So-called PFPB cells give best results at current densities between 0.8 and 0.9 A/cm2, and the anode effect frequency can be decreased to very low figures in this cell type. The energetic improvement margin is negligible but there is no apparent boundary to the cell size.

Today, there is no alternative to conventional electrolysis for two reasons: technical problems (metal quality, stability) hinder the technical application of inert anodes and the imagined economic advantages of inert anodes are small. The highest improvement potential in the field of electrolysis lies in the development and usage of "wettable" cathodes in drained cells, though economic improvement levers are limited.

Fluoride emissions no longer play an important role because of the installed emissions control systems. The amount of CO_2 emissions is directly related to the consumption of anode carbon, and modern cells almost reach the theoretically achievable minimum. Emissions of fluorinated hydrocarbons (CF_4/C_2F_6 with high glass house potential) can be avoided through the installation of point feeder technology and automatic process control. Given current emission control systems, a further decrease in HF emissions can only be achieved by avoiding diffuse sources.

Bag filters are superior to electrostatic gas cleaning. The dry gas cleaning is better for the control of fluorides and dusts than the wet gas cleaning technology. The one exception is that of SO_2, which cannot be controlled in dry gas cleaning. However, remedies to this problem are already in development.

Anode production has adopted the high environmental standards of the smelters and now meets their emission control requirements. What remains to be solved, however, is how to cool down the used anode and remove sulphur from the petrol coke.

KEYWORDS

Bauxite, alumina, aluminum, aluminum production, Bayer process, calcination electrolysis, alternative method, carbon anode, worldwide aluminium consumption, CO_2 emission, HF emission

RESOURCE CONSERVATION BY IMPROVEMENTS OF PRIMARY ALUMINIUM PRODUCTION*

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ABSTRACT

This paper presents the balance of mass flows due to the primary aluminium production from bauxite to molten metal and the identification of optimisation potentials. To balance the mass flows and energy requirements of the worldwide aluminium production the developed process chain is divided into technique specific modules. There are nearly 70 alumina refineries with a total capacity of 56 Mio. t/a of alumina and nearly 200 smelters with a total capacity of 26 Mio. t/a of aluminium in operation. Different smelter technologies are classified in terms of the specific energy demand, anode consumption and emissions like fluorides or SO_2. The specific electrical energy requirements for electrolysis range from 13.0 to 17.5 kWh/t of molten aluminium with a capacity weighted average of 14.9 kWh/t. Two case studies show that by an increase of the annual aluminium production of 8 Mt, the specific energy requirement will decrease to 14,1 kWh/kg Al due to the installation of new smelters and changes in the applied technology.

KEY WORDS

Primary aluminium, resource conservation, smelter technologies, fluorides, SO_2

* Source: Proceedings of Light Metals 2001

Introduction

Further developments of industrial sectors like aluminium production are often the subject of investigation. For a known market growth rate, future production can be extrapolated for years or decades. This is much more difficult to predict for technical progress, especially when considering technical and environmental aspects in the understanding of sustainable developments. Furthermore, technical progress is different for different steps of a process chain and for different locations and its application is not predictable generally. Nevertheless realistic assumptions for future technology can be made, when the estimation of the maximum technical potential, which is known today in every process step is divided from the forecasting of its application in a certain time. Then the combination of them together with site-related analysis could give reliable results. This paper will give an overview of energy and raw materials demand and process-related emissions of processes during aluminium production. Furthermore, the impact of progress and change in aluminium electrolysis is analysed in two case studies in terms of energy demand, anode consumption and emissions of CO_2, CF_4/C_2F_6, global warming potential and SO_2.

Alumina production by the Bayer process

Today the total capacity of alumina refineries approaches 56,326,000 t Al_2O_3, compared to a production of 46,379,000 t in 1997 and 41,745,000 t in 1994. The distribution of bauxite type used for alumina production, determined by the predominant alumina bearing mineral, in 1994 is shown in Table I [1, 2, 3].

Table I: Alumina production in % from ore type [1]

Bauxite type	Share of world alumina production (%)
Gibbsitic	54
Boehmitic	30
Diasporic	11
Nephelin (+ Alunite)	5

The type of bauxite determines the process technology from which the following results could be estimated:

Table II: Alumina production in % according to process technology [1]

Bauxite type	Share of world alumina production (%)
Bayer LTD & AD	48
Bayer HTD & Sweetening	12
Bayer HTD (partly with lime)	18
Bayer & soda lime sintering	17
Nephelin (+ Alunite) sintering	5

LTD: Low Temperature Digestion
AD: Atmospheric Digestion
HTD: High Temperature Digestion

Energy requirements for the Bayer process

Detailed data are not available relating to the average energy consumption of the different types of alumina plants. Table III shows the energy consumption of five different alumina plants. It can be seen that it is possible to reduce the energy consumption to 5.1 MJ/kg Al_2O_3 by using a tube digester, which has been in operation for 25 years in Stade, Germany. Despite of its advantages this technology is applied very rarely. Natural gas (40 %) as well as fuel oil (38 %) are the typical energy sources for the Bayer Process.

Table III: Energy requirements (MJ/kg Al_2O_3) for some alumina refineries [1]

Plant	Digestion	Evaporation	Others	Total	%
Stade	3.5	0.5	1.1	5.1	100
Wagerup	2.5	2.5	3.2	8.2	160
Gove	2.5	2.5	3.2	8.2	160
Damanjodi	1.4	3.6	4.7	9.7	190
HTD Autocl.	4.0	3.0	3.0	10.0	196

Calcination of alumina

The aluminium hydroxide produced in the Bayer process has to be calcined to aluminium oxide. This is done in stationary fluid bed calciners and rotary furnaces. An average of 4.8 MJ/kg Al_2O_3 is required for calcination in the rotary furnaces and only 3.3-3.1 MJ/kg in the stationary furnaces. Natural gas as well as heavy fuel oil can be used for the calcination. The share of rotary and stationary furnaces according to the total worldwide installed capacity is not well known, but we assume that one third of the alumina is calcined in rotary furnaces and two thirds in the stationary type. According to the data above, the world average energy consumption from both stationary as well as rotary furnaces is 4.3 MJ/kg Al_2O_3, amounting to 130 % of today's applied technical minimum.

Aluminium electrolysis

In 1997 there were worldwide nearly 200 smelters in operation with a total capacity of 26 Mio. t/a, of which the greatest is the Bratsk smelter in Siberia (800,000 t/a) and the smallest one (in the western world) the smelter at Kinlochleven, Scotland (11,000 t/a). The latter was shut down in the summer of 2000. Furthermore some 5,000 t/a or even smaller smelters exist in the PR China.

Different smelter technologies were examined with respect to the specific energy consumption and anode consumption as well as to emissions of CO_2, fluorides, SO_2 and CF_4/C_2F_6.

Aluminium smelting technology can be roughly divided into five different technologies:

HSS: Horizontal Stud Söderberg
VSS: Vertical Stud Söderberg
SWPB: Side Worked Prebake
CWPB: Centre Worked Prebake (with centre brake bar system for alumina feeding)
PFPB: Point Feeder Prebake (with point feeder technology for alumina feeding)

Even at the same smelter location different technologies have been applied in different pot lines, e.g. at the smelters at Kurri Kurri in Australia and Sorocaba in Brazil.

For an analysis of current and future energy requirements and mass flow, considerable data on smelters around the world have been collected and analysed. Further, each smelting technology mentioned above has been divided into three categories of technical standard: Old Technology (OT), Present Technology (PT) and Newest Technology (NT). Criterion for the classification was purely the electrical energy requirement, following Table IV. Smelters for which the energy requirements were not available, were appointed to these technical categories using other criteria, such as start-up. Smelters, for which the technology was not available, were not examined and excluded from the following analysis. These are predominantly small smelters in PR

China. With regard to the old technologies used in PR China smelters up to the present, the results on this analysis seem to be moderate.

Table IV: Energy requirements of different technical smelter categories

	Old Technology (OT) kWh/kg Al	Present Technology (PT) kWh/kg Al	Newest Technology (NT) kWh/kg Al
HSS	> 16.5	16.5 - > 14.5	≤ 14.5
VSS	> 16.5	16.5 - > 14.0	≤ 14.0
SWPB	> 15.5	15.5 - > 13.5	≤ 13.5
CWPB	> 15.5	15.5- > 13.5	≤ 13.5
PFPB	> 14.5	14.5 - > 13.5	≤ 13.5

By following these criteria, in 1997 a smelting capacity of nearly 22 Mt was analysed.

Table V: Installed capacities for each technical category and share of world production

Technology	Technical category	Capacity (t/a)	Share of total production (%)
HSS	OT	1,204,000	5.5
	PT	779,000	3.5
	NT	--	--
VSS	OT	1,916,000	8.73
	PT	2,698,000	12.3
	NT	--	--
SWPB	OT	--	--
	PT	1,455,000	6.6
	NT	572,000	2.6
CWPB	OT	1,060,000	4.8
	PT	2,165,000	9.7
	NT	--	--
PFPB	OT	2,106,000	9.6
	PT	4,502,000	20.5
	NT	3,485,000	15.9
Total		21,944,000	100.0

The electrical energy requirements and demand of anodes for each technical category and the total averages, weighted by the production, are listed in Table VI. Figure 1 shows the comparison of production share and energy requirements for each technical category in 1997.

Table VI: Installed production of each technical category and share of world production

Technical category	Elec. energy demand (kWh/kg Al)	Net anode consumption (kg/t Al)
HSS-OT	17.1	536
HSS-PT	14.9	557
VSS-OT	17.1	572
VSS-PT	15.8	529
SWPB-PT	14.5	427
SWPB-NT	13.2	409
CWPB-OT	16.4	474
CWPB-PT	14.7	431
PFPB-OT	15.1	436
PFPB-PT	14.0	426
PFPB-NT	13.3	410

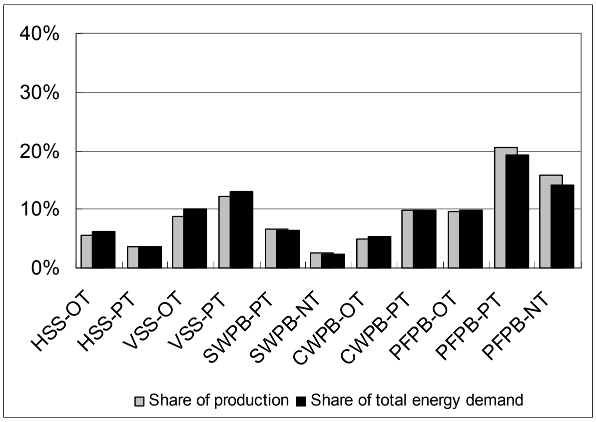

Figure 1: Share of production and total energy requirement for different technical category of Al electrolyses cells in 1997.

Electrical energy case study 1 for the year 2010

To answer the question, how much energy will be required for each kg of aluminium in the future, some boundary conditions have to be defined.

Between 1997 and 2003 some smelters already have or will restart their shut-down capacities, also some new smelters have come online, or will go online until 2003 (e.g. the Alma project of Alcan, the Ikot Abasi smelter in Nigeria or the Maputo smelter in Mozambique). Some other smelters will shut down their capacity (e.g. Isle Maligne in Canada). This will result in an increase of worldwide primary aluminium production of 3 Mt/a. Beside these changes we assume an increase of primary aluminium production worldwide of another 5 Mt/a before 2010, so that the total aluminium production will increase from 22 Mt in 1997 to 30 Mt in 2010, resulting in a yearly increase of 2.5 %. This seems to be a moderate and conservative value in comparison to other studies. It is assumed that the new projects will be exclusively PFPB-NT technology. Furthermore, we assume that the other smelters will not change technology and energy requirements. Under these conditions, the average electrical energy requirements will decrease from 14.9 kWh/kg in 1997 to 14.6 kWh/kg in 2010 (amounting to 98.2 % of the 1997 value), caused only by the installation of new smelters and shut- down of some smaller less efficient capacities.

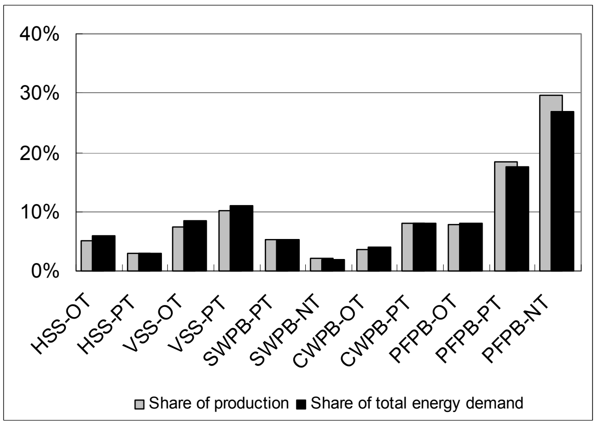

Figure 2: Share of production and total energy requirement for different technical category of Al electrolysis cells in 2010 according to case study 1.

The relationship of production and energy requirements for this case study 1 is shown in figure 2.

Electrical energy case study 2 for 2010

What is the impact if the technology in the existing smelters changes? It seems most likely that smelters will optimise their operation and decrease their energy consumption by installation of automatic pot control or optimisation of the manual work at the pots, in order to minimise direct costs further

We assume that all changes from 1997 to 2010 will take place as described in the case study 1. Additionally, some smelters will change their technical categories shown in Table VII. These changes consider that it is not possible to change the pot type from HSS or VSS to PB technology without accepting and paying for substantial changes in the superstructure of the pot. It is also difficult to change from SWPB to PFPB, but easier to change from CWPB to PFPB technology. Moreover, it is difficult, or impossible, to decrease the energy demand of PFPB-OT/PT to the demand of a large, magneto-hydrodynamic compensated cell typical of the PFPB-NT technology.

Table VII: Change of technical categories of Al electrolysis cells in case study 2

1997	HSS-OT	VSS-OT	SWPB-OT	CWPB-OT	CWPB-PT	PFPB-OT
2010	HSS-PT	VSS-PT	SWPB-NT	PFPB-PT	PFPB-PT	PFPB-PT

These changes result in a decrease of the average energy demand to 14.1 kWh/kg Al (or 94.9 % of the 1997 value).

Figure 3 shows the share of production and energy requirements for each technical category in 2010 according to case study 2.

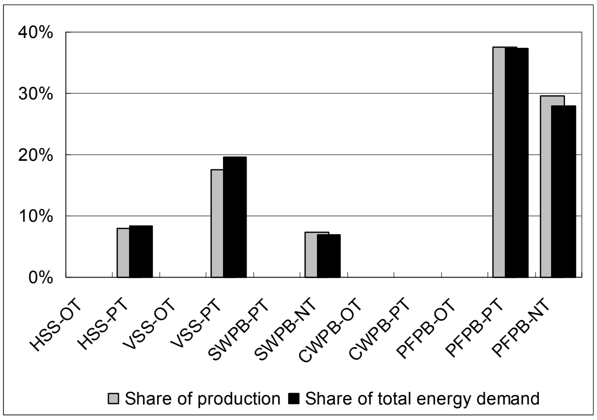

Figure 3: Share of production and total energy requirements of different technical categories of electrolysis cells in 2010 according to case study 2.

Anode consumption (status and case studies)

The average anode consumption in 1997 is 463 kg/t Al (Söderberg and Prebake). Generally, the share of anode consumption is higher for Söderberg technology and less for Prebake technology compared to their share of production (excluded for CWPB-OT, but there are few data available). This situation does not change in case studies 1 and 2. The average anode consumption will decrease in case studies 1 and 2 to 424.1 and 415.6 kg/t Al, respectively, amounting to 98.1 % and 96.9 % of the 1997 value.

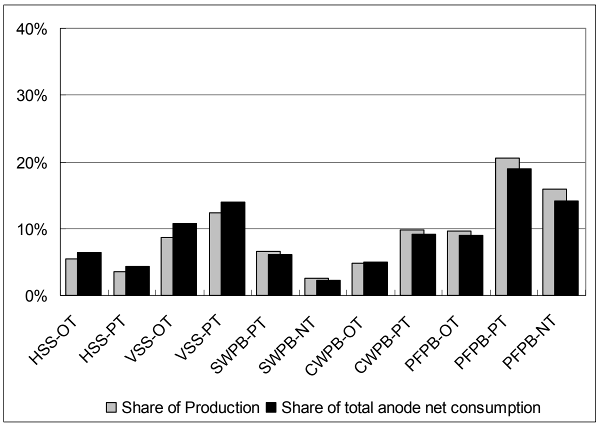

Figure 4: Share of production and total anode consumption of different technical categories of Al electrolysis cells in 1997.

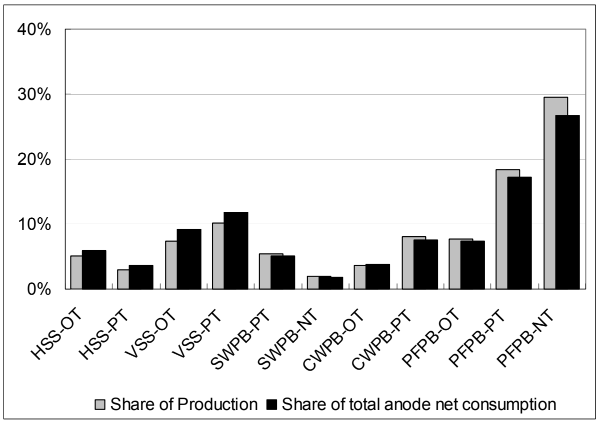

Figure 5: Share of production and total anode consumption of different technical categories of Al electrolysis cells in 2010 according to case study 1.

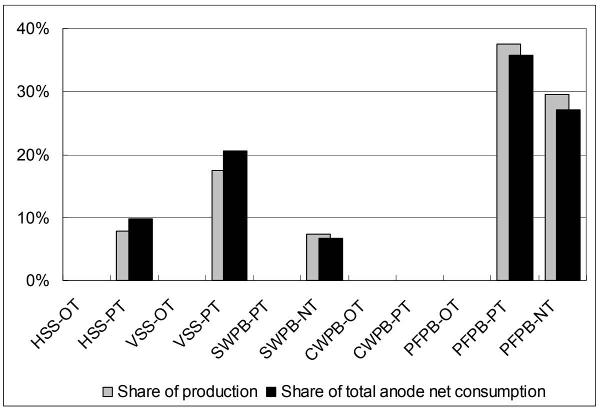

Figure 6: Share of production and total anode consumption of different technical categories of Al electrolysis cells in 2010 according to case study 2.

Emissions of greenhouse gases

CF_4 emission in 1997

What amount of CF_4/C_2F_6 is emitted today from primary aluminium smelters?

CF_4 and C_2F_6 are emitted from electrolysis cells only during the so-called anode effect. The specific amount of the emissions depends of the anode effect frequency, duration of the anode effect, cell amperage and current efficiency. We assume that the different technical smelter categories lead to the following specific amounts of CF_4/C_2F_6 emitted to the atmosphere. The data were taken from [4, 5] and modified.

Table VI: Specific emissions of CF_4/C_2F_6 caused by different technical categories of Al electrolysis cells

Technical category of Al electrolysis cells	CF_4 (kg/t Al)	C_2F_6 (= 10% of CF_4) (kg/t Al)
PFPB-NT	0.05	0.005
PFPB-PT	0.30	0.030
PFPB-OT	0.50	0.050
CWPB-PT	0.30	0.030
CWPB-OT	0.50	0.050
SWPB-NT	0.70	0.070
SWPB-PT	1.20	0.120
VSS-PT	0.55	0.055
VSS-OT	1.10	0.110
HSS-PT	0.07	0.007
HSS-OT	0.40	0.040

In 1997 primary aluminium smelters emitted 10,032 t of CF_4 and 1,003 t of C_2F_6, corresponding to an average specific emission rate of 0.46 kg/t Al. The comparison of CF_4 emissions and total Al production shows that some technical categories emit much more CF_4 compared to their share of production, especially VSS-OT, SWPB-PT and PFPB- PT.

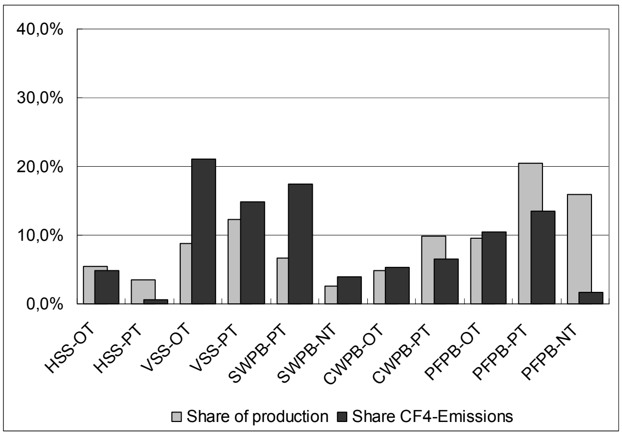

Figure 7: Share of production and total anode consumption of different technical categories of Al electrolysis cells in 2010 according to case study 1.

CF_4/C_2F_6 emission case study 1 for 2010

How much will the emissions of CF_4/C_2F_6 change by 2010?

Under the conditions outlined in the **electrical energy case study 1** described above, the total emitted amount of CF_4/C_2F_6 will increase to 10,907 t/a CF_4 by 2010, representing an increase of 8.7 % of the total amount in 1997. The specific emitted amount will decrease to 84.8 % of the 1997 value, or 0.39 kg/t Al of CF_4. The comparison of production and emission share with respect to technology is only slightly different to 1997.

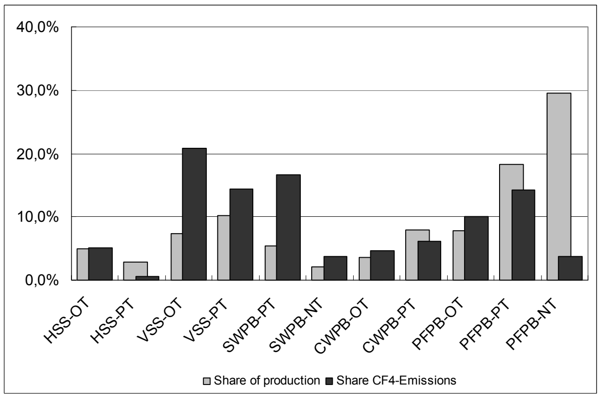

Figure 8: Share of production and total CF_4 emissions of different smelter categories in 2010 according to case study 1.

CF_4/C_2F_6 emission case study 2 for 2010

Under the conditions outlined in **electrical energy case study 2** described above, the total emitted amount of CF_4/C_2F_6 will decrease to 7,914 t/a CF_4 by 2010, corresponding to a decrease of 21.1% of the total amount in 1997. The specific emitted amount will decrease to 60.9 % of the 1997 value or 0.28 kg/t Al of CF_4.

Figure 9 shows that nearly 35 % of the total amount is emitted from the VSS-PT pots, which produce only 17 % of the aluminium. On the other hand, the PFPB-NT pots produce nearly 30 % of the world aluminium production and emit only 5 % of the total CF_4 amount. This is mainly due to an ongoing reduction of the number of anode effects extending almost to 2010.

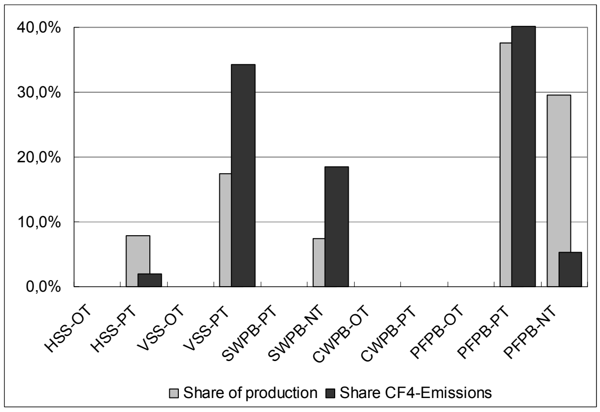

Figure 9: Share of production and total CF_4 emissions from smelters of different technical categories in 2010 according to case study 2 .

Comparison of CF_4/C_2F_6 and CO_2 emissions

The GWP of CF_4/C_2F_6 is very high, at 6,500 and 9,200 times that of CO_2, respectively, on a 100 year basis.

It can be seen from figure 10 that the share of greenhouse gases emitted from the smelters depends on technical category and differs from their share of production. The most critical seems to be the smelters of VSS-OT and SWPB-PT technical categories. Their share of greenhouse gas emissions is twice as large as their share of production, most of it coming from CF_4.

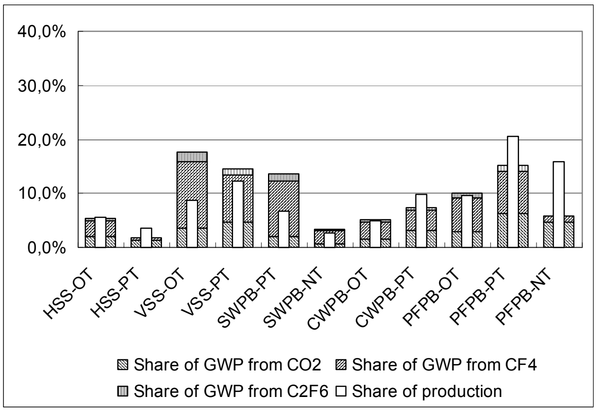

Figure 10: Share of production and emissions of CO_2 and CF_4 caused by different technical smelter categories in 1997.

An average of 5.1 t/t Al of GWP is emitted from aluminium smelters, including 1.7 t directly as CO_2 from consumption of the anode.

What will happen by 2010?

Emission of GWP gases case study 1 for 2010

Under the conditions of case study 1, with no change of smelter technology and an additional production of 5 Mt/a Al the production share of PFPB-NT smelters will increase to nearly 30 %. There is little difference in the share of production and GWP emissions, compared with the situation in 1997.

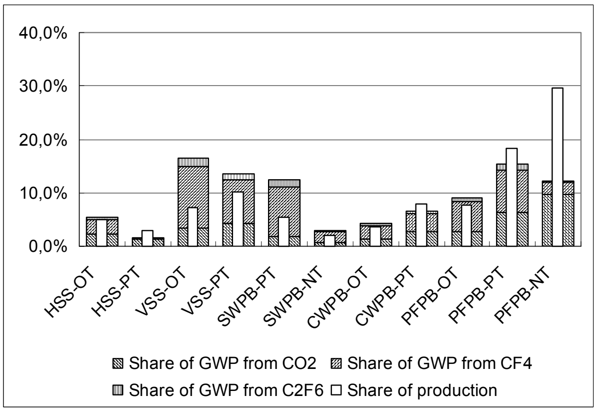

Figure 11: Share of production and emissions of CO_2 and CF_4 caused by different technical smelter categories in 2010 according to case study 1.

The total amount of GWP emitted from smelters increases to 114.4 % of the 1997 value. Certainly the specific amount of GWP emitted decreases to 4.5 t/t Al corresponding to 89.2 % of the 1997 specific value, including 1.7 t/t Al directly as CO_2 arising from anode consumption.

Emission of GWP gases case study 2 for 2010

In case study 2 there is an assumed change in the smelter technology, so aluminium is only produced by smelters in the HSS-PT, VSS-PT, SWPB-PT, PFPB-PT and PFPB-NT categories.

The total amount of GWP emitted from smelters decreases to 94.0 % of the 1997 value. The specific amount of GWP emitted decreases to 3.7 t/t Al corresponding to 73.2 % of the 1997 specific value, including 1.6 t/t Al directly as CO_2 from anode consumption.

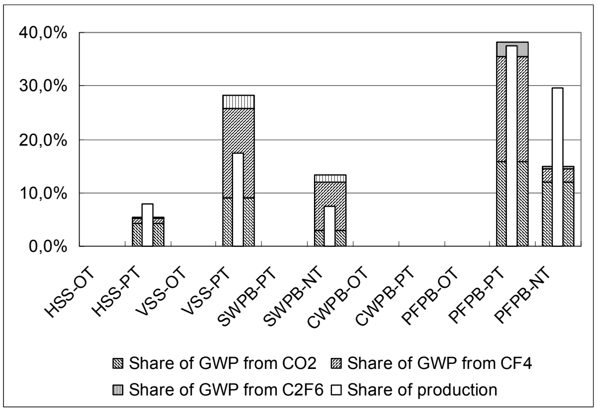

Figure 12: Share of production and emissions of CO_2 and CF_4 caused by different technical smelter categories in 2010 according to case study 2.

CO_2-emissions caused by anode production

The production of prebaked anodes causes emissions of GWP gases, in particular CO_2 from the combustion of baking furnace fuel. In 1997 8.7 Mt of anodes were produced, corresponding to 568 kg anodes/t Al. Under the conditions of case studies 1 and 2, by 2010 the production of anodes will increase to 11.7 Mt and 11.5 Mt, respectively, corresponding to 560 and 548.9 kg anodes/t Al, respectively. As 140 kg of CO_2 are actually emitted during the production of 1 t of anodes, the total CO_2 emissions will increase from 1.2 Mt CO_2 to 1.6 Mt by 2010 (case studies 1 and 2). The specific emissions caused by the lower consumption of anodes in the electrolysis will decrease from 79.6 kg CO_2/t Al in 1997 to 78.4 kg/t Al and 76.8 kg/t Al in 2010 in case studies 1 and 2 respectively. The data are compared in figure 13 relative to the 1997 data.

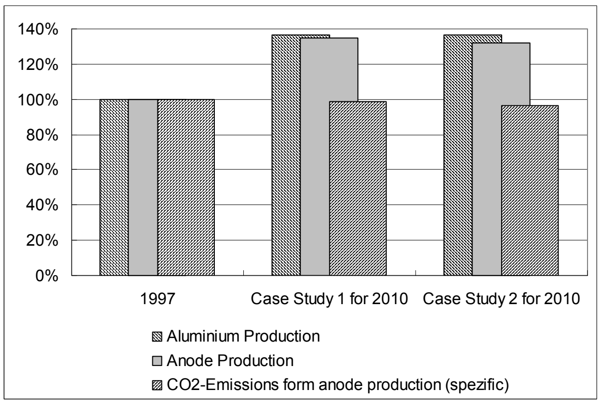

Figure 13: Comparison of aluminium production, anode production and specific CO_2 emissions due to anode production.

SO_2 Emissions from Smelters

The SO_2 emissions from cells depend on the S content of the petroleum coke, the net anode consumption, the cell hooding efficiency and the type of gas cleaning. With dry gas cleaning as the state of the art, no SO_2 fixation may be expected. If prebake cell technology is applied, there is also an amount of SO_2 emitted from the baking furnaces (20 % of the total emissions) if sulphur-containing fuels are used for baking. In 1997 ca. 10 Mt of anodes were consumed. This results in 406,000 t of SO_2 emitted from the cells, corresponding to 18.5 kg of SO_2/t Al based on an S content in the anode of 2 %. Not all of this SO_2 is emitted to the atmosphere, as some smelters clean their off- gas with wet scrubbers.

The fraction of smelters using wet scrubbing is not well known, but assuming 30 % of the world smelter capacity is doing this, the world average of specific SO_2 emissions to the atmosphere decreases to 13.5 kg SO_2/t Al. The total world emissions of SO_2 are shown in figure 14 for different shares of smelters operating with wet scrubbers. It is assumed that the efficiency of the scrubbers is 90 % in removing SO_2 emitted from the cells.

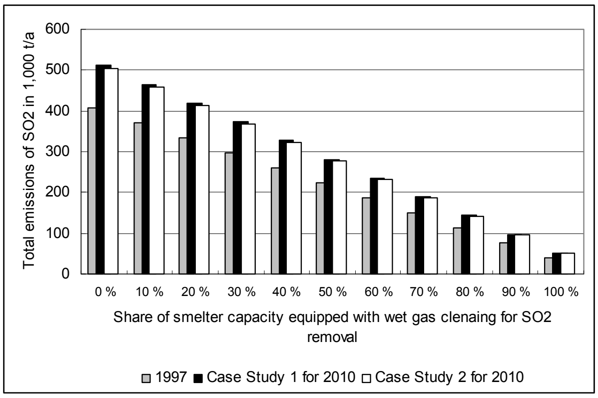

Figure 14: Total amount of SO_2 emitted to the atmosphere depending on the proportion of smelters operating with wet gas cleaning, assuming 2% sulphur in anodes.

What will happen in the future?

SO_2 emissions in 2010 case studies 1 and 2

In case study 1 the SO_2 amount emitted from the cell will decrease slightly to 18.2 kg SO_2/t Al due to the decreasing specific consumption of anodes (an S content of 2 % in the anode is also assumed for this case). If 30 % of the smelters apply wet scrubbers, the world average specific SO_2 emissions will also decrease to 13.3 kg/t Al. The total emissions of SO_2 depending on the proportion of smelters operating with wet scrubbers, are shown in figure 14.

In case study 2, the specific amount of SO_2 emitted from the cells will decrease to 17.9 kg/t Al due to the decreasing world average net anode consumption (again assuming an S content of 2 % in the anode). If 30 % of the smelters apply wet scrubbers, the world average specific SO_2 emissions will also decrease to 13.1 kg/t Al. The total emissions of SO_2, depending on the number of smelters operating with wet scrubbers, are shown in figure 14.

Conclusions

Most of the data from the case studies are shown in Table VII. For case studies 1 and 2 we assume that primary aluminium production will increase from nearly 22 Mt in 1997 to over 28 Mt in 2010, corresponding to 128.2 % of the 1997 amount. With no change in cell operations (case study 1) the specific electrical energy requirements will decrease to 14.6 kWh/kg Al, corresponding to 98.2 % of today's energy consumption, due to the installation of a modern smelter capacity of 3 Mt. At the same time the total electrical energy demand will increase to 126 % of the 1997 amount. With changes and optimisation of the smelter technologies (case study 2) the specific energy amount will decrease to 94.9 %, and the total energy consumption will increase to 121.6 % of the 1997 value. The decrease in the specific energy demand appears to be not very spectacular, but this is based only on the energy requirements of smelters, which are in operation today. Further developments in electrolysis technology are not included, such as larger cells and drained cells with wettable cathodes.

Table VII: Energy demand, anode net consumption, CO_2, CF_4 and C_2F_6 emissions from smelters for 1997, case study 1 and 2.

		1997		Case Study 1 for 2010		Case Study 2 for 2010	
Production	**t**	**21.943.639**	**100,0%**	**28.138.639**	**128,2%**	**28138639**	**128,2%**
Electrical energy	**total MWh**	**326.648.478**	**100,0%**	**411.437.178**	**126,0%**	**397.304.652**	**121,6%**
	kWh/kg Al	**14,9**	**100,0%**	**14,6**	**98,2%**	**14,1**	**94,9%**
Anode net consumption	**t**	**10.158.939**	**100,0%**	**12784597**	**125,8%**	**12616797**	**124,2%**
	kg/t Al	**463,0**	**100,0%**	**454,3**	**98,1%**	**448,4**	**96,8%**
CO_2 from anode consumption	**t**	**37.249.442**	**100,0%**	**46.876.855**	**125,8%**	**46.261.589**	**124,2%**
	kg/t Al	**1.698**	**100,0%**	**1.666**	**98,1%**	**1.664**	**98,0%**
CF_4	**t**	**10.032**	**100,0%**	**10.907**	**108,7%**	**7.913**	**78,9%**
	kg/t Al	**0,457**	**100,0%**	**0,388**	**84,9%**	**0,281**	**61,5%**
C_2F_6	**t**	**1.003**	**100,0%**	**1.091**	**108,8%**	**791**	**78,9%**
	kg/t Al	**0,046**	**100,0%**	**0,039**	**84,8%**	**0,028**	**60,9%**
GWP from CF_4	**t**	**65.208.182**	**100,0%**	**70.896.657**	**108,7%**	**51.438.479**	**78,9%**
	kg/t Al	**2.972**	**100,0%**	**2.520**	**84,8%**	**1.828**	**61,5%**
GWP from C_2F_6	**t**	**9.229.466**	**100,0%**	**10.034.604**	**108,7%**	**7.280.523**	**78,9%**
	kg/t Al	**421**	**100,0%**	**357**	**84,8%**	**259**	**61,5%**
Total GWP	**t**	**111.687.090**	**100,0%**	**127.808.115**	**114,4%**	**104.980.591**	**94,0%**
	kg/t Al	**5.090**	**100,0%**	**4.542**	**89,2%**	**3.737**	**73,4%**

Furthermore, 50 % of the aluminium is already produced in PFPB –smelters. Thus the major decreases have been made over the last 20 years due to the installation of this technology. On the other hand the decrease in emissions of gases with global warming potential is much larger, particularly the decrease of CF_4/C_2F_6 emissions. In case study 1, without any change in smelter technology, the specific emissions of CF_4/C_2F_6 will decrease to 85 % of the current value, with a slight increase to 108.7 % of total emissions. If recent existing smelters are optimised (shown in case study 2), the specific as well as the total emissions of CF_4/C_2F_6 will decrease to 61.5 % and 78.9 %, respectively, of the 1997 value. This leads to a decrease of total GWP emissions (including CF_4, C_2F_6 and CO_2 from anode consumption) to 94 % of the 1997 value. The specific GWP emissions can be reduced to 73.4 % of the 1997 value.

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PRIMÄRENERGIEAUFWAND UND KUMULIERTE EMISSIONEN VERSCHIEDENER ELEKTROLYSESYSTEME ZUR ALUMINIUMHERSTELLUNG*

(PRIMARY ENERGY DEMAND AND CUMULATED EMISSIONS OF DIVERSE ELECTROLYSIS FOR THE PRODUCTION OF PRIMARY ALUMINIUM)

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ABSTRACT

An essential element of a holistic view concerning material flows is the energetic analysis of processes. The process chain of aluminium production is marked by the high need for electricity of the primary aluminium smelter. Thus the efforts to optimise the energy supply concentrate on this step of the process. Subject of the present examination is an exemplary comparison of three different aluminium smelters. The systems are compared regarding both final- and primary energy demand, because the amount of the primary energy demand of the aluminium production, depends on the applied electrolysis technology as well as on the type of electricity supply. Furthermore the influence on cumulated emissions of selected substances is examined. On the whole it is shown, that the primary energy use as well as cumulated emissions, evoked by the aluminium production, are more influenced by the kind of energy supply than by electrolysis technology. From this point of view the identification of global potentials concerning energy reduction and emissions decrease connected with the smelter requires the inclusion of its power supply.

KEY WORDS

aluminium, cumulative energy demand, emission, primary energy, final energy, holistic view

* Source: Erzmetall 52 (1999), S. 393-402

1 Einleitung

Metallische Werkstoffe bilden eine wichtige Basis für die Entwicklung der modernen Industriegesellschaft. Die durch die Bereitstellung und Nutzung von Metallen hervorgerufenen Massenflüsse sind ein wesentlicher Bestandteil anthropogener Stoffströme, die den globalen Stoff- und Energiehaushalt in zunehmendem Maße beeinflussen und ökologische, ökonomische sowie soziale Wirkungen auslösen.

Um bei der Ressourcennutzung der Forderung einer nachhaltigen Entwicklung gerecht zu werden, bedarf es umfassender Stoffstromanalysen und der verstärkten Anwendung von Stoffstrommanagementsystemen. An der methodischen und inhaltlichen Verwirklichung dieses Forschungszieles arbeiten verschiedene Institute der RWTH Aachen und des Forschungszentrums Jülich innerhalb des Sonderforschungsbereichs (SFB) 525 "Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe". Ziel der Arbeiten ist die Entwicklung eines integrierten Ressourcenmanagementsystems. Grundlage ist die detaillierte Abbildung von Stoffströmen und resultierenden Wirkungen primärer und sekundärer Bereitstellungsprozesse metallischer Rohstoffe.

Insbesondere die Analyse energetischer Aspekte bei der Primäraluminiumerzeugung ist Gegenstand der Zusammenarbeit der Teilprojekte Verhüttung und Energiebereitstellung innerhalb des SFB. Ein energetischer Vergleich verschiedener Prozesse kann grundsätzlich auf End- oder Primärenergiebasis erfolgen. Die endenergetische Analyse ermöglicht den Vergleich unterschiedlicher Verfahrenstechniken in Hinblick auf ihre Energieeffizienz bei gleichen Energieträgern. Die primärenergetische Analyse berücksichtigt den Einfluß der Energiebereitstellung und ermöglicht den Vergleich des Gesamtenergieaufwands von Prozessen an verschiedenen Standorten. Außerdem lassen sich in einer Stoffstromanalyse durch die Einbeziehung der Energiebereitstellung verschiedene Systeme in Hinblick auf kumulierte Emissionen und damit auf ökologische Wirkungen untersuchen und vergleichen.

Im folgenden werden exemplarisch drei Primäraluminiumhütten, die sich sowohl in der Art der Elektrolysetechnik als auch der Strombereitstellung unterscheiden, hinsichtlich End- und Primärenergiebedarf sowie kumulierter Emissionen verglichen. Dabei zeigt sich, daß im Rahmen eines ressourcenorientierten Stoffstrommanagements für den Rohstoff Aluminium neben der endenergetischen Optimierung der Elektrolysetechnik auch vor allem die Verbesserung der Stromversorgung berücksichtigt werden muß.

2 Primäraluminiumerzeugung

Aluminium und seine Legierungen haben sich aufgrund werkstofftechnischer Vorteile aus Dichte, Festigkeit, Leitfähigkeit und Korrosionsbeständigkeit zu bedeutenden Werkstoffen entwickelt. Die steigende Verwendung von Aluminium führt trotz steigender Sekundärproduktion zu einem weiteren Anstieg der Primärerzeugung [1].

Primäraluminium wird weltweit an 155 Standorten hergestellt. Fast 80% der weltweiten Primäraluminiumproduktion, die sich 1996 auf 21 Mio. t belief, wird von 10 Ländern gedeckt (Abbildung 1) [2].

2.1 Technische Aspekte der Primäraluminumerzeugung

Primäraluminium wird großtechnisch durch die Reduktion von Aluminiumoxid in der Schmelzflußelektrolyse erzeugt. Dazu wird Al_2O_3 in einem Fluoridelektrolyten gelöst und bei einer Stromstärke bis 320 kA und einer Spannung von ca. 4,5 V kathodisch abgeschieden. Flüssiges Aluminium sammelt sich am Boden der Zelle und kann dort abgesaugt werden.

Die eingesetzten Elektrolysezellen unterscheiden sich hinsichtlich der Art der Anoden sowie in der Art der Tonerdechargierung. Bei den Anoden werden zwischen Söderberg-Anoden und vorgebrannten Anoden unterschieden. Söderberg-Anoden bestehen aus einer vorgemischten Anodenmasse aus (Steinkohlen-) Teerpech und kalziniertem (Petrol-)Koks, die kontinuierlich während des Elektrolysebetriebs durch die Ofenhitze zu fester Anodenkohle verbackt. Bei der Stromzuführung werden horizontal (HSS = Horizontal Stud Söderberg) oder vertikal (VSS = Vertikal Stud Söderberg) in die Anodenmasse ragende Strombolzen unterschieden.

Qualitative Anforderungen und unzureichende Kapselung der Zellen führten zur Entwicklung der vorgebrannten Anoden. Diese werden in einem vorgelagerten Prozeßschritt aus Pech, Petrolkoks und Anodenresten hergestellt. Die Mischung wird geformt und in gas- oder ölbeheizten Ringkammeröfen gebrannt. In die Oberseite dieser Anodenblöcke werden anschließend Stromzuführungsbolzen eingelassen. So vorbereitete Anoden werden in das Elektrolysebad eingehängt und an die Stromzuführung angeschlossen. Zellen mit solchen Anoden werden als PB-Zellen bezeichnet (PB = Pre Baked).

Hinsichtlich der Art der Tonerdezugabe lassen sich drei PB-Techniken unterscheiden. Bei der ältesten Methode wird die Kruste aus erstarrtem Elektrolyt und Tonerde seitlich mit Brechhämmern oder -rädern aufgebrochen und eine größere Menge Tonerde in das Elektrolysebad nachchargiert. So werden die sogenannten Side Worked-PB-Zellen (SWPB), wie auch HSS-und VSS-Zellen mit Tonerde versorgt. Aufgrund der auftretenden Verstaubung sowie unzureichender Möglichkeit der Dosierung und Automatisierung wurden die PB-Zellen weiterentwickelt. In CWPB-Zellen (Center Worked Pre Baked) wird die Kruste in der Mitte zwischen zwei Anodenreihen durch einen Stahlbalken durchbrochen und die Tonerde dort nachchargiert. Dieser Zellentyp wurde schließlich zu den sogenannten PFPB-Zellen (Point Feeder Pre Baked) weiterentwickelt, bei denen mehrere Dosierstößel den Brechbalken der CWPB-Zelle ersetzen. Die Tonerdezufuhr erfolgt öfter, in kleineren Mengen und wird durch kontinuierliche Überwachung der Zellenspannung gesteuert. So wird eine wesentlich konstantere Al_2O_3-Konzentration im Elektrolyten erreicht, wodurch die Zahl der Anodeneffekte sinkt, Emissionen insbesondere von Fluorkohlenstoff vermindert werden und die Stromausbeute gesteigert wird.

Die insgesamt fünf Zelltypen unterscheiden sich durch den spezifischen Stromverbrauch (Abbildung 2). Die auftretenden Bandbreiten sind im jeweiligen Stand der eingesetzten Technik hinsichtlich Prozeßüberwachung, Automatisierungsgrad, Optimierung der Stromzufuhr, Kompensation der Magnetfelder, Badzusammensetzung und Qualität der Anodenmaterialien begründet. Jedoch lassen kapazitätsgewichtete Mittelwerte die Tendenz erkennen, daß die Söderberg-Technik als ältestes Verfahren den höchsten und moderne PFPB-Zellen den geringsten spezifischen Stromverbrauch aufweisen. Dabei beinhaltet der Stromverbrauch der Söderbergzellen allerdings auch den Energieaufwand zum Brennen der Anodenmasse in der Elektrolysezelle, das bei den PB-Zellen in einem getrennten Prozeßschritt erfolgt.

Für eine energetische Gesamtbetrachtung müssen außerdem jeweils die spezifischen Verbräuche von Anodenkohle, Kryolith und anderen Stoffen bzw. mit deren Bereitstellung verbundene Energieaufwendungen berücksichtigt werden. Auch bei diesen Stoffen erfordern die neueren Elektrolysetechnologien geringere Aufwendungen als die älteren Verfahren.

Die Anteile der verschiedenen Elektrolysesysteme an der weltweit installierten Kapazität zeigt Abbildung 3 [2]. Danach wird in fast der Hälfte der Primäraluminiumhütten moderne PFPB-Technik eingesetzt, und knapp ein Drittel der Kapazität wird durch Söderbergöfen gedeckt.

2.2 Stromversorgung von Aluminiumhütten

Für die primärenergetische Bilanzierung der Aluminiumherstellung ist die Kenntnis der Stromversorgungsstruktur der Aluminiumhütten entscheidend. Die meisten Aluminiumhütten beziehen elektrische Energie nicht aus dem landestypischen Verbundnetz, sondern aus eigenen bzw. eindeutig zuweisbaren Kraftwerken. Diese Kombination einer Hütte mit einem Kraftwerk wird als Insellösung bezeichnet. Oft weichen die Anteile der Primärenergieträger an der Stromerzeugung für die Aluminiumhütten deutlich vom landestypischen Strommix ab.

Wie aus Abbildung 4 hervorgeht, dominiert als Primärenergie für die Elektrizitätsversorgung von Aluminiumhütten (Insellösung) in den wichtigsten Erzeugerländern Wasserkraft. Diese ist bezogen auf z.B. SO_2 und NO_x in der Betriebsphase als emissionsfrei anzusehen. Über ein Drittel der Elektrolysen werden mit Strom aus fossil gefeuerten Kraftwerken betrieben, die neben CO_2 auch beträchtliche Mengen von SO_2, NO_x und Staub emittieren. Neben den Länderbeispielen zeigt Abbildung 4 auch die Anteile der Primärenergieträger am gesamten Weltstrommix. Hier trägt Wasserkraft nur zu einem Fünftel zur Stromproduktion bei, und fossile Energieträger leisten mit knapp zwei Dritteln den weitaus größten Beitrag zur weltweiten Stromerzeugung. Dieser Unterschied verdeutlicht nochmals die Relevanz der korrekten Wahl des Strommixes bei der Ermittlung des Primärenergieaufwandes oder kumulierter E-missionen für die Aluminiumherstellung. Eine Berechnung auf der Grundlage landes- oder regionentypischer Strommixe kann somit wegen der meist anzutreffenden Insellösungen bei Primäraluminiumhütten zu stark verfälschten Ergebnissen führen.

3 Methodik zur end- und primärenergetischen Analyse

Im Rahmen einer ressourcenorientierten Gesamtbetrachtung des Aluminiumstoffstroms stellt der mit der Gewinnung von Primäraluminium verbundene energetische Aufwand eine wesentliche Größe entlang der gesamten Prozeßkette dar.

Um verschiedene Elektrolyseprozesse energetisch zu vergleichen, sind die spezifischen Endenergieeinsätze zu analysieren. Dabei müssen die thermodynamischen Energiequalitäten berücksichtigt werden, d.h. elektrische Energie kann nicht unmittelbar mit thermischer Energie oder der chemisch in Brennstoffen gebundenen Energie verglichen werden.

Die Erfassung der Energieaufwendungen ausschließlich auf der Ebene von Endenergien (Brennstoffe, Dampf, Strom) ist problematisch, da der gesamte energetische Aufwand eines Prozesses nicht durch einfache Addition der verschiedenen Endenergien ermittelt werden kann. Außerdem könnten keine Aussagen über die Energieaufwendungen und Verluste für ihre Bereitstellung und über die Energieressourcennutzung gemacht werden.

Der gesamte energetische Aufwand eines Prozesses kann für bestimmte Standorte bzw. Regionen durch die Ermittlung der zur Endenergiebereitstellung erforderlichen Menge Primärenergie bestimmt werden, also dem Verbrauch von Energie die in Primärenergieträgern (Rohkohle, Erdöl, Erdgas, Uran, ...) gespeichert ist. Als nachteilig erweist sich bei einer derartigen Aggregation, daß Informationen über Prozeßenergien verlorengehen und einzelne Techniken bzw. Einzelstandorte nicht mehr verglichen werden können.

Im Sinne einer ganzheitlichen Betrachtung sind energetische Analysen bzw. Vergleiche von Prozessen also sowohl auf Endenergie- als auch auf Primärenergiebasis durchzuführen.
Den Zusammenhang zwischen nutzbarer Endenergie und dem Primärenergieaufwand zu ihrer Bereitstellung beschreiben die Bereitstellungsnutzungsgrade g_{el} für Elektrizität und g_{fuel} für Brennstoffe:

$$g_{el} = \frac{W_{el}}{m_B^{prim} \cdot H_u^{prim} + \sum_i KEA_{Anlage,i}} \text{ bzw. } g_{fuel} = \frac{m_B \cdot H_u}{m_B^{prim} \cdot H_u^{prim} + \sum_i KEA_{Anlage,i}} \quad \text{(vergl. [4])}$$

Das Produkt aus der Masse des Primärenergieträgers m_B^{prim} und seinem Heizwert H_u^{prim} beschreibt den Energieinhalt des Primärenergieträgers und $\sum_i KEA_{Anlage,i}$ die kumulierten Energieaufwendungen für die Herstellung, den Betrieb und die Entsorgung sämtlicher Anlagen, Maschinen und Betriebsstoffe, die zur Bereitstellung der nutzbar gemachten Energie W_{el} bzw. $m_B \cdot H_u$ benötigt werden. Der Bereitstellungsnutzungsgrad charakterisiert damit ähnlich einem Wirkungsgrad die Effizienz einer Energiebereitstellung unter Berücksichtigung sämtlicher energetischer Aufwendungen. Somit kann der Einsatz von Endenergien, z.B. von elektrischem Strom oder Heizöl primärenergetisch bewertet werden.

Die Ermittlung der Primärenergieaufwendungen erfolgt zweckmäßigerweise durch eine Prozeßkettenanalyse. Hierfür werden zunächst alle bezüglich Stoff- oder Energieströmen relevanten Prozesse als Module dargestellt und deren In- und Outputs in der Betriebsphase in einer Sachbilanz erfaßt. Anschließend werden die Endenergieeinsätze mit Hilfe der Bereitstellungsnutzungsgrade primärenergetisch bewertet. Eine weitergehende Untersuchung der Stoff- und Energieeinsätze zur Herstellung bzw. Entsorgung der erfaßten Stoffe, zur Bereitstellung der Endenergien sowie die zusätzliche Berücksichtigung der Herstellungs- und Entsorgungsprozesse von Betriebsmitteln und Anlagen führt zu praktisch unendlich komplexen Prozeßketten, deren vollständige Analyse unmöglich ist. Grundsätzlich muß mit Hilfe zielorientierter Systemgrenzen und Abschneidekriterien zwischen relevanten und nicht relevanten Stoffen und Energieströmen unterschieden werden.

In gleicher Weise können auch kumulierte Emissionen ermittelt werden, die sich dann aus prozeßbedingten Emissionen der Hauptprozeßkette bzw. der betrachteten Vor- und Nebenketten und aus den Emissionen durch die Energiebereitstellung zusammensetzen.

4 Modellbildung

Ein allgemeines Modell zur Abbildung einer Aluminiumhütte umfaßt neben der Elektrolysezelle die vor- bzw. nachgelagerten Prozeßschritte der Anodenherstellung und der Abgasreinigung, wobei das Modul Anodenherstellung bei Hütten mit Söderbergöfen keinen Brennprozeß enthält. Rohstoff ist in jedem Fall Aluminiumoxid, das weltweit hauptsächlich im Bayerprozeß aus Bauxiterz extrahiert und anschließend kalziniert wird. Das Produkt der Hütte ist flüssiges Primäraluminium, das dann in der Gießerei zu Formaten vergossen wird. Abbildung 5 veranschaulicht die allgemeingültige Prozeßkette einer Aluminiumhütte mit den relevanten ein- und austretenden Stoff- und Energieströmen.

Die energetischen Analysen der vorliegenden Untersuchung konzentrieren sich auf die Energieeinsätze der Elektrolyse und der Anodenherstellung sowie deren Bereitstellung. Innerbetriebliche Transportprozesse, die Bereitstellung diverser Hilfsstoffe und Nebenprozesse werden aufgrund der vergleichsweise geringen Relevanz vernachlässigt.

5 Beispielrechnung

Die vorgestellte Methodik wird im folgenden beispielhaft auf drei Aluminiumhütten mit jeweils verschiedenen Elektrolysesystemen (VSS, SWPB und PFPB) und unterschiedlicher Stromversorgung (Wasserkraft-, Steinkohle- bzw. Kernkraftwerk) angewendet.

Tabelle 1 zeigt charakteristische Daten der einzelnen Systeme, die sich endenergetisch vor allem im spezifischen Strom-, Brennstoff- und Anodenverbrauch unterscheiden [2, 5]. Um eine Vergleichbarkeit der genannten Prozesse gewährleisten zu können, wird angenommen, daß die Tonerde aus demselben Werk und in gleicher Weise bezogen wird. Die kumulierten Energieaufwendungen sollen dabei gleich groß sein.

5.1 Endenergetischer Vergleich

Um die ausgewählten Aluminiumhütten hinsichtlich der jeweils verwendeten Elektrolysetechnik energetisch zu vergleichen, sind die spezifischen Endenergieeinsätze zu analysieren. In Abbildung 6 ist der Vergleich der Einsätze von Strom und chemischer Energie in den verschiedenen Hütten dargestellt. Dabei ist neben dem Stromaufwand für die Elektrolyse auch der für das Mischen der Anodenmasse dargestellt, welcher allerdings um fast drei Größenordnungen geringer und daher am Kopf der Säulen kaum zu erkennen ist.

Erwartungsgemäß benötigt die PFPB-Anlage etwa 25% weniger elektrische Energie als die VSS-Elektrolyse, der Stromeinsatz der SWPB-Hütte liegt dazwischen.

Der Vergleich der Gesamteinsätze von chemischer Energie läßt dagegen kaum Unterschiede bei den einzelnen Techniken erkennen. Die Kohlenstoffanoden werden zwar in erster Linie durch Oxidation verbraucht, wegen der freigesetzten Energie werden sie allerdings in der Energiebilanz erfaßt. Obwohl das VSS-Verfahren einen deutlich höheren (Netto-)Anodenverbrauch aufweist als die PB-Elektrolysen, ergeben sich durch den Einsatz von Erdgas und Koksgruß für das Backen der Anoden insgesamt etwa gleich große Aufwendungen chemischer Energie. Wegen des zusätzlichen Energieaufwands zum Backen der Anodenreste liegt der chemische Energieeinsatz der PFPB-Anlage sogar knapp über dem der VSS-Elektrolyse.

5.2 Primärenergieaufwand

Werden nun die ermittelten Endenergien mit den relevanten Bereitstellungsnutzungsgraden (Tabelle 2) in Primärenergie umgerechnet, ergibt sich für die drei Standorte ein völlig anderes Bild, da der Primärenergieverbrauch einer Aluminiumelektrolyse maßgeblich von der Stromerzeugungstechnik bzw. dem Primärenergieträger abhängt. In Abbildung 7 ist der Primärenergieaufwand der in Tabelle 1 beschriebenen Elektrolysen einschließlich der vorgelagerten Anodenherstellung dargestellt.

Erwartungsgemäß wird der gesamte Primärenergieeinsatz von der elektrischen Energie bzw. ihrer Bereitstellung dominiert. Insbesondere der Wirkungsgrad des Kraftwerks bestimmt die Höhe des gesamten Primärenergieaufwands für die Verhüttung. Somit muß für die Aluminiumherstellung in Norwegen nur etwa halb so viel Primärenergie eingesetzt werden wie in Deutschland, obwohl der spezifische Strombedarf der Elektrolyse deutlich höher ist. Lediglich der primärenergetische Vergleich der Hütten in Deutschland und Australien spiegelt den unterschiedlichen spezifischen Strombedarf für die Elektrolyse wieder, da sich in diesem Fall die Bereitstellungsnutzungsgrade für die elektrische Energie nur wenig unterscheiden.

5.3 Energieressourceneinsatz für die Strombereitstellung

Aus dem Primärenergiebedarf der Strombereitstellung resultiert über den Energieinhalt des jeweiligen Primärenergieträgers seine Einsatzmenge und somit ein Maß für die Energieressourcenintensität eines Prozesses, d.h. den Verbrauch einer Energieressource.

Für regenerative Energieträger wie Wasserkraft ist eine derartige Betrachtung nicht sinnvoll, da es sich in diesem Fall definitionsgemäß um nicht erschöpfliche Energien handelt.
In Tabelle 3 ist der spezifische Energieressourceneinsatz der Strombereitstellung für die Aluminiumhütten in Deutschland und Australien gegenübergestellt. Der Unterschied von vier Zehnerpotenzen ist durch die Differenz der Energieinhalte von Steinkohle mit einem Heizwert von 25 MJ/kg und Uran mit einem Energieinhalt von 450.000 MJ/kg, was einem mittleren Abbrand der Brennelemente von 34.000 MWd/t entspricht, begründet [7, 8]. Um die Energiebereitstellung unter dem Aspekt der Ressourcenschonung zu analysieren, müssen die spezifischen Verbräuche von Primärenergieträgern auf die entsprechenden Vorräte bezogen werden. Dabei sind heute bzw. zukünftig wirtschaftlich gewinnbare und geologische Vorräte zu unterscheiden. Weiterhin sind Möglichkeiten der Wiederaufarbeitung von abgebrannten Brennelementen oder der Einsatz von Kernbrennstoffen in Brutreaktoren zu berücksichtigen, die ausgewiesene Vorräte um den Faktor 100 erhöhen können.

5.4 Kumulierte Emissionen

Analog zur Ermittlung des Primärenergieaufwands der Aluminiumhütten sind kumulierte Emissionen von CO_2, SO_2 und Staub als ausgewählte Stoffe berechnet worden, die zum einen bei der Elektrolyse sowie der Anodenherstellung und zum anderen durch die Energiebereitstellung entstehen (Abbildung 8) [9, 10, 11, 12, 13].
Für die Berechnung der CO_2-Emissionen wurde für die Anoden ein Kohlenstoffanteil von 99 Gew.-% und ein CO_2-Anteil von 90% angenommen. 50% des entstehenden CO reagiert innerhalb der Hütte zu CO_2 weiter. Bei Söderberg-Anlagen wird das Zellenabgas zur Teerentfernung nachverbrannt. Dadurch steigt der Umsatzgrad des CO auf 90%. Der Schwefelgehalt der Anoden betrage 1 Gew.-%, die Hütten A und B sind mit einer nassen Abgasreinigung ausgerüstet, die für SO_2 einen Abscheidegrad von 95% haben. Die spezifischen Staubemissionen sind abhängig von der eingesetzten Elektrolyse- und Abgasreinigungstechnik [10]. Das Erdgas als Brennstoff im Anodenofen enthalte 85 Gew.-% Methan. Bei den Emissionen durch die Strombereitstellung werden für Wasser- und Kernkraftwerk jeweils kumulierte Emissionen für Bau, Betrieb und Entsorgung der Anlagen angesetzt, für das australische Steinkohlekraftwerk die Emissionen eines Referenzkraftwerks.

Die Abbildung 8 zeigt, daß für alle berücksichtigten Stoffe erwartungsgemäß nur die Steinkohleverstromung in Australien einen bedeutenden Einfluß auf die Gesamtemissionen hat. Ansonsten dominieren die durch den Anodeneinsatz hervorgerufenen Emissionen. Dadurch ergibt sich insgesamt im Vergleich zum Endenergieeinsatz (vergl. Abbildung 6) ein qualitativ umgekehrtes Bild. Die Aluminiumhütte mit der modernsten Elektrolysetechnik und dem folglich geringsten Endenergieeinsatz weist die höchsten und das veraltete VSS-Verfahren die geringsten kumulierten CO_2-, SO_2- und Staubemissionen auf. Besonders drastisch ist der Unterschied bei den spezifischen SO_2-Emissionen, die für das Beispiel C um ein (Hüttenbetrieb) bis zwei (Stromerzeugung) Größenordnungen über den Beispielen A und B liegen. Aufgrund fehlender SO_2-Grenzwerte in Australien sind nämlich weder in der Aluminiumhütte noch im Kraftwerk Entschwefelungsanlagen installiert.

6 Zusammenfassung

Im Rahmen der Prozeßkettenanalyse des Aluminiumstoffstroms spielt der Energieaufwand zur Verhüttung von Tonerde eine bedeutende Rolle. Da der Endenergieeinsatz für diesen Prozeßschritt den Energieaufwand entlang der gesamten Aluminiumprozeßkette dominiert, existieren hier auch absolut die größten Energieeinsparpotentiale, die durch einen detaillierten Vergleich verschiedener Systeme identifiziert werden können. Die Beispielrechnungen zeigen, daß unterschiedliche Verfahrenstechniken auf Endenergiebasis verglichen werden können, wobei jeweils nur gleiche Energieträger betrachtet werden dürfen. Für den Vergleich des Gesamtenergieaufwands mehrerer mehrerer Systeme (Aluminiumhütte und Energiebereitstellung) muß der jeweilige Primärenergieaufwand ermittelt werden. Dann werden auch Einflüsse der Strombereitstellung berücksichtigt, die für den gesamten Energieeinsatz bei der Aluminiumerzeugung von großer Bedeutung sind. Dies wird im Rahmen der vorgestellten Analysen deutlich, da die Aluminiumelektrolyse durch einen hohen Bedarf an elektrischer Energie geprägt ist, und die Art ihrer Bereitstellung sowohl den spezifischen Primärenergieaufwand als auch die kumulierten Emissionen pro kg Al stärker beeinflußt als die Elektrolysetechnik. Die ökologische Bewertbarkeit eines Systems ist somit nur unter Einbezug von Ressourcennutzung und Emissionen aussagekräftig.

Während hier drei Beispiele zur energetischen Analyse der Primäraluminiumerzeugung ausgewählt worden sind, können mit dem entwickelten Prozeßkettenmodell des SFB 525 die weltweiten Aluminiumhütten, einschließlich relevanter Vor-, Neben-, und nachgelagerter Ketten sowie deren Energieversorgung abgebildet werden. Damit sind umfassende Analysen bzw. Szenariorechnungen zur optimalen Gestaltung von Stoffströmen im Zusammenhang mit der Herstellung, der Nutzung und dem Recycling von Aluminium möglich. Dabei liegt ein Schwerpunkt der Teilprojekte Verhüttung und Energiebereitstellung bei der Identifikation globaler Einsparpotentiale von End- und Primärenergie.

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Tabellen/Graphiken

allgemeine Daten				
		Beispiel A	Beispiel B	Beispiel C
Standort[1]		Norwegen	Deutschland	Australien
Elektrolysetyp[1]		VSS dry paste	SWPB kontinuierlich	PFPB
Kapazität[1]	1000 t/a	50	70	440
Stromversorgung[1]		Wasserkraftwerk	Kernkraftwerk	Steinkohlekraftwerk
Stromstärke[1]	kA	115	130	187
Stromausbeute[1]	%	91,0	90,8	96,0
Ofenspannung[1]	V	5,44	4,66	4,16
Ofenzahl[1]		168	204	760
Stoffinputs				
Tonerde[2]	g/kg_{Al}	1.930	1.930	1.930
Steinkohlenteerpech[1, 3]	g/kg_{Al}	130,00	65,25	79,55
Petrolkoks[1, 3]	g/kg_{Al}	370,00	369,75	352,27
Anodenreste[1, 4]	g/kg_{Al}	0,00	0,00	76,20
Kryolith[1]	g/kg_{Al}	25,00	1,50	0,00
AlF_3[1]	g/kg_{Al}	54,00	20,00	12,50
Packmaterial[5]	g/kg_{Al}	0,00	19,58	22,86
Stoffoutputs				
Aluminium	kg_{Al}	1,00	1,00	1,00
CO_2[6]	g/kg_{Al}	1.796,85	1.645,55	1.659,00
CO[6]	g/kg_{Al}	11,55	50,24	49,88
SO_2[6]	g/kg_{Al}	0,50	0,44	8,64
Energieinputs				
elektr. Energie				
Anodenherstellung[7]	kWh/kg_{Al}	0,07	0,12	0,11
Elektrolyse[1]	kWh/kg_{Al}	17,90	15,30	13,20
chem. Energie				
Energieinhalt Anoden[8]	MJ/kg_{Al}	15,00	13,05	12,95
Brennstoff Anodenofen[9]	MJ/kg_{Al}	0,00	1,31	1,52
Packmaterial	MJ/kg_{Al}	0,00	0,59	0,69

1: [2, 5]; 2: Annahme gleicher Tonereeinsatzmenge; 3: 15 (26) Gew.-% Steinkohlenteerpech, 85 (74) Gew.-% Petrolkoks in PB-Anode (Söderberg-Anode); 4: 15 Gew.-% Anodenreste bei Beispiel C, keine Anodenreste bei Beispiel B wegen kontinuierlicher Nachführung der Anoden; 5: Annahme: 45 g/kg_{Anode} Koksgruß (100% C) als Packmittel im Anodenofen; 6: Emissionen aus Erdgas-, Koksgruß- und Anodenverbrennung; 7: Annahme: spez. Strombedarf 0,266 kWh/kg_{Anode} verteilt sich gleichmäßig auf das Mischen der Anodenmasse und das Formen der Anodenblöcke; 8: Heizwert der Anoden $H_{U, Anode}$ = 30 MJ/kg; 9: Annahme: 3 MJ/ kg Anode spez. Energieeinsatz zum Brennen der Anoden

Tabelle 1: Daten zu Stoff- und Energieeinsätzen verschiedener Elektrolysesysteme

Energieträger	$\eta_{el,netto}$ (%)	g_{fuel} (%)	g_{el} (%)
Steinkohle	35 (Dampfkraftprozeß)	95,0	35,2
Kernbrennstoffe	32 (Druckwasserreaktor)	99,0	31,7
Wasserkraft	80	100,0	80,0
Anodenkohle	-	90,0	-
Koksgruß	-	90,0	-
Erdgas	-	90,0	-

Tabelle 2: Bereitstellungsnutzungsgrade verschiedener Energieträger [5, 6, 7]

Deutschland (Kernkraftwerk)	U_3O_8	$3{,}69 \cdot 10^{-4}$
Australien (Steinkohlekraftwerk)	Steinkohle	5,51

Tabelle 3: Spezifischer Einsatz von Primärenergieträgern für die Stromversorgung von Aluminiumhütten in kg/kg_{Al} [7, 8]

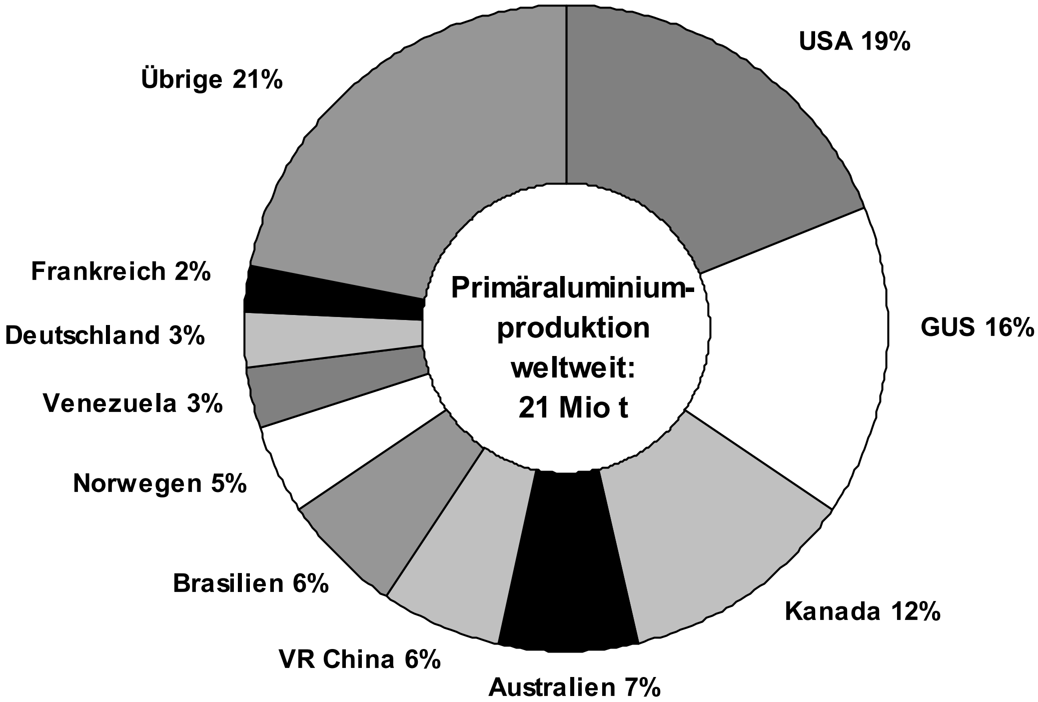

Abbildung 1: Führende Staaten der Primäraluminiumerzeugung (1996) [2]

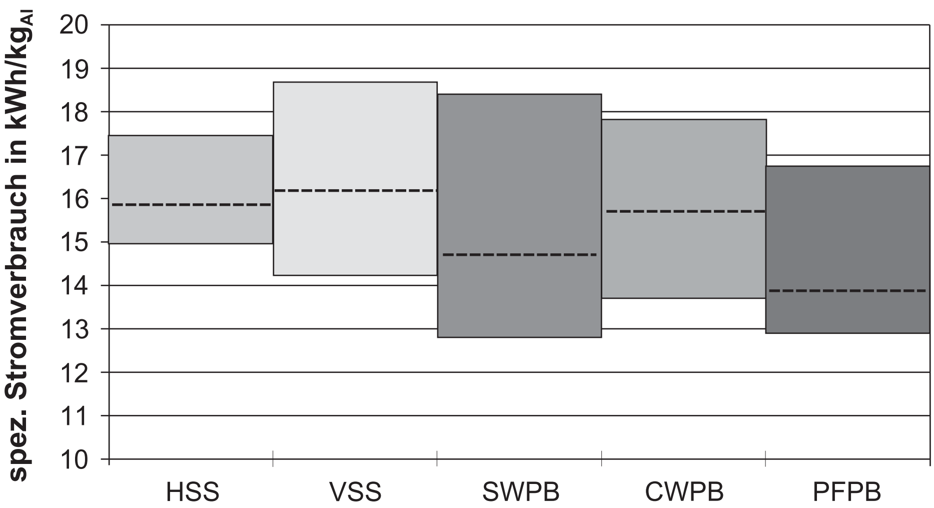

Abbildung 2: Stromverbräuche verschiedener Elektrolysesysteme [2]

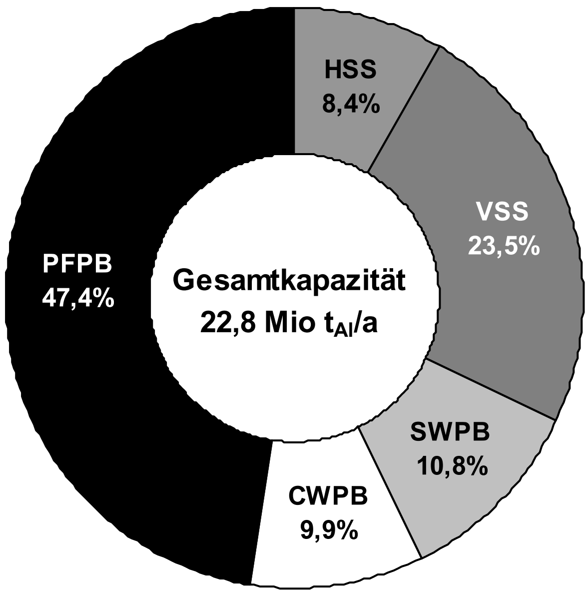

Abbildung 3: Anteile verschiedener Zelltypen an der weltweit installierten Kapazität [2]

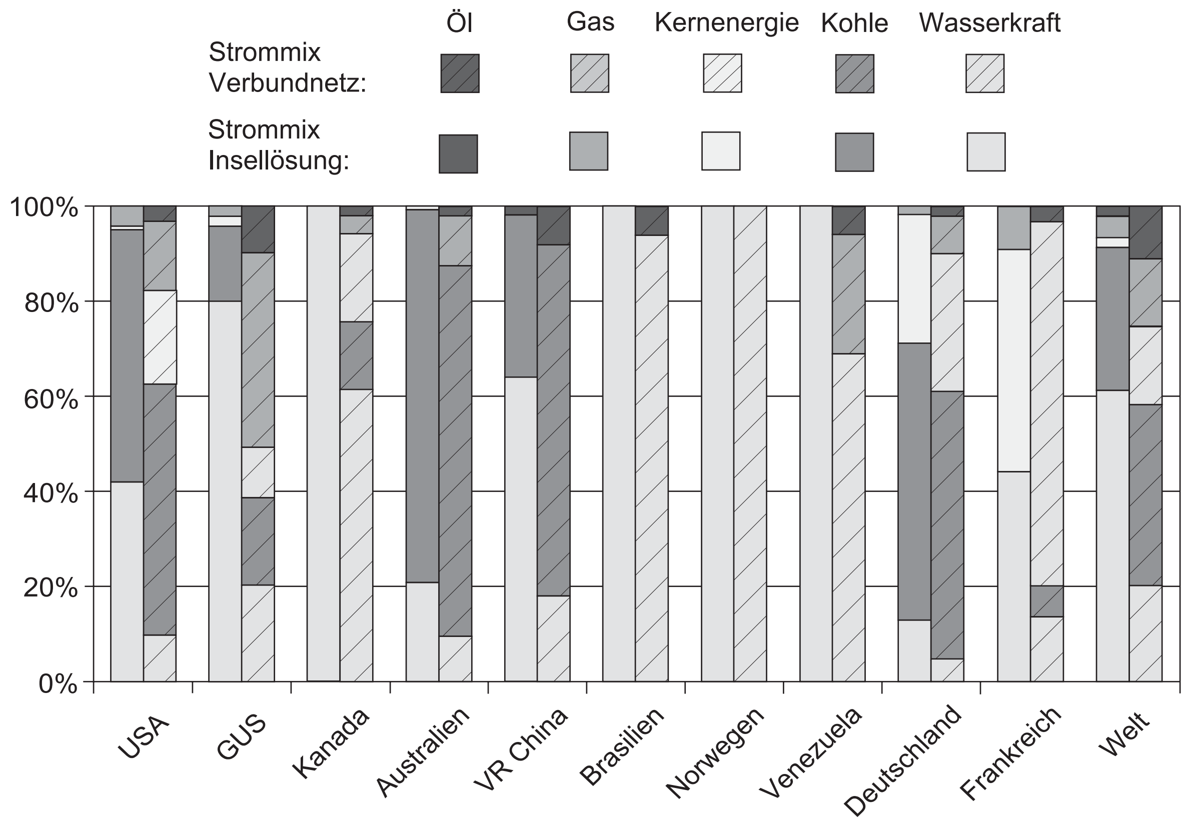

Abbildung 4: Vergleich der Energieträger für die Strommixe von Insellösungen und Verbundnetzen [2, 3]

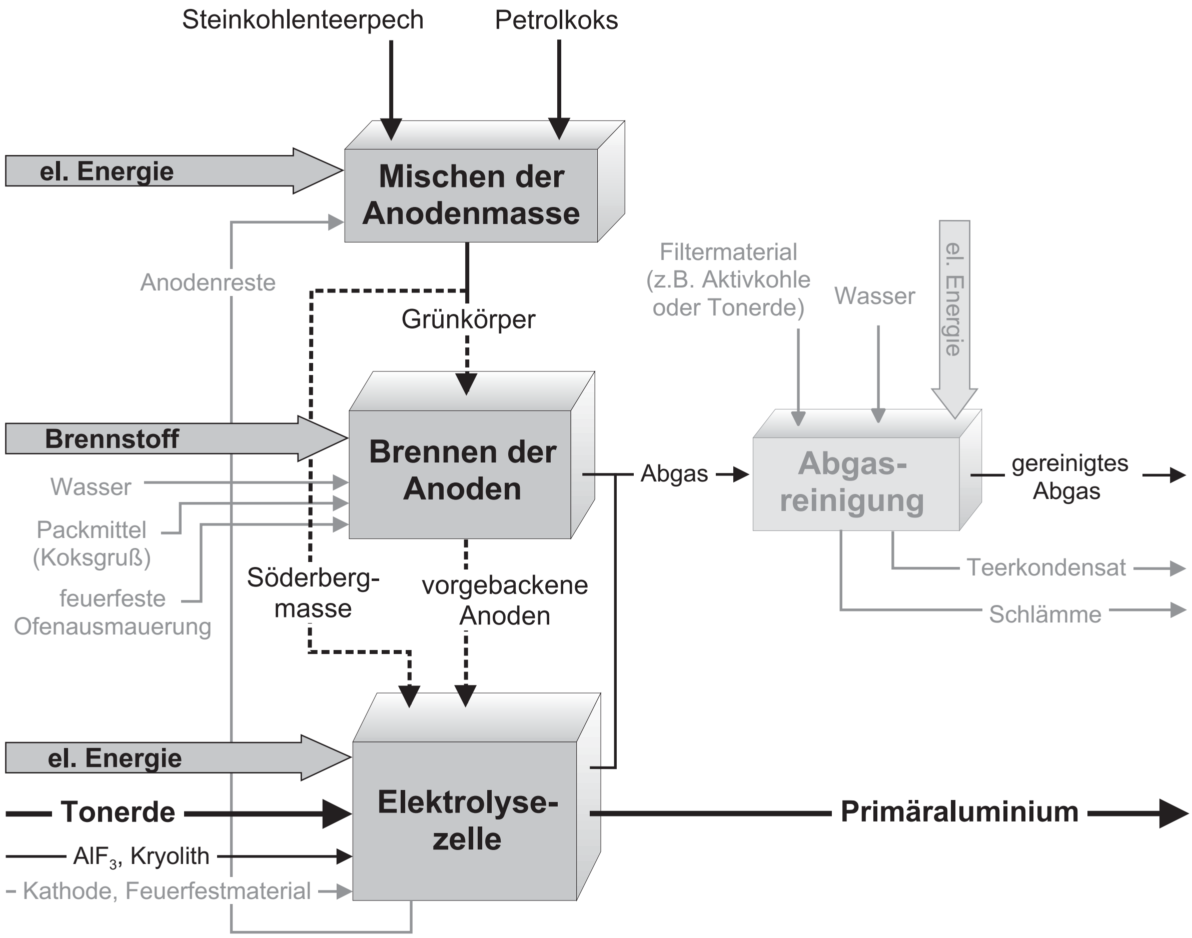

Abbildung 5: Relevante Module, Stoff- und Energieströme der Aluminiumhütte

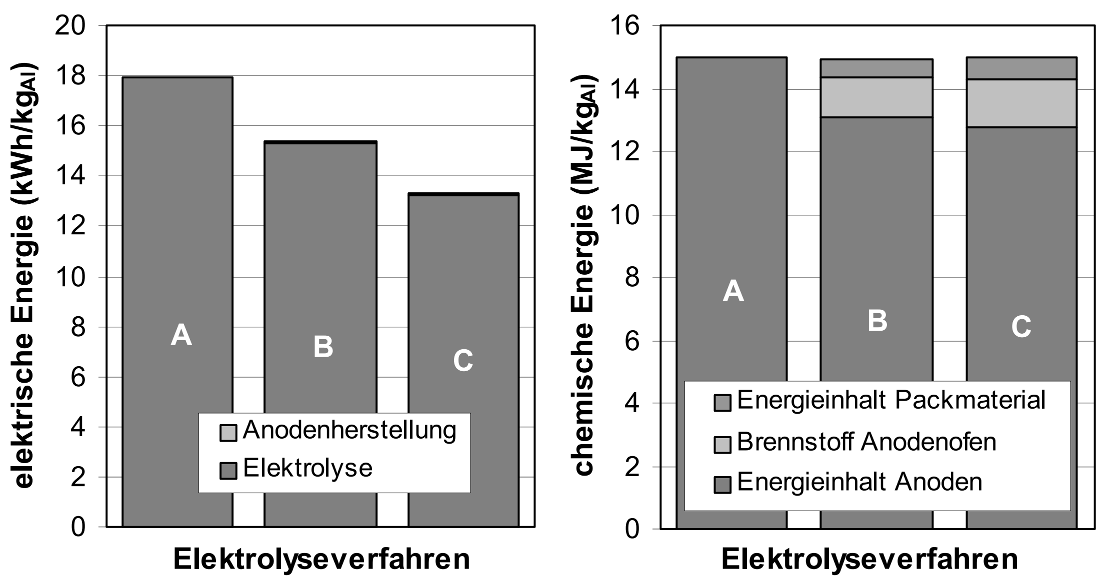

Abbildung 6: Vergleich der Einsätze von Strom bzw. chemischer Energie in den betrachteten Aluminiumhütten

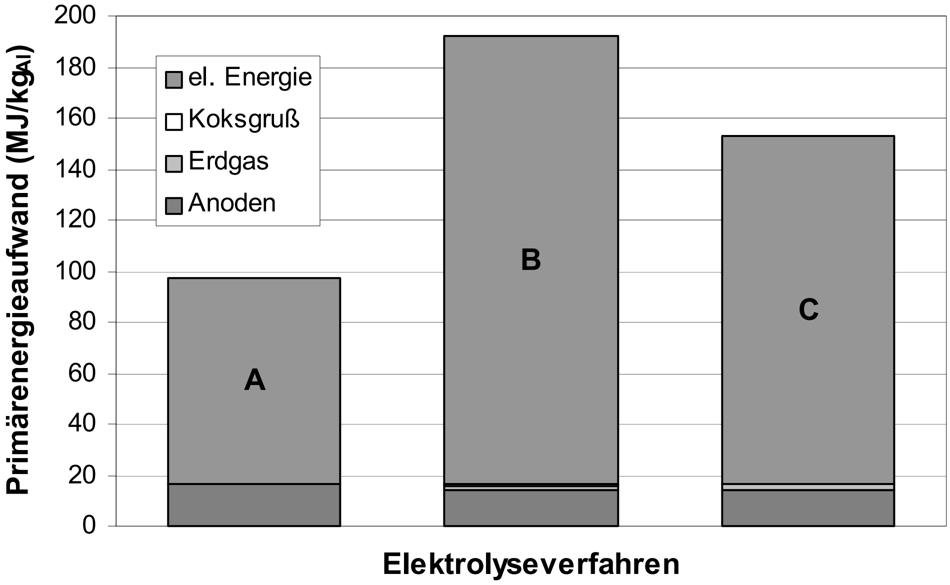

Abbildung 7: Primärenergiebedarf der betrachteten Aluminiumhütten

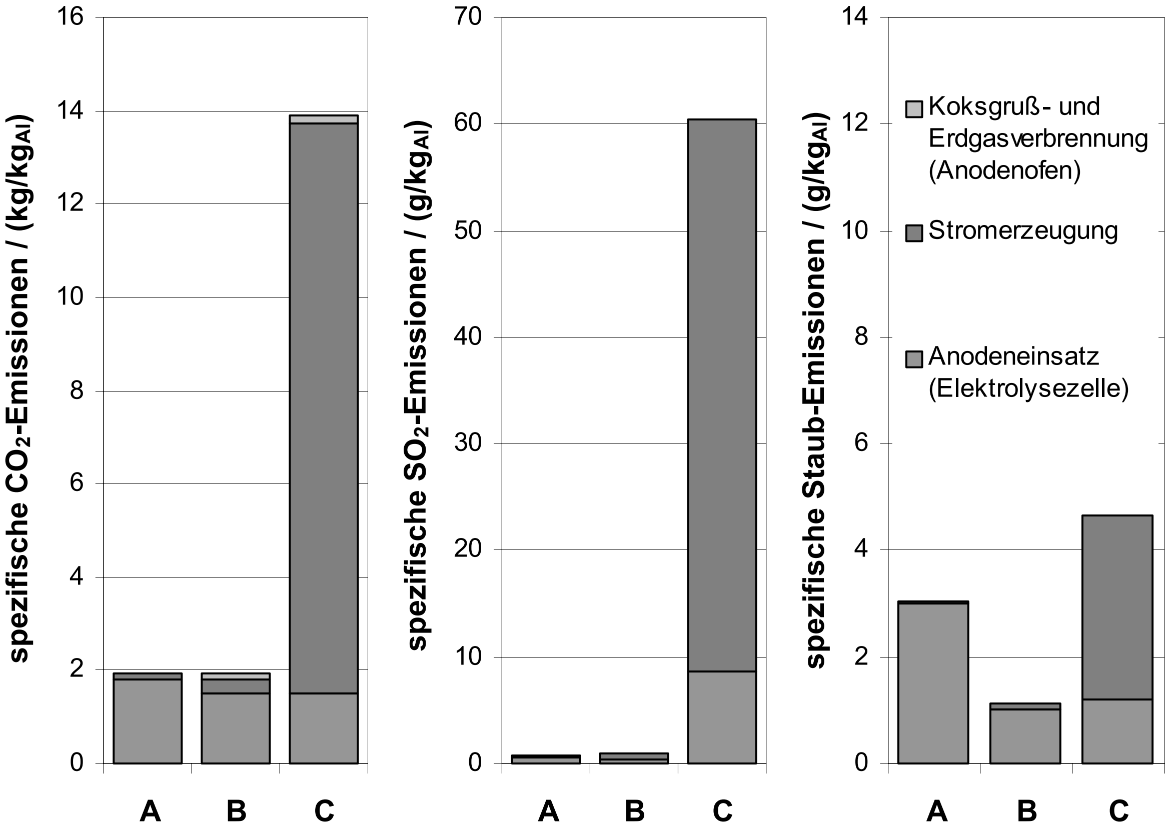

Abbildung 8: Kumulierte spezifische Emissionen ausgewählter Stoffe in Luft [9, 10, 11, 12, 13]

ENTWICKLUNG DES ENERGIEBEDARFS UND DER ENERGIEBEDINGTEN CO_2-EMISSIONEN DER SCHMELZFLUSSELEKTROLYSE ZUR PRIMÄRALUMINIUMHERSTELLUNG*

(DEVELOPMENT OF ENERGY CONSUMPTION AND ENERGY-INDUCED CO_2 EMISSIONS OF ELECTROLYSIS FOR THR OPRODUCTION OF PRIMARY ALUMINIUM)

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ABSTRACT

Taking the energy-intensive process of primary aluminium production by melt electrolysis as an example, this article deals with developments in electrolysis and power generation technology and examines their importance in relation to the potential for saving primary energy and reducing specific CO2 emissions. The relevance of energy production in the context of material flow consideration is discussed.

KEYWORDS

energy demand, power plants, primary energy demand, CO_2 emissions, melt electrolysis

* Source: ALUMINIUM, 7/6, pp. 502-506

1 Einleitung

Die begrenzte Reichweite der fossilen Energieträger sowie die mit ihrer Umwandlung in sekundäre Energieformen wie z.B. Elektrizität verbundenen Emissionen machen eine möglichst effiziente Umwandlung und Nutzung dieser Energieressourcen erforderlich. Regenerative Energiequellen stellen unter diesen Gesichtspunkten interessante Alternativen dar, doch stehen in vielen Fällen ökonomische und technische Gründe - insbesondere in Hinblick auf die Versorgungssicherheit - einer verstärkten Nutzung entgegen. Kurz- und mittelfristig werden in der Optimierung sowohl der energiezehrenden Prozesse als auch der Energiebereitstellung und in der Substitution der Energieträger untereinander die größten Potentiale zur Reduktion des Primärenergiebedarfs und zur Emissionsminderung gesehen. Am Lehrstuhl für Reaktorsicherheit und -technik der RWTH-Aachen wird im Rahmen der Arbeiten des Sonderforschungsbereichs 525, „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“, ein Energiemodell entwickelt. Dieses Modell dient gegenwärtig der energetischen und stofflichen Analyse von Prozessen der Energiebereitstellung für Prozesse der Metallherstellung [1].

Am Beispiel des energieintensiven Prozesses der Primäraluminiumherstellung in der Schmelzflusselektrolyse werden im folgenden die Entwicklungen in der Elektrolysetechnik und der Kraftwerkstechnik betrachtet. Ihre Bedeutung hinsichtlich der Potentiale zur Primärenergieeinsparung sowie Reduktion der spezifischen CO_2-Emissionen werden untersucht und die Relevanz der Energiebereitstellung für Stoffstrombetrachtungen diskutiert.

2 Energiebedarf der Primäraluminiumherstellung

Die Herstellung von Primäraluminium erfolgt in mehreren aufeinanderfolgenden Prozessen, die jeweils durch ihren spezifischen Bedarf an fossilen Endenergieträgern und Elektrizität charakterisiert sind. In Bild 1 ist eine vereinfachte Prozesskette der Herstellung von Halbzeugen aus Primäraluminium mit typischen Spannbreiten des Endenergiebedarfs der einzelnen Prozesse nach thermischer Energie (Brennstoffe) und Elektrizität differenziert dargestellt. Transportprozesse wurden hier aufgrund des vergleichsweise geringen Energiebedarfs vernachlässigt.

Dem Prozess der Schmelzflusselektrolyse kommt durch den erheblichen Strombedarf von durchschnittlich rund 15 kWh_{el}/kg_{Al} sowohl endenergetisch als auch primärenergetisch besondere Bedeutung zu. Die Spannbreite des Strombedarfs von 12,9 bis 18,3 kWh_{el}/kg_{Al} resultiert wesentlich aus technisch unterschiedlichen Elektrolysetypen und verschiedenen Betriebsweisen. Der Aufschlussprozess von Bauxit im Tonerdewerk ruft den nächstgrößten Anteil am Energieaufwand der Primäraluminiumproduktion hervor. Im Vergleich zum Energiebedarf der Elektrolyse ist die Bedeutung dieses Prozesses jedoch geringer. Die vorliegende Betrachtung beschränkt sich daher auf den Elektrolyseprozess.

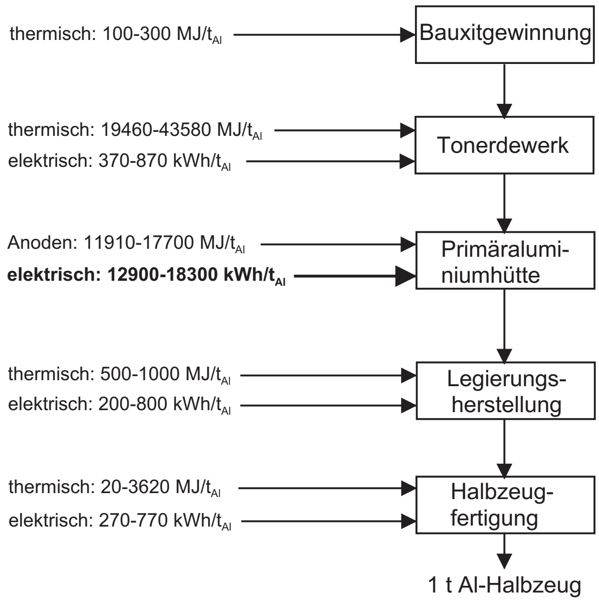

Bild 1: Vereinfachte Prozesskette und Endenergieeinsätze der Primäraluminiumproduktion

3 Entwicklung des spezifischen Strombedarfs der Schmelzflusselektrolyse

Die Reduktion des spezifischen Strombedarfs der Elektrolysen ist insbesondere wegen des maßgebenden Einflusses der Energiekosten für Elektrizität an den Gesamtproduktionskosten des Primäraluminiums stets Ziel der Entwicklungen der Prozesstechnik gewesen. Schmelzflusselektrolysen mit PFPB-Technik kennzeichnen heute den Stand der Technik. In ihnen lässt sich eine weitgehend optimierte und automatisierte Prozessführung mit einer hinsichtlich effizienter Energienutzung vorteilhaften Anlagentechnik verbinden.

Bild 2 zeigt die zeitliche Entwicklung des spezifischen Strombedarfs von PFPB-Elektrolysen in einigen ausgewählten europäischen Ländern. Als Bezugsjahr wurde das Jahr der Inbetriebnahme bzw. das Jahr der letzten für die Elektrolysetechnik relevanten Modernisierungsmaßnahme gewählt [2].

Seit ihrer Einführung in den frühen 60er Jahren konnte der spez. Strombedarf der PFPB-Systeme um rund 15% reduziert werden. Die starke Abnahme zwischen 1960 bis 1990 wird sich jedoch nicht vergleichbar in den nächsten Jahren fortsetzen lassen, da die Potentiale für energetische Optimierungen in diesem System schon weitgehend erschlossen sind. Entsprechend verläuft die Kurve in Bild 2 in neuerer Zeit zunehmend flach. Es wird erwartet, dass ein spezifischer Strombedarf von etwa 12,5 kWh_{el}/kg_{Al} bei diesem System eine realistische untere Grenze darstellt.

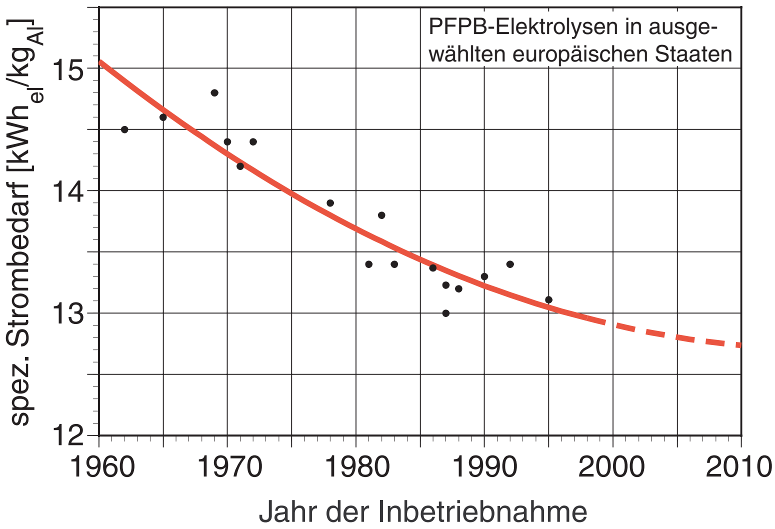

Bild 2: Entwicklung des Strombedarfs von PFPB-Elektrolysen

4 Entwicklungen in der Kraftwerkstechnik

Technische Weiterentwicklungen und Optimierungen in der Kraftwerkstechnik haben dazu geführt, dass der Primärenergieaufwand der Strombereitstellung seit 1960 drastisch reduziert werden konnte. Bild 3 zeigt für einige fossil befeuerte Kraftwerke sowie für Leichtwasserreaktoren und ein exemplarisches Wasserkraftwerk die zeitliche Entwicklung des Primärenergiebedarfs der Strombereitstellung sowie den korrespondierenden Bereitstellungsnutzungsgrad. Der Bereitstellungsnutzungsgrad entspricht hier einem Wirkungsgrad der Stromerzeugung, bei dem Energieaufwendungen für die Brennstoffbereitstellung mit erfasst werden. Zugrundegelegt wurden überwiegend deutsche Kohlekraftwerke sowie weltweit installierte Erdgas-GuD-Systeme [3]. Während in den sechziger Jahren noch etwa drei kWh Primärenergie pro kWh Elektrizität aufgewendet werden mussten - dies entspricht einem Bereitstellungsnutzungsgrad von 0,33 - benötigen heute moderne fossil befeuerte Kraftwerke bis zu einem Drittel weniger Brennstoff. Dies beruht im wesentlichen auf der Entwicklung hochwarmfester Werkstoffe, die höhere Prozesstemperaturen der Wärmekraftprozesse zulassen und dadurch höhere Wirkungsgrade sowie hocheffiziente Kombiprozesse (GuD) ermöglichen. Bei Wasserkraftwerken und Leichtwasserreaktoren waren hingegen praktisch keine bzw. nur geringfügige Steigerungen der Wirkungsgrade zu verzeichnen. Im Fall der Wasserkraftwerke beruht dies auf den bereits weitgehend optimierten Turbinen. Bei Druckwasserreaktoren sind durch sicherheitstechnische Auslegungsmerkmale die Optimierungspotentiale stark begrenzt und schon heute weitgehend ausgereizt. Steigerungen der Wirkungsgrade auf Werte oberhalb von 45% wird mit der Entwicklung von Hochtemperaturreaktoren in Verbindung mit Kombiprozessen erwartet [4].

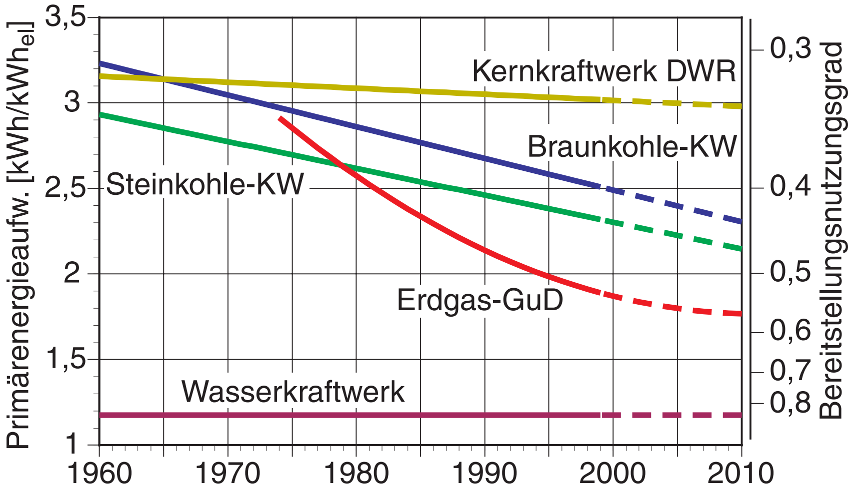

Bild 3: Entwicklung des Primärenergiebedarfs und des Bereitstellungsnutzungsgrades verschiedener Kraftwerkssysteme

Die Energieträger Steinkohle, Braunkohle sowie Erdgas unterscheiden sind erheblich durch ihre Kohlenstoffgehalte. Entsprechend unterschiedlich fallen die spezifischen CO_2-Emissionen der Stromerzeugung aus. In Bild 4 sind für die in Bild 3 erfassten fossil befeuerten Systeme die spez. CO_2-Emissionen dargestellt, die außer vom Brennstoff auch unmittelbar vom Wirkungsgrad der Kraftwerke abhängen.

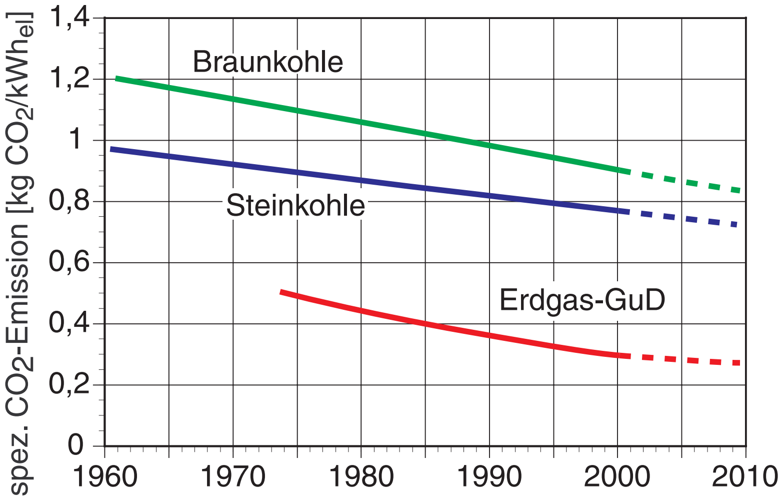

Bild 4: Entwicklung der spezifischen CO_2-Emissionen fossil befeuerter Kraftwerke

Hier wird der Vorteil der erdgasbefeuerten GuD-Kraftwerke hinsichtlich der CO_2-Emissionen deutlich, die heute etwa einen Faktor drei niedriger sind als die Emissionen von modernen Braunkohlekraftwerken.

5 Entwicklung der spezifischen CO_2-Emissionen und des Primärenergiebedarfs der Aluminiumherstellung

Die Verknüpfung der Energiebereitstellung mit dem Elektrolyseprozess erlaubt die Ermittlung des spez. Primärenergieaufwandes und der energiebedingten CO_2-Emissionen der Primäraluminiumherstellung. In der Darstellung der zeitlichen Entwicklung überlagern sich damit die Entwicklungen der Kraftwerks- und der Elektrolysetechnik. In den Bildern 5 und 6 sind die entsprechenden zeitlichen Entwicklungen bezüglich des Primärenergieaufwandes und der energiebedingten spezifischen CO_2-Emission aufgetragen. Kohlendioxidemissionen, die aus der Oxidation der Kohlenstoffanoden resultieren, werden hier nicht als energiebedingt sondern prozessbedingt betrachtet und daher in der Darstellung nicht berücksichtigt. Wasserkraft und Kernkraft werden vereinfachend als CO_2-frei bewertet und entsprechend in Bild 6 nicht aufgenommen.

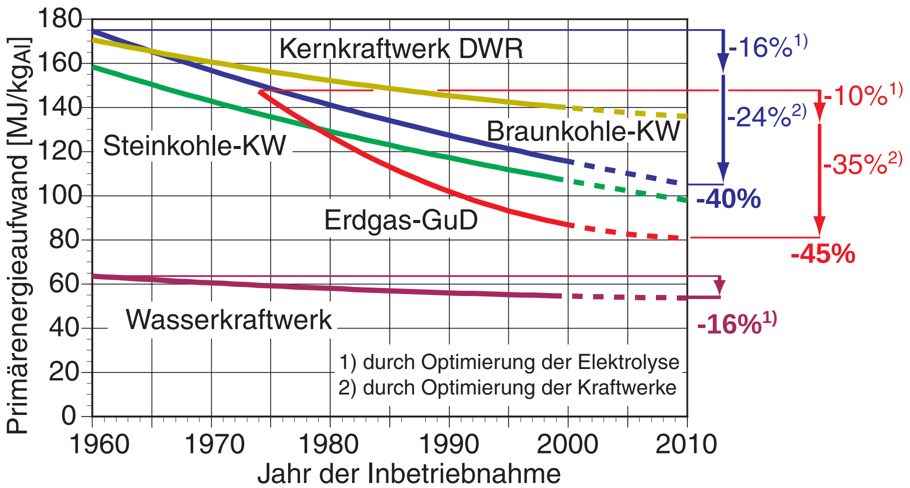

Bild 5: Entwicklung des spezifischen Primärenergieaufwandes der Primäraluminiumerzeugung in der Schmelzflusselektrolyse für verschiedene Stromerzeugungssysteme

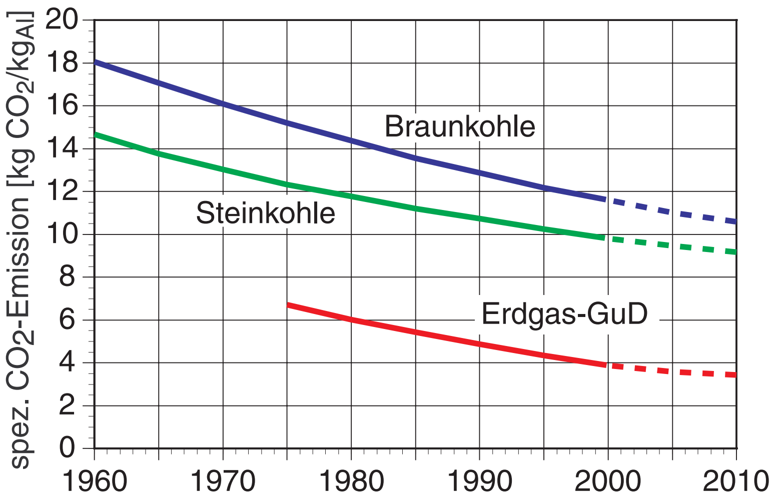

Bild 6: Entwicklung der energiebedingten spezifischen CO_2-Emission der Primäraluminiumerzeugung in der Schmelzflusselektrolyse für verschiedene Stromerzeugungssysteme

Aus Bild 5 wird deutlich, dass sich über den Zeitraum von 1960 bis 2010 bei Zugrundelegung von fossil gefeuerten Kraftwerkssystemen ein Primärenergieeinsparpotential von bis zu 45% ergibt. Eine im Jahr 1960 moderne Elektrolyse, die über ein damals modernes Braunkohlekraftwerk mit Strom versorgt wurde, benötigte rund 175 MJ Primärenergie pro kg Al. Für ein im Jahr 2010 erwartetes modernes System (PFPB-Elektrolyse und Kraftwerk entsprechen dem Stand der Technik) wird mit einem Energieaufwand von rund 105 MJ/kg_{Al} gerechnet. Dies entspricht einer Reduktion um 40%, wobei 16% durch Optimierungen der Elektrolyse selbst und die übrigen 24% durch gesteigerte Umwandlungseffizienzen der Kraftwerke bewirkt werden. Bei Systemen, deren Elektrolyse durch Erdgas-GuD-Kraftwerke mit Strom versorgt werden, fällt die mögliche Reduktion des Primärenergiebedarfs trotz eines kürzeren Betrachtungszeitraums (1974-2010) mit 45% noch größer aus. Hier liegt der Beitrag durch die Elektrolysetechnik bei 10%, 35% trägt die extrem schnelle Entwicklung der hocheffizienten GuD-Kraftwerke zur Einsparung bei. Das Reduktionspotential von 16% bei Nutzung der Wasserkraft beruht nach dieser Modellrechnung ausschließlich auf der Optimierung der E-lektrolyse. Es wird deutlich, dass in Abhängigkeit vom für die Stromerzeugung eingesetzten Energieträger und dem Stand der Technik der Primärenergieaufwand der Primäraluminiumherstellung in der Schmelzflusselektrolyse um einen Faktor drei variieren kann.
Die in Bild 6 als Funktionen des Standes der Technik und des jeweiligen Energieträgers dargestellten energiebedingten CO_2-Emissionen unterscheiden sich über den gesamten Betrachtungszeitraum um bis zu einen Faktor 5.
Sowohl der Primärenergiebedarf als auch die energiebedingten CO_2-Emissionen sind damit äußerst stark an die zugrunde liegende Technik, d.h. den Stand der Elektrolyse- und Kraftwerkstechnik, und an den jeweils verstromten Energieträger gebunden.

6 Identifizierung der relevanten Strombereitstellung

Im Rahmen von Stoffstromanalysen - beispielsweise für Ökobilanzen - kommt durch die starke Abhängigkeit der Stoffströme von der Art der Energiebereitstellung der Identifizierung des tatsächlich vorliegenden Systems aus Schmelzflusselektrolyse und Energiebereitstellung entscheidende Bedeutung zu. Eine unzutreffende Charakterisierung der Elektrolysetechnik und der Energiebereitstellung (spez. Strombedarf, Energieträger und Stand der Kraftwerkstechnik) kann entsprechend den Bildern 5 und 6 zu Abweichungen um ganzzahlige Faktoren und damit zwangsläufig zu fehlerhaften Interpretationen z.B. bezüglich Ressourcenbedarf und Umweltrelevanz führen. Oft ist jedoch die Identifizierung der Energiebereitstellung für einen Verbraucher nur schwer möglich. Insbesondere bei Strombezug aus Verbundnetzen sind komplexe Strukturen zu analysieren, in der eine Vielzahl technisch verschiedener Kraftwerke mit unterschiedlichen Anteilen zur Strombereitstellung beitragen. Sensitivitätsanalysen hinsichtlich der Stoffströme von verschiedenen Versorgungsstrukturen unter Einbezug von Verbundnetzen in verschiedenen Staaten weisen ebenfalls Schwankungsbreiten von ganzzahligen Faktoren auf [5]. Bild 7 verdeutlicht dies anhand der Betrachtung der spezifischen energiebedingte CO_2-Emissionen der Primäraluminiumzerzeugung in der Schmelzflußelektrolyse für verschiedene Systeme der Strombereitstellung. Der spezifische Strombedarf der Elektrolyse wurde hierfür einheitlich zu 13 kWh_{el}/kg_{Al} gesetzt.

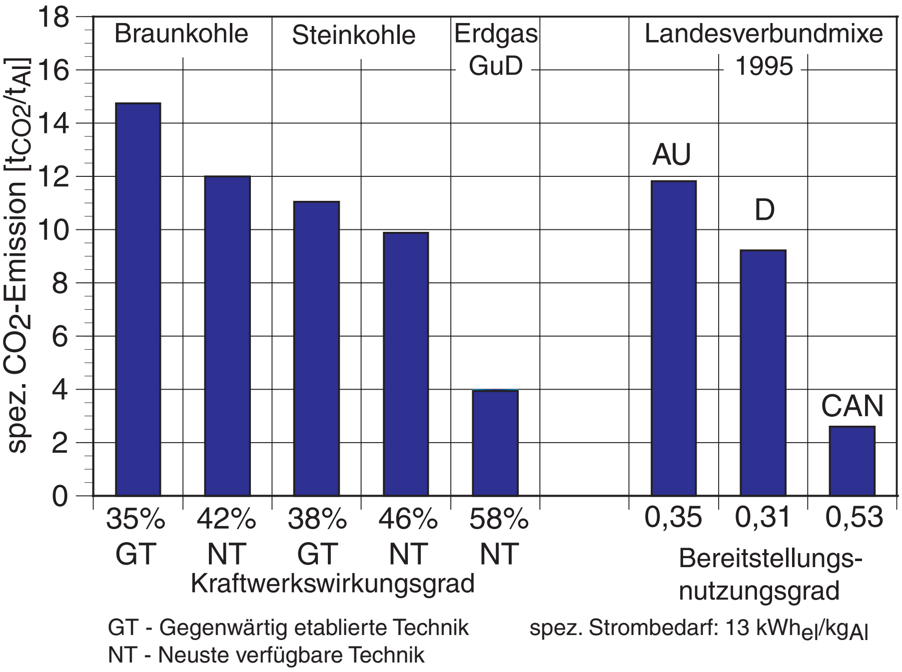

Bild 7: Spezifische CO_2-Emissionen der Primäraluminiumerzeugung in der Schmelzflußelektrolyse für verschiedene Szenarien der Strombereitstellung

Betrachtet werden hier Kraftwerksysteme auf Braunkohle-, Steinkohle- und Erdgas-GuD-Basis sowie Landesverbundmixe der Staaten Australien, Deutschland und Kanada. Die Einzelkraftwerke werden hier durch den Stand der Technik, d.h. ihren Wirkungsgrad, mit *GT* für *gegenwärtig etablierte Technik* und *NT* für *neuste verfügbare Technik* charakterisiert. Die Landesverbundmixe beziehen sich auf das Jahr 1995. Es wird deutlich, daß die energiebedingten Stoffströme außer vom verstromten Energieträger und vom Stand der Technik auch erheblich von den zugrunde gelegten Verbundnetzen abhängen. Die Identifizierung des tatsächlich relevanten Stromerzeugungssystems ist damit unerlässlich, diese Aufgabe ist jedoch in vielen Fällen sowohl methodisch als auch praktisch kaum eindeutig lösbar.

7 Zusammenfassung und Ausblick

Im Rahmen von Modellrechnungen wurden Untersuchungen zu Einsparpotentialen und zur bereits erreichten Reduktion des Primärenergieaufwands und der energiebedingten CO_2-Emissionen durchgeführt. Im Betrachtungszeitraum von 1960 bis 2010 werden bei Zugrundelegung von jeweils dem Stand der Technik entsprechenden Kraftwerks- und Elektrolysesystemen Minderungen des Primärenergiebedarfs zwischen rund 16% bei Wasserkraftnutzung und bis zu 45% bei Einsatz von erdgasgefeuerten GuD-Kraftwerken erwartet. Die größten Potentiale zur Reduktion der spezifischen CO_2-Emissionen bestehen selbstverständlich im Übergang von der Stromerzeugung auf fossiler Basis hin zur Nutzung von Wasser- und Kernkraft, die als weitgehend kohlendioxidarm betrachtet werden. Hier sei angemerkt, dass heute bereits knapp 60% des weltweit produzierten Primäraluminiums unter Einsatz von Wasserkraft erzeugt werden. Doch selbst bei Nutzung fossiler Brennstoffe bestehen große Potentiale zur Minderung der CO_2-Emission, beispielsweise durch die Substitution von älteren Kraftwerken, die kohlenstoffreiche Energieträger wie z.B. Braunkohle nutzen, durch moderne Systeme auf Basis von Erdgas-GuD-Kraftwerken.

Im Vergleich zur Optimierung in der Elektrolysetechnik, die sich in dieser Betrachtung in einer Senkung des spezifischen Strombedarfs zeigt, haben die Fortschritte in der Technik der fossil gefeuerten Kraftwerke erheblich größere Sparpotentiale eröffnet. Auch zukünftig werden in dieser Kraftwerkstechnik noch erhebliche Optimierungspotentiale gesehen, während in der PFPB-Technik die Möglichkeiten zur Reduktion des Strombedarfs als weitgehend ausgereizt betrachtet werden.

Die starke Abhängigkeit des Primärenergiebedarfs und der energiebedingten spezifischen CO_2-Emissionen von den Techniken der Elektrolyse und der Strombereitstellung erfordern im Rahmen von Stoffstromanalysen eine sichere Identifizierung der jeweils tatsächlich vorliegenden Techniken.

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INFLUENCE OF DIFFERENT ENERGY MODELS ON OVERALL BALANCING OF PRIMARY ALUMINUM SMELTING*

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ABSTRACT

Assessing an overall balance of primary aluminum production shows an substantial influence of the energy supply. Especially the kind of electricity supply for primary aluminum smelters can cause significant environmental effects. Due to this fact the electricity supply systems of aluminum smelters have to be indicated and described by appropriate energy models. Different methods are used modeling the energy supply of aluminum smelters.

Beside the most commonly used “national grid” and surveys of electrolysis operators, the authors will introduce the “national or regional base load mix“ and the “contract mix” models. This paper will point out the advantages and disadvantages of these approaches. The influence of the chosen model on the primary energy demand and carbon dioxide equivalent emissions will be shown on the basis of German aluminum smelters. Concluding the authors recommend the best suited power supply model for overall balancing primary aluminum smelters.

KEYWORDS

Energy model, primary energy demand, CO_2 emissions, power plants, energy supply, aluminium smelting

* Source: Proceedings Light Metals, New Orleans, 2001

Introduction

In 1997, 39 industrialized countries accepted their responsibility for our future climate. The ultimate objective of the resulting 'Kyoto Protocol' is to achieve 'stabilization of greenhouse gas concentrations in the atmosphere at the level that would prevent dangerous anthropogenic interference with the climate system' [1]. Besides the ongoing improvements in the efficiency of the aluminum industry, like higher amperage or improved current efficiency, further efficiency improvements in the energy supply associated with aluminum production are necessary. It is especially important to pay attention to the electricity supply of the smelter because of

- the great influence of this process on holistic assessments (e.g. Life Cycle Assessments)

and

- often equivocal physical identification of the electricity supply system.

Although numerous scientific papers about primary energy demand and emissions of primary aluminum production have been published, the approaches in determining electricity supply systems obviously differ. This paper presents the great influence of different power supply systems on entire balancing of primary aluminum production using primary energy demand and greenhouse gas emissions as exemplifying parameters. Then a perpetrator related assessment of the electricity supply for electrolysis will be proposed.

Such and further problems concerning entire assessments of energy systems is the working scope of the sub-program 'Energy' of the Institute for Reactor Safety and Reactor Technology in the framework of the Collaborative Research Center 525 (CRC 525).

The CRC 525 „Resource-Orientated Analysis of Metallic Raw Material Flows“ analyses the material flows of aluminum from mining over the period of use up to recycling. The project was started in 1997 at the University of Technology in Aachen and the Forschungszentrum Jülich in Germany. Nine sub-programs develop methods for resource management considering technical, economic, ecological and social aspects. Raw material, energy, and environmental media (soil, water, air) are referred to as resources.

Resource use of primary aluminum production including its energy supply

Neglecting transport processes and further processing steps like casting, the primary aluminum production process can be sub-divided into bauxite mining, alumina refining and aluminum smelting. Due to their energy demand and supply, technology and further parameters, the processes have different environmental impacts. Figure 1 illustrates the range of the total primary energy demand and the greenhouse gas emissions in the aluminum production process.

Thereby greenhouse gas emissions are summarized to carbon dioxide-equivalents (CO_2-e) using the global warming potentials (GWP) of different greenhouse gases (GHG). The used values are uncertain, but this is nevertheless the best tool available for summarizing the different greenhouse gases. The following internationally accepted GWP factors, listed in Table I, are used to characterize greenhouse gas emissions to CO_2-e.

Table I: Global warming potentials compared to CO_2 for a time horizon of 100 years [2]

CO_2	CH_4	N_2O	CF_4	C_2F_6
1	21	310	6,300	12,500

Besides the perfluorocarbons released during anode effects in Hall-Héroult cells, carbon dioxide, nitrous oxide and methane are emitted during alumina reduction and the energy supply caused by aluminum production.

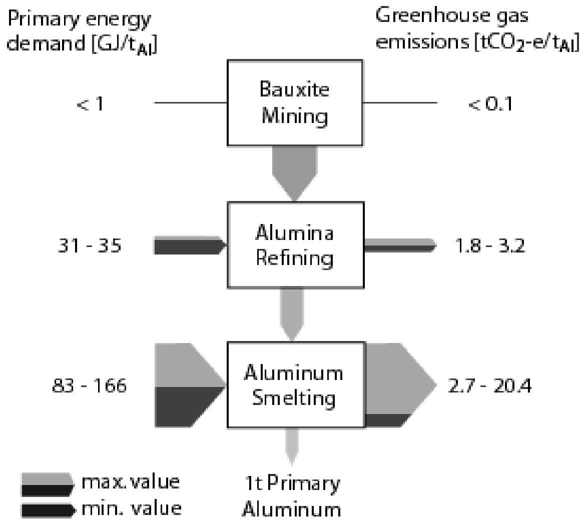

Figure 1: Range of energy related primary energy demand and GHG emissions of the primary aluminum production process

Neglecting transport processes, Figure 1 shows the simplified primary aluminum production process. Primary energy demand as well as GHG emissions caused by bauxite mining are comparatively insignificant.

Low temperature digestion and fluidized bed calcination for alumina refining commonly cause a primary energy demand between 31 and 35 GJ/t_{Al} [1] and release GHG emissions of 1.8 resp. 3.2 tCO_2-e/t_{Al}. These amounts mainly depend on the energy carriers used and their conversion efficiencies. A natural gas-based energy supply for steam production, calcination and for electricity supply by a combined cycle power plant results in the lowest values. Using coal for steam and electricity production means greater energy resources demand and GHG emissions.

Undoubtedly, during aluminum production the alumina reduction causes the largest resource use of both, primary energy sources and environmental sinks like the atmosphere. A primary energy resources demand between 83 and 166 GJ/t_{Al} as well as energy related GHG emissions between 2.7 and 20.4 tCO_2-e/t_{Al} characterize the aluminum smelting process including its electricity supply. A modern PFPB-electrolysis (13.9 kWh/kg_{Al}) in conjunction with a hydropower plant (80% efficiency [2]) in a boreal region [3] is the most favorable system to avoid environmental impacts (primary energy demand: 83 GJ/t_{Al} and GHG 2.7 tCO_2-e/t_{Al}). Due to the visible progress in the control technique of electrolysis in avoiding anode effects, the GHG emissions caused by perfluorocarbons (CF_4 and C_2F_6) are below 0.4 tCO_2-e/t_{Al}. The predominate emissions derive from anode manufacturing and particularly their oxidation in the electrolysis (1.6 tCO_2-e/t_{Al}). In this special case, the contribution of GHG emissions released by hydropower is low (less than 0.7 tCO_2-e/t_{Al}). Because of high efficiencies of hydropower plants as well as PFPB-systems the primary energy demand of about 83 GJ/t_{Al} is moderate.

In case of a VSS-electrolysis (15.5 kWh/kg_{Al}) and a coal-based power plant with an average efficiency of 38%, environmental impacts raise significantly. The primary energy demand doubles up to 166 GJ/t_{Al} [4] in contrast to the hydropower and PFPB-electrolysis. Therefore, GHG emissions increase obviously (20.4 tCO_2-e/t_{Al}), whereby the coal fired power plant contribution is nearly 70% (14 tCO_2-e/t_{Al}). Due to the older VSS technology, perfluorocarbons increase tenfold (up to 4 tCO_2-e/t_{Al}) in comparison to a modern PFPB-electrolysis.

This really simple example shows the great importance of the electricity supply system for electrolysis, concerning primary energy demand and GHG emissions. In the following chapter, the impacts of different power plants on resource use will be examined in further detail.

[1] In the following t_{Al} represents metric tons aluminum
[2] World wide average conversion efficiency from hydro power to electricity
[3] In contrast to common opinion, the renewable energy source hydropower causes carbon dioxide and methane emissions depending on climate, hydrology and further conditions (see next chapter).
[4] Electricity supply by a nuclear power plant would increase the primary energy demand of the VSS-electrolysis up to 184 GJ/t_{Al}.

Electricity related resource use of aluminum smelting depending on its energy supply

Depending on the energy carrier used, efficiency, technology and location, power plants show a wide range of resource use. Figure 2 shows the primary energy demand and GHG emissions of different power plants caused by an electricity demand of an aluminum electrolysis of 13.9 kWh/kg_{Al}. Expenditures for mining, preparation and transportation of the fuel have been taken into account. Owing to the high voltage level of power supply for alumina refining, transmission losses are estimated to be less than 0.5% and can therefore be neglected.

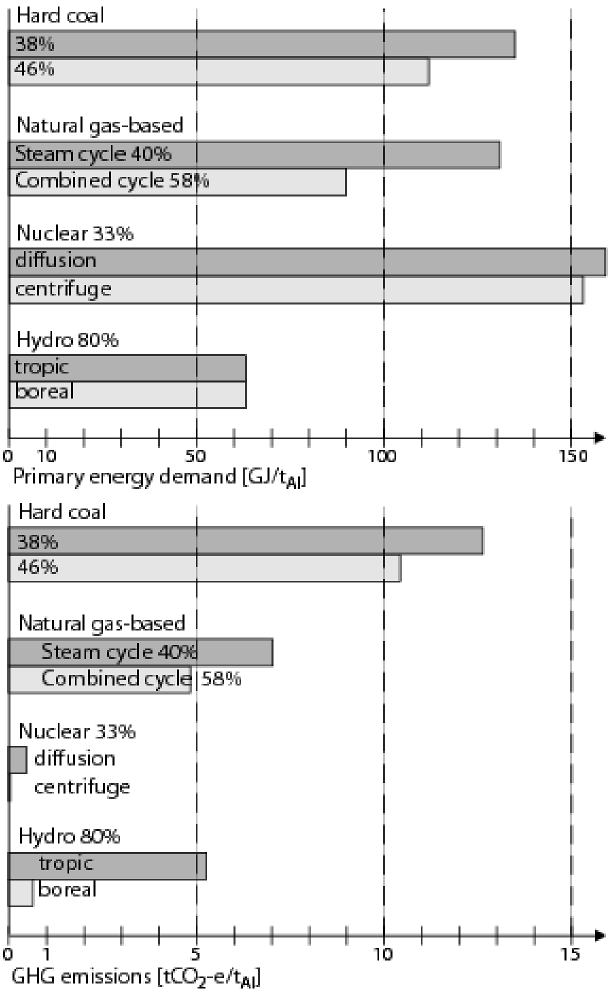

Figure 2: Primary energy demand and GHG emissions of different power plants (including fuel supply) related to 1 t primary aluminum of an aluminum smelter with an electricity demand of 13.9 kWh/kgAl

A state-of-the-art hard coal fired power plant with an efficiency of 38% has a primary energy demand of 135 GJ/t_{Al} and releases 12.65 tCO_2-e/t_{Al}. Modern plants decrease the energy demand and GHG emissions of about 17%.

Gas-based plants, using only a steam cycle, with an efficiency of 40% cause a primary energy demand of 131 GJ/t_{Al}. Due to lower carbon content of natural gas compared with coal, GHG emissions of approximately 7 tCO_2-e/t_{Al} are released. Rapid developments in gas turbine technology promote the introduction of combined cycle power plants with efficiencies between 56 and 58% (60% are expected in the

near future). Such high efficiencies mean an energy demand of only 90 GJ/t_{Al} and nearly 5 tCO_2-e/t_{Al} emissions.
Today, light water reactors (LWR) are the most commonly used nuclear power plants. Their low efficiency of 33% results in a high primary energy demand of about 155 GJ/t_{Al}. Small differences in energy demand and especially in emissions are caused by the used enrichment process of the nuclear fuel. Diffusion technology, used particularly in France and United States, needs fifty-fold of electricity compared to the centrifuge technology, which is used in the UK, the Netherlands and Germany. In this paper, electricity required for nuclear fuel supply has been supplied by U.S. national grid. But even in the most unfavorable case (diffusion), nuclear power plants show the lowest climate impact.
The environmental impacts of hydropower, especially methane emissions caused by anaerobic decomposition of biomass, have been discussed for years. At present, scientists only agree that all reservoirs in tropical as well as in boreal regions emit GHG emissions for decades. But until today there is no agreement in the amount of GWP emissions from hydropower. It is not as easy to determine emissions of hydropower as in the case of fossil fired power plants where only the efficiency and the carbon content of the used energy carrier must be known. A range of factors like

- emergent and flooded biomass (inclusive carbon in soil),
- depth,
- residence time,
- climate,
- age of reservoir or
- electricity production

significantly influence GHG emissions from dams. Hence, published papers regarding released greenhouse gases differ significantly. A study of the World Commissions on Dams about nine Brazilian reservoirs found that their greenhouse emissions varied per unit of electricity by a factor of 500! Using a study from Fearnside [3] about the Brazilian Tucurui dam GHG emissions amount to 380 $kgCO_2$-e/MWh, slightly more than a combined cycle gas power plant and slight below half of a coal–based power plant. But it has to be considered, that this is a conservative estimate and that under unfavorable conditions GHG emissions raise dramatically. GHG emissions in boreal regions have a smaller relevance. Duchemin [4] published area specific GHG emissions of Canadian dams. Calculating greenhouse relevant emissions per unit of electricity the amount is only one eighth (47 $kgCO_2$-e/MWh) of the Brazilian. This value cannot be used for all boreal or semiarid regions, e.g. in U.S. or Canada, because climate, depth and other factors vary from dam to dam. But in our calculations it is used as a first approximation.

Possible approaches to allocate electricity demand

Due to the great influence of electricity supply on balancing primary aluminum production the electricity supply system for electrolysis has to be chosen very accurately. In case of self-generating power by the smelter it is trivial to identify the relevant supply system. But in case of an electricity supply by a public grid difficulties in balancing electricity are obvious. Here several approaches are possible to allocate the electricity supply system to the smelter, which will be presented now:

National grid

Many studies about aluminum production use national electricity mixes which is unsuitable in our opinion. On the one hand

- aluminum smelters are not uniformly distributed across the country

and on the other hand

- electricity supplied by the national grid and the electricity demand of electrolysis differ significantly over time.

Figure 3 shows a qualitative daily draw of the base-, average- and peak load of a country. As can be determined, the power usually required for electrolysis correlate nearly exactly to the base load of public grids. Thus, using base load and no average- or peak load power plants is an especially suited approach.

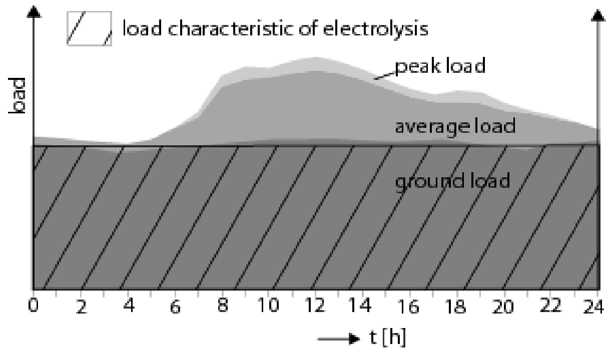

Figure 3: Qualitative daily load-development of an electrical grid compared to the load demand of an electrolysis

National electricity base load mix
This electricity mix is determined by balancing all power plants of a country running in base load. Thus the load correlation between electrolysis and electricity base load is taken into account. Because of their low operation cost hydro- or nuclear power stations are exclusively running in base load. But in large countries like the United States due to regional differences different fuels like coal or natural gas are utilized in base load power plants. This fact complicates the determination of the national electricity base load mix, which increase the labor–intensive of this approach compared to the national grid approach. Furthermore the fact that smelters are mostly not distributed uniformly across a country is disregarded.
Regional electricity base load mix
Considering non-uniform local distribution of smelters in large countries the regional electricity base load mix can be used to improve the accuracy of the balancing approach. Here the state of Washington in the north-west of the U.S. with a large amount of smelters is an excellent example. But without statistical data about the particular regions and further technical knowledge of the operated power stations balancing the regional electricity base load mix is based on a lot of assumptions.
Contract mix
Another possibility is using the so called "contract mix". Here, the "contracted" electrical energy supplier of the smelter has to be determined. Then, his national resp. regional base load mix is used for balancing primary aluminum production. This approach is a perpetrator related assessment of the electricity supply for electrolysis due to the correlation between base load of grids and power demand of electrolysis as well as allocating the responsibility of each smelting operator for his energy supply. Until this day, smelting operators choose their electricity supplier according to economically favorable conditions and reliability, but for the future resource use and released emissions may be further criteria [5].

Other studies use data collections like Pawlek [5] or carry out surveys [6] among smelters. Both methods are better suited due to the fact that self-generated electricity of the smelters is recorded.

Used approaches of other studies

Showing the wide range of possibilities for balancing electrical supply to smelters the following summary will be given:

IPAI
The International Primary Aluminium Institute (IPAI) presented a „Life Cycle Inventory of the Worldwide Aluminium Industry with Regard to Energy Consumption and Emissions of Greenhouse Gases" [6]. Data was obtained by a survey asking all primary smelters to name the sources of either self-

[5] Perhaps in a few years we will see advertisements on cars like:
"I was made by 100% Canadian hydro power" which emphasize environmentally sound manufacturing of the product.

generated or purchased energy. In the case of purchased electricity which applies for most of the smelters this would require knowledge about the energy mix of the power supplier. If this information was not available, which can be assumed for most smelters, the national or regional grid was set as energy supply. This again results in the discussed inaccuracies.

<u>EAA</u>
For their „Ecological Profile Report“ the European Aluminium Association (EAA) [7] introduced an own model especially to provide environmental data for primary smelter electricity production in Europe. For balancing power supply of smelters, national as well as regional grids and single power plants were taken into account. However the high aggregation of published data does not reveal which approach was used in particular. For the energy related LCI data of imported primary aluminum the IPAI database (see above) was applied.

<u>DoE</u>
In 1997 the U.S. Department of Energy (DoE) published an ‘Energy and Environmental Profile of the U.S. Aluminum Industry’ [8]. Due to the concentration of aluminum smelters in regions of relatively cost-efficient electric power (particularly Pacific Northwest), specific regional grids are used to calculate electricity used for smelting aluminum. Unfortunately no approaches are given how the regional grids and therefore resulting “U.S. Aluminum Smelting Fuel Mix” was calculated.

Examples

A national electricity supply which is strongly focused only on one energy carrier facilitates identification of electric supply structures of smelters. Table II shows primary aluminum producing countries which are heavily mono-structured in electricity production. The countries listed in Table II represent 27% of 1998 world aluminum production.

Table II: Primary aluminum producing countries with mono-structured electricity production in order of dependence on one energy carrier [9, 10]

Country	Energy carrier	Share of power supply
Bahrain	Gas	100%
Norway	Hydro	99,4%
Brazil	Hydro	93,3%
Iceland	Hydro	93,2%
South Africa	Coal	92,9%
Australia	Coal	80,1%
France	Nuclear Hydro	79,3% 12,5%
Venezuela	Hydro	76,3%

To determine the electricity supply structure in diversified public grids like the United States or Germany following presented national-, regional electricity base load mixes or the “contract mix” of aluminum smelters are the better suited approaches in contrast to the national grid. To point out the differences of the procedures to determine these mixes the German aluminum industry will serve as an example.
<u>National grid</u>
Public domain data [11] facilitate this approach. The national or public grid mix of Germany is dominated by coal-based power stations (hard coal and lignite with a share of nearly 52%), nuclear power stations (31%) and a rising share of almost 9% of natural gas (see Table III).
<u>National electricity base load mix</u>

Due to the high fuel cost of hard coal and natural gas in Germany almost only nuclear-, lignite- and hydro power stations are operating in the base load. Viewed simplistically the small shares of hard coal and natural gas used in base load are neglected. Thus the national base load mix consist only of nuclear-, lignite- and hydro power stations, corresponding to their shares to the public grid.

Regional electricity base load mix

The base load electricity production in both states, were the German aluminum smelters are located, exclusively depends on the one hand on nuclear- and on the other hand on lignite- and a small share of hydro power stations. Using the capacities and the specific electricity demand of the 5 German smelters listed in Pawlek [5], the share of the western and northern regional mix can be determined. The resulting regional base load mix of German aluminum smelters is listed in Table III. Due to the concentration of aluminum smelters in western Germany the amount of lignite gain in importance compared with the other approaches.

Contract mix

First of all the contractual power suppliers and their base load mixes have to be identified. The base load electricity production of the two relevant power suppliers of the 5 German smelters consists of nuclear resp. lignite and nuclear power as well as small shares of hydroelectric power (see Table III). Due to the fact that one regarded power supplier operates nationwide the resulting contract mix resembles to the national base load mix significantly.

Table III: Different electricity mixes of aluminum smelters in Germany 1997

Primary energy	Public grid mix [11]	National electricity base load mix	Regional electricity base load mix	Contract mix
Nuclear	31%	51.1%	34%	53.5%
Hard coal	26%	-	-	-
Lignite	25.8%	42.6%	64%	44.5%
Gas	8.7%	-	-	-
Hydro	3.8%	6.3%	2%	2%
Oil	1.1%	-	-	-
Miscellaneous [a]	3.6%	-	-	-

[a] Wind, Waste, Biomass and Solar

After this a computer-based balancing program is used calculating all relevant energy-related energy and mass flows of the electricity supply to the smelters. An example is given in Figure 4 showing the relevant energy flows (including fuel supply) of the German aluminum contract mix necessary for the electricity supply of the smelters. In the last years our sub-program has determined all necessary processes like fuel supply or different power plants for different relevant countries and technologies.

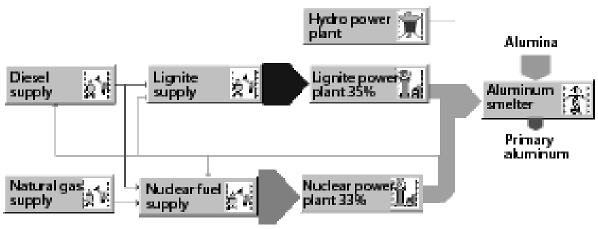

Figure 4: Scheme of the German aluminum contract mix 1997. The quantity of the energy flows is represented by the width of the flow symbols.

Results

Regarding the approaches mentioned above the differences of the public mix, the national- and regional base load mix and the contract mix will be pointed out. Analogous above analyzed single power plant (see Figure 2) the primary energy demand and GHG emissions associated with a power demand of 13.9 MWh per metric ton aluminum will be shown.
Due to similar primary energy carrier (coal and nuclear fuel) used, also having a high primary energy demand, the primary energy demand required to supply smelters does not significantly different in Germany for all approaches (s. Figure 5). But applying the contract mix or the national base load mix the GHG emissions obviously decrease by 27% in comparison to the national grid in Germany. In spite of the high carbon content of lignite the nearly 'carbon free' nuclear energy cut greenhouse gas emissions clearly.

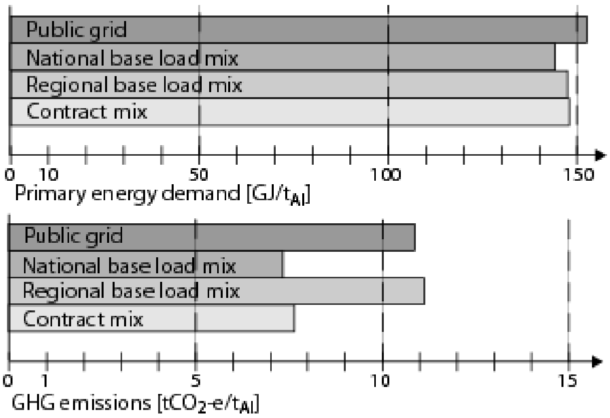

Figure 5: Primary energy demand and GHG emissions of national grid mix, national-, regional base load mix and contract mix in Germany (including fuel supply) related to 1 t primary aluminum of an aluminum smelter with an electricity demand of 13.9 kWh/kg_{Al} [6]

This example points out which deviations can occur using an unsuited approach like national mix for overall balancing of primary aluminum production. Surprisingly the national base load mix shows as well results as the contract mix. That means if the data collection for the contract mix is difficult or too labor-intensive the national base load mix offers a suited alternative. But the national base load mix is only an appropriate approach in 'small' countries like Germany. In large countries like Canada, U.S. or Russia regional base load mix may be preferred to increase the accuracy.

Conclusion

Assessing overall balances of primary aluminum production, the high energy demand in particular during aluminum smelting requires precise identification of the related electricity supply system. This is necessary due to the fact that different power plants show a large range of resource use. Concerning primary energy demand hydropower stations are much more favorable than coal-based or nuclear power stations. Relating to GHG emissions, nuclear and hydropower [7] are the better solutions in contrast to coal-based power plants.
In case of purchased power from a public grid an accurate physical allocation of the electricity supply system is impossible. Viewed simplistically only countries or regions strongly focused on one primary energy carrier for electricity supply allow a simple approach. In case of diversified national grids, the national grid is unsuitable for overall balancing of aluminum production. To realize a perpetrator related approach and considering regional smelters distribution, smelter operator surveys or the presented con-

[6] Without transmission losses
[7] Especially in boreal regions

tract mix method are better suited. In particular the contract mix allows to model the correlation between base load power plants and pot-lines. In case of Germany the differences between national grid and contract mix especially for GHG emissions have been shown.
Unfortunately, it is very labor-intensive to determine necessary data for the contract mix in comparison with using national grids for balancing primary aluminum production. If necessary data are accessible national or in case of large countries regional base load mixes offer a suitable alternative.

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EINBINDUNG VON NUTZUNGSASPEKTEN IN DIE STOFFSTROMANALYSE METALLISCHER ROHSTOFFE -DAS BEISPIEL ALUMINIUM-*

(INTEGRATION OF USE ASPECTS IN THE MATERIAL FLOW ANALYSIS OF METALLIC RAW MATERIALS)

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ABSTRACT

Production and use of goods initiate direct and induced material flows, which complexity and global effects challenge the development of an integrated analysis methodology. The use of products or supply of services depend on the consumers perception and value judgement which can be grouped by the satisfied needs such as nutrition or mobility. Through analysis and description of the requirements in these groups, the resulting material characteristics, and the dispersion and depot generation the use phase will be integrated in the material flow analysis of metallic raw material.

KEYWORDS

Material flow, use phase, aluminium, dispersion, depot generation

* Source: Metall 54, Nr. 5 (2000), S. 205-209

1. Einleitung

Der Einsatz von Metallen wird durch ihre physikalisch/chemischen Eigenschaften bestimmt, die in vielfältigster Weise genutzt werden, um die für die Bedürfnisse des heutigen Lebensstandards nötigen Materialeigenschaften zu erreichen. Produktion und Nutzung der nachgefragten Güter sind der Auslöser anthropogener Stoffströme, deren Komplexität und globale Auswirkungen Anlaß zur Entwicklung einer ganzheitlichen Analysemethodik geben. Dieses Ziel verfolgt der Sonderforschungsbereich „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“ (SFB 525) [1, 2] der RWTH Aachen und des Forschungszentrums Jülich. Dazu wird ein integriertes Ressourcenmanagementsystem aufgebaut, mit dem Handlungsoptionen für eine ressourcenschonende Bereitstellung und Verarbeitung metallischer Rohstoffe im Spannungsfeld technischer Entwicklungen sowie ökonomischer, ökologischer und gesellschaftlicher Zielsetzungen identifiziert werden sollen.

Um dieses Instrumentarium methodisch zu vervollständigen, ist es unerläßlich, die Nutzungsphase zu berücksichtigen. Über die Beschreibung und Analyse der Anforderungen in den Bedürfnisfeldern, der resultierenden Materialeigenschaften sowie der Dispersion und Depotbildung wird die Nutzungsphase in die Gesamtbetrachtung integriert.

2. Die Nutzung als Teil des Stoffstroms

Die Integration der Nutzungsphase erfolgt durch die Verbindung mit der Prozesskettenanalyse und den Modellstrukturen für Energiebereitstellung, Umweltauswirkung und Ökonomie. Dabei sind angrenzende Module bereits produktspezifisch variiert und somit verknüpfbar [3]. Hier ist eine differenzierte Schnittstellenanalyse zwischen Produktion, Nutzung und Recycling erforderlich, da die verschiedenen Produktlegierungen auf unterschiedlichen Wegen hergestellt, verarbeitet und nach der Nutzung zurückgewonnen werden.

Der Stoffstrom metallischer Werkstoffe wird in drei Abschnitte unterschiedlicher Aufgaben unterteilt, die Materialherstellung, die Produktfertigung und die Nutzung (Tabelle 1).

Entsprechend den Aufgaben werden an die Materialien unterschiedliche Anforderungen gestellt. Die Werkstoffauswahl wird hauptsächlich von den in den Bedürfnisfeldern und Produktionsprozessen geforderten Produkt- bzw. Materialeigenschaften geprägt, und nur indirekt von den Anforderungen bei der Metallerzeugung selbst. Es findet ein Übergang von der Werkstoff- zur Produktbetrachtung statt. Wird die Nutzungsphase in das modulare Schema der Prozeßkette der Aluminiumerzeugung eingefügt, so ist dabei zu beachten, daß in Produkten meist eine Vielzahl von Werkstoffen eingesetzt wird.

Die bisherigen Methoden bei der Betrachtung von Werkstoffen müssen durch die Einbeziehung der Nutzungsaspekte wie folgt erweitert werden:

1. Das stärkere Gewicht ökonomischer und gesellschaftlicher Aspekte in der Nutzungsphase erfordert neben der rein technisch objektiven Betrachtung auch die Berücksichtigung subjektiver Aspekte. Ausgehend von den Bedürfnisfeldern muß der Entscheidungsprozeß bei der Werkstoffauswahl, der von verschiedenen Personenkreisen und ihren Wertvorstellungen auf dem Lebensweg geprägt wird, berücksichtigt und die Kopplung von Werkstoff und Wertvorstellungen untersucht werden.
2. Beim Übergang von der Werkstoff- zur Produktbetrachtung sind die Eigenschaften der Materialien von entscheidender Bedeutung. Die Relevanz der unterschiedlichen Materialeigenschaften für die verschiedenen Einsatzbereiche ist hierbei zu ermitteln.
3. Durch Einbezug der Nutzung wird die Bilanzierung um induzierte Stoffströme erweitert. So sind beispielsweise der Energie- und Materialverbrauch bei der Produktnutzung zu untersuchen und der spezifische Einfluß des Werkstoffes zu analysieren, um die induzierten Stoffströme dem Werkstoff anteilsgerecht zuweisen zu können.
4. Zeitliche Aspekte kommen ins Spiel, die sich aus der Lebensdauer von Produkten aber auch aus Veränderungen in den Bedürfnisfeldern ergeben. So wird in Szenariorechnungen beispielsweise ein aus der Lebensdauer resultierendes zeitlich versetztes Aufkommen von Sekundärmaterialien zu berücksichtigen sein.

Die Nutzungsaspekte beinhalten somit die Auswirkungen der Materialeigenschaften auf die eigentliche Produktnutzung und auf den gesamten Lebensweg. Der Zusammenhang zwischen Werkstoff und induzierten Stoffströmen wird hier über die inhärenten Materialeigenschaften zu suchen sein, während beim Einsatz des Werkstoffes oder Produktes subjektive Wertvorstellungen zu berücksichtigen sind. Eine Gesamtbetrachtung aller Nutzungsbereiche und der Produktfertigung wird aber nicht angestrebt, vielmehr sollen produktbezogene Szenariorechnungen durchgeführt werden. Stehen repräsentative Beispiele fest, werden spezifische Daten der Produktfertigung eingesetzt, um die Stoffkreisläufe im Modell zu schließen. Wird eine werkstoffbezogene Quantifizierung der Nutzungsaspekte als Teil der Gesamtbetrachtung durchgeführt, hat auch die vorgenommene Allokation, insbesondere bei mehrkomponentigen Systemen, ganz entscheidenden Einfluß auf das Ergebnis. Hier sind neue Ansätze zu erarbeiten.

3. Beschreibung der Nutzungsphase

Die oben genannte Methodenerweiterung bedingt eine intensive Analyse der Nutzungsphase. Insbesondere müssen hierbei neu hinzukommende Aspekte und ihre Wechselwirkung zum Stoffstrom beachtet werden. Im folgenden werden nun die Nutzungsaspekte und ihre Einbeziehung in die bisherige Methodik diskutiert.

3.1 Bedürfnisfelder und Produktanforderungen

Die Nutzung von Produkten und Dienstleistungen ist eng an Bedürfnisfelder wie Ernährung, Wohnen, Kleidung, Gesundheit oder Mobilität geknüpft, die z.B. von der Enquête-Kommission des Deutschen Bundestages „Schutz des Menschen und der Umwelt“ 1994 [4] definiert worden sind. Dabei sind die Bedürfnisse selbst sehr unterschiedlicher Natur, sie reichen von physiologischen Grundbedürfnissen bis hin zu den individuellen Bedürfnissen der Selbstverwirklichung. Ebenso unterliegt die Bedürfnisbefriedigung subjektiven Empfindungen, die durch die Wertvorstellungen des jeweiligen Personenkreises geprägt sind. Zwischen diesen stehen die Produktanforderungen bzw. –eigenschaften und die entsprechende Materialauswahl. Der „Nutzen“ kann damit als der Zustand einer erreichten Bedürfnisbefriedigung verstanden werden.

Letztlich wird jeder Schritt auf dem Entscheidungsweg zum Einsatz eines bestimmten Werkstoffes von unterschiedlichen Wertvorstellungen geprägt (Abbildung 1).

Vielfach sind also subjektive Kriterien verschiedener Personenkreise wie Endverbraucher, Konstrukteure und Regelungsberechtigte für den Einsatz eines Werkstoffes entscheidend, die sich beispielsweise aus der Umweltverträglichkeit, ökonomischen Vorteilen oder ästhetischen Gesichtspunkten ableiten. Für den Endverbraucher ist auch entscheidend, ob das Material direkt sichtbar, fühlbar bzw. diskutierbar ist. Wenn in der Elektrotechnik beispielsweise Kleinteile versteckt eingesetzt werden, bestimmt nur der Konstrukteur über den Werkstoff. Eine Kaufentscheidung anhand der Materialeigenschaften findet hier nicht statt.

Jeder Anwendungsbereich wird durch andere relevante Wertvorstellungen und Standpunkte der Personenkreise beeinflußt, deren Vielschichtigkeit am Beispiel Aluminium durch Tabelle 2 verdeutlicht wird.

3.2 Materialeigenschaften

Die Anforderungen, die in den Bedürfnisfeldern auftreten, sind zunächst materialunabhängig, erst bei der Werkstoffauswahl werden die in Produktion und Nutzung relevanten Eigenschaften bestimmend. Dabei können metallische Werkstoffe in reiner Form eingesetzt werden oder bestimmte Eigenschaften durch spezielle Werkstoffbehandlungen wie Legieren, thermomechanische oder Oberflächenbehandlung, Einsatz von Verbundwerkstoffen und Werkstoffverbunden sowie kontrolliertes Ur- und Umformen gezielt eingestellt werden.

Betrachtet man die Materialeigenschaften in den Anwendungsbereichen von Aluminium, so sind vor allem technologische Eigenschaften für seinen Einsatz relevant (Tabelle 3). Beispielsweise ist die geringe Dichte für die Anwendung im Automobil und Flugzeug ein ganz entscheidendes Kriterium. Einige Auswirkungen von Materialeigenschaften sind dabei direkt bewertbar, andere lassen sich nur durch einen Werkstoffvergleich einordnen.

Für die Lebenswegabschnitte Material- und Produktfertigung (Tabelle 4) sind technologisch relevante Eigenschaften zu betrachten, die positive und negative Einflüsse auf einzelne Prozessschritte der Metallerzeugung und -verarbeitung sowie der Produktnutzung haben. Beispielsweise ist bei Aluminium die geringe Dichte und die starke Oxidationsneigung bei der Metallerzeugung nachteilig, da hierdurch die Phasentrennung erschwert wird und Metallverluste auftreten. Demgegenüber stehen jedoch die wichtigsten Argumente für den Einsatz von Aluminium, die Eignung für den Leichtbau und die gute Korrosionsbeständigkeit. Hier findet der Übergang von der Material- zur Produktbetrachtung statt.

3.3 Induzierte Stoffströme

Während bei der Betrachtung von Werkstoff- und Produktherstellung bzw. -rückgewinnung nur die hiermit direkt verbundenen Stoffströme berücksichtigt werden, wird bei der Betrachtung der Nutzungsphase unterschieden in

- den direkten Materialstrom und
- die induzierten Stoffströme.

Als direkter Materialstrom soll hier wie bei der Hauptprozeßkette der Metallerzeugung und -verarbeitung der resultierende Stoffstrom verstanden werden, der letztlich zu einem Materialinput in Form von Guß- und Knetlegierungen in die verschiedenen Nutzungsbereiche führt. Zur Beschreibung der Nutzungsphase ist es darüber hinaus erforderlich, die dort ausgelösten (induzierten) Stoffströme, wie beispielsweise der Energieträger- und Materialeinsatz bei der Produktnutzung, zu analysieren. So sind beispielsweise bei der Betrachtung von Aluminium-Menüschalen neben den direkten Stoffströmen die mit ihrer Herstellung verbunden sind, auch die mit Distribution, Befüllung und Erwärmung des Inhalts verbundenen induzierten Stoffströme zu beachten.

Eine wichtige Aussage der Stoffstromanalyse ist die Relevanz der Nutzungsphase in Bezug auf Energie- und Massenströme, d.h. in welchen Anwendungsfällen die Nutzungsphase einen großen/mittleren/kleinen Anteil an den Stoffströmen während des gesamten Lebenszyklus eines Produktes ausmacht. Auf dem Lebensweg eines Produktes sind somit Auswirkungen zu unterscheiden, die bei Metallerzeugung und Produktion entstehen und die hauptsächlich während der Nutzungsphase von Bedeutung sind. Hier sind auch kurz- und langlebige Produkte zu unterscheiden [5].

Die Auswirkungen der Materialeigenschaften sollen sich auf die direkten und induzierten Stoffströme in der Nutzungsphase beschränken und nicht die subjektiven Aspekte der Bedürfnisbefriedigung enthalten. Diese Verknüpfung zwischen induzierten Stoffströmen während der Nutzung und den Aufwendungen entlang des Materialstroms wird derzeit weitgehend über energetische Aspekte hergestellt [6]. Andere Kriterien wie Flächengebrauch, Toxizität oder Ästhetik werden selten in dieser Relation abgebildet. Innerhalb der Normung ist eine solche Auswahl von Vergleichsindikatoren lediglich optionaler Bestandteil der Wirkungsabschätzung [7].

3.4 Dispersion und Depotbildung

Betrachtet man metallische Stoffströme aus globaler Sicht, stellt jegliche Nutzung prinzipiell eine Dispersion des eingesetzten Metalls dar. Dies ist die Umkehr der zuvor durch aufwendige Konzentrationsprozesse erreichten Metallerzeugung aus primären und sekundären Rohstoffen. Die Dispersion erfolgt räumlich, stofflich und zeitlich und wird im wesentlichen durch das Verbraucherverhalten und den technologischen Entwicklungsstand gesteuert.

Während der Produktnutzung ist das Metall in Materialspeichern bzw. Depots gebunden. Die Depoteigenschaften des Aluminiums können anhand ausgewählter Produktgruppen, Produkte, Produktteile oder Nutzungsarten beschrieben werden (Tabelle 5). Für Verpackungen aus Aluminium liegt beispielsweise eine hohe räumliche Dispersion bei kleiner Produktgröße und großer Verteilung vor. Die stoffliche Reinheit kann dabei hoch (Menüschale, Getränkedose), mittel (Verschlußkappen, lackierte Folien) oder gering (bedampfte Chipstüten, Tetrapack) sein. Die Verweilzeit ist mit einer mittleren Lebensdauer von einem halben Jahr gering.

Die eingesetzten Metalle verweilen aufgrund der unterschiedlichen Lebensdauer der Produkte unterschiedlich lange in der Nutzungsphase, woraus sich eine zeitliche Verschiebung sekundärer Stoffströme im Gesamtstoffstrom ergibt. Die räumliche Dispersion beschreibt die Größe und Verteilung des jeweiligen Depots. Die Verteilung und der davon abhängige Gehalt an Metall im einzelnen Depot stellt hauptsächlich ein logistisches Problem der Erfassungsstrukturen dar. Die stoffliche Dispersion kann sowohl aus recyclingtechnischer Sicht als auch insbesondere aus metallurgischer Sicht zu irreversiblen Materialveränderungen führen, die einen hohen Aufwand für die Rückführung in den Produktionsprozeß hervorrufen.

Aus den in der Technosphäre angelegten Depots können in den meisten Fällen Sekundärrohstoffe zurückgewonnen werden. Die Rückgewinnung ist an den Metallgehalt, die Qualität und die Verweilzeit im Depot gebunden. Aufgrund des hohen Wertes von Metallen in Bezug auf den Energieinhalt ihrer Primärerzeugung kann dabei die Rückgewinnung auch bei geringen Gehalten und Qualitäten ökonomisch und ökologisch sinnvoll sein. Hier müssen bestehende und neue Recyclingkonzepte in die Betrachtung einbezogen werden, die insbesondere dann Bedeutung erlangen, wenn Aluminium beispielsweise in einem Werkstoffverbund die Minoritätskomponente darstellt.

Über diese Betrachtungsweise kann der Massendurchfluß einer Stoffeinheit, bzw. der Lebenswegabschnitt eines Produktes innerhalb der Nutzungsphase durch die Beschreibung der Depotbildung modelliert und quantitativ in den Gesamtstoffstrom eingebunden werden.

4. Die Nutzung als Teil der Gesamtbetrachtung

Um die im Rahmen des SFB 525 angestrebte Gesamtbetrachtung um den Bereich der Nutzung zu erweitern, müssen neben den quantifizierbaren und durch die Prozeßkettenanalyse beschriebenen Aspekte auch weitere Gesichtspunkte berücksichtigt werden.

Eine sinnvolle Quantifizierung der durch den Einsatz von Aluminium in den verschiedenen Bedürfnisfeldern erzielten Auswirkungen gestaltet sich schwierig, da bei der Befriedigung von Bedürfnisfeldern und den erfolgenden Entscheidungsprozessen auch qualitative und subjektive Aspekte entsprechend der Wertvorstellungen eine Rolle spielen.

Technische Materialeigenschaften und Depotbildung lassen sich demgegenüber einfacher quantifizieren. Zwar lassen sich günstige Materialeigenschaften in bestimmten Anwendungen über die Veränderung der induzierten Stoffströme quantifizieren, wie etwa die geringe Dichte, die zu einem geringeren Energieverbrauch im Verkehrsbereich führt, oft aber wird die Werkstoffauswahl erst durch das Zusammenspiel mehrerer Eigenschaften entschieden, wie etwa Leitfähigkeit, Festigkeit, Preis und Recyclingfähigkeit, die sich nicht in gleicher Art und Weise bewerten lassen. Die hierbei auftretenden Probleme sind aus dem Bereich der vergleichenden Bewertung von Umweltauswirkungen bekannt (z.B. Vergleich von Treibhauspotential und Flächengebrauch) [8, 9]. Hier sind ebenfalls methodische Ansätze zu entwickeln und zu diskutieren, um eine Quantifizierung der Einsatzvorteile bestimmter Produkte und der eingesetzten Werkstoffe zu ermöglichen. Sofern die betrachteten Aufwendungen während der Nutzung mehrkomponentiger Produkte wesentlich von einer Werkstoffkomponente abhängen, kann dieser Werkstoff Produktvor- und -nachteile „erben“.

Darüber hinaus unterliegen die Bedürfnisse der Gesellschaft ständigen Veränderungen die sich auch auf die bedürfnisorientierten Stoffströme auswirken. Dies erschwert die Modellierung der Depotbildung, die Festlegung des Ist-Zustandes sowie die Formulierung praxisrelevanter Szenarien. Diese Punkte entscheiden letztlich über die Definition der Systemgrenzen sowie der Allokations- und Abschneidekriterien.

5. Zusammenfassung

Der methodische Einbezug der Nutzungsphase von Aluminium ist ein wichtiger Bestandteil der Prozeßkettenmodellierung im Rahmen des SFB 525. Die Betrachtung der Stoffströme, die mit der Bereitstellung von metallischen Rohstoffen verbunden sind, muß daher um die Betrachtung spezifischer Produkte oder Produktgruppen und der ihnen zugrunde liegenden Bedürfnisfelder erweitert werden. Die Relevanz der unterschiedlichen Materialeigenschaften ist insbesondere beim Übergang von der Werkstoff- zur Produktbetrachtung von Bedeutung. Die Analyse der direkten Materialströme wird durch die induzierten Stoffströme in der Nutzung ergänzt. Über eine Beschreibung der Depotbildung während der Nutzung können die Stoffströme modelliert und quantitativ eingebunden werden. Der Einfluß der Nutzungsphase auf den gesamten Lebensweg variiert für unterschiedliche Produkte bzw. Produktgruppen und stellt einen wichtigen Aspekt in der Gesamtbetrachtung dar.

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Abbildungen/Tabellen

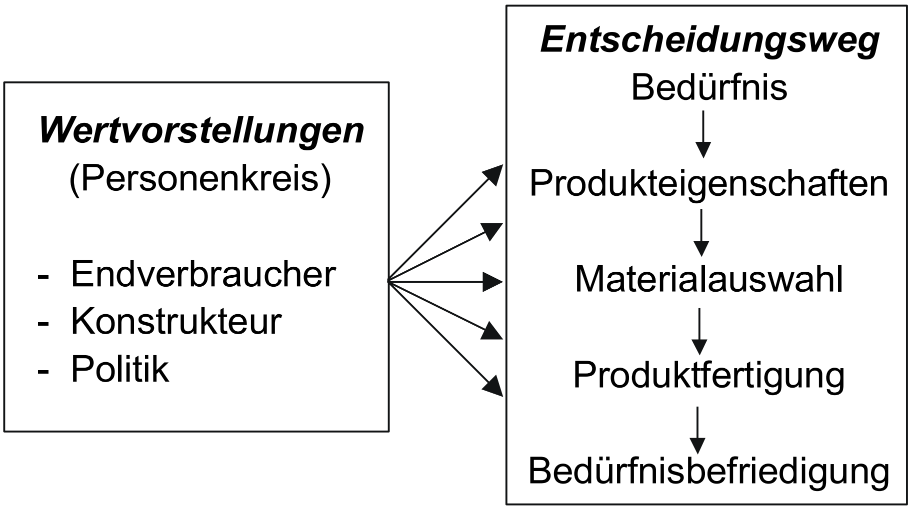

Abbildung 1: Verknüpfung von Wertvorstellungen und Entscheidungsweg

Abschnitt	Bilanzgrenzen	Aufgabe
Materialherstellung	Von Rohstoffgewinnung (Primär u. Sekundär) bis zur 1. Verarbeitungsstufe	Werkstoff mit definierten physikalischen und chemischen Eigenschaften
Produktfertigung	2. Verarbeitungsstufe bis Endverbraucher	Produkt mit definierter Funktionalität
Nutzung	Gebrauch, Instandsetzung bis Entsorgung	Bedürfnisbefriedigung in den Bedürfnisfeldern

Tabelle 1: Abschnitte, Bilanzgrenzen und Aufgaben bei der Stoffstrombetrachtung

	Verkehr	Bau	Masch.bau	E-Technik	Verpackung	Haushalt
ökonomisch	sparsam, Nutzlast	langlebig, wartungsarm	langlebig, vielseitig	kostengünstig, geringer Stromverlust	rationeller Materialeinsatz, Haltbarkeit	langlebig
ökologisch	leicht, ressourcenschonend, recyclingfähig	recyclingfähig, langlebig,	leicht, recycling-fähig	recyclingfähig	ressourcenschonend, recyclingfähig	recyclingfähig
gesellschaftl.	modern, fortschrittlich, sportlich	ästhetisch, modern, funktionell	modern, fortschrittlich	modern, fortschrittlich	sicher, sauber, benutzerfreundlich	ästhetisch, modern, funktionell

Tabelle 2: Mögliche relevante Wertvorstellungen und Assoziationen bei der Aluminiumanwendung

	Auto	Flugzeug	Bau	Masch.-bau	Elektrotechnik	Verpackung	Haushalt
Dichte	++	++	++	+	+	++	+
elektrische Leitfähigkeit	o	o	o	+	++	o	+
Wärmeleitfähigkeit	++	o	+	++	+	++	++
Korrosionsbeständigkeit	++	++	++	++	++	++	++
Festigkeit	++	++	++	++	+	+	+
Zähigkeit	++	++	++	++	+	++	+
Tieftemperatureignung	+	++	++	+	+	+	o
physiologische Unbedenklichkeit	o	o	+	o	o	++	++

Tabelle 3: Relevanz der Materialeigenschaften für die Anwendungsbereiche von Aluminium (o ohne besondere Bedeutung, + mäßige Bedeutung, ++ große Bedeutung)

	Primärproduktion	**Sekundärproduktion**	**Formguß**	**Halbzeugherstellung**	**Produktfertigung**	**Al-Einsatz als Knetlegierung**	**Al-Einsatz als Gußlegierung**
Dichte	Phasentrennung	Phasentrennung	Formfüllung	Handling	Handling	Leichtbau	Leichtbau
Wärmeleitfähigkeit		Schrottvorwärmung	gerichtete Erstarrung	effektive Kühlung	effektive Kühlung	Wärmetauscher	Motorkühlung
Umformvermögen		mech. Aufbereitung		Umformgrad	Gestaltungsfreiheit	Zähigkeit	
Spanbarkeit				Blockbearbeitung	Gestaltungsfreiheit		
Schweißbarkeit	flexible Stromzufuhr			z.B. Walzen von Endlosbändern	Gestaltungsfreiheit	Kombination mit Gußteilen	Kombination mit Knetteilen
chem. Potential	Reduktion	Raffination					
Löslichkeit	Aufnahme von Verunreinigungen	Aufnahme von Verunreinigungen	Legierungsvielfalt, Veredelung etc.	Rekristallisation und Aushärtung		hohe Festigkeit	hohe Festigkeit
OF-Spannung		Koagulation	Formfüllung	Eignung für Strangguß			
OF-Oxidation	Krätzebildung	Koagulation, Krätzebildung	Einschluß von Oxiden	Schutz, Einschluß von Oxiden	Anodisieren etc.	geringe Korrosion	geringe Korrosion

Tabelle 4: Möglicher Einfluß der Materialeigenschaften auf die Lebenswegabschnitte Material- und Produktfertigung von Aluminiumprodukten

Dispersion	**Depot**	**Verpackung**	**Verkehr**		**Bau**	**Masch.-bau**	**Elektrotechnik**
			Zug/Flugzeug	Auto			
räumlich	Größe	-	+	o	+	o	o
	Verteilung	+	-	+	o	o	+
stofflich	Reinheit	+/o/-	+	-	+	o	+/-
zeitlich	Verweilzeit	-	+	o	+	+	+/o

Tabelle 5: Mögliche Depoteigenschaften von Aluminiumprodukten in ausgewählten Nutzungsbereichen (- gering, o mittel, + hoch)

THE USE PHASE IN THE ALUMINIUM MASS FLOW -AN APPROACH FOR INTEGRATION-*

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ABSTRACT

In mass flow analyses the use phase is often not adequately integrated. Above all user-related effects, life-time of products or product-systems are frequently unconsidered. Looking at the entire process chain the total demand for aluminum is important. But balancing the environmental impacts of the use phase of aluminum-bearing products such as cars, trains, window frames, or beverage cans three other targets win importance. These are the identification of environmental impacts during the use phase itself and its integration in the process chain. Using this data the third target aims at case studies which point out various user-related effects.

For this purpose mass flows and induced environmental impacts of the particular product use, startup, maintenance and repair have to be quantified separately using LCA. For this targets the consideration of the multifunctional material properties is important which requires the choice of a suitable functional unit in order to reproduce all parameters. Furthermore, those mass flows have to be considered which are influenced by the user. Besides socio-economic factors the individual user behavior is determined by exogenous parameters such as distribution and availability of product information. Additionally, it is important to include the life-time of products, because the effects can only be shown after a certain time of usage or, due to the high life time of some products, by summation. On the basis of examples from the aluminum sector particular spectra of the usage are represented with focus either on user behavior, technological potential, recycling ability or life span

KEYWORDS

Mass flow analyses, use phase, user-related effects, life-time, process chain, aluminum, environmental impacts, case study, product use, LCA, multifunctional material properties, functional unit, socio-economic factors, user behavior, user behavior, technological potential, recycling ability, life span.

* Source: Proceedings of European Metallurgical Conference EMC 2003, Vol. 1, pp. 307 – 320

1 Introduction

The process chain of aluminium production is described by the several studies of the Collaborative Research Center (CRC) 525 “Resource-orientated analysis of metallic raw material flows” described but the use phase was excluded up to now. The purpose of this study is on one hand to close the gap and on the other hand to develop a method for integration the use phase in the mass flow. Aluminium is well suited for many uses because of its properties and processing methods. The total demand of aluminium in Germany, which amounts to 2.7 mio. Tonnes (2001), is shared into eight comsumer sectors (see figure 1 (left). It can be calculated that that about 11 % (285000 tonnes) is covered by the automobile industrie (3.341 mio. newly admitted vehicles). In these sectors aluminium is bounded in depots during the usephase. According to the lifespan of the different product components, products respectivley product systems it is estimated that this amount sums up to approx. 700 mio. Tonnes (2001).

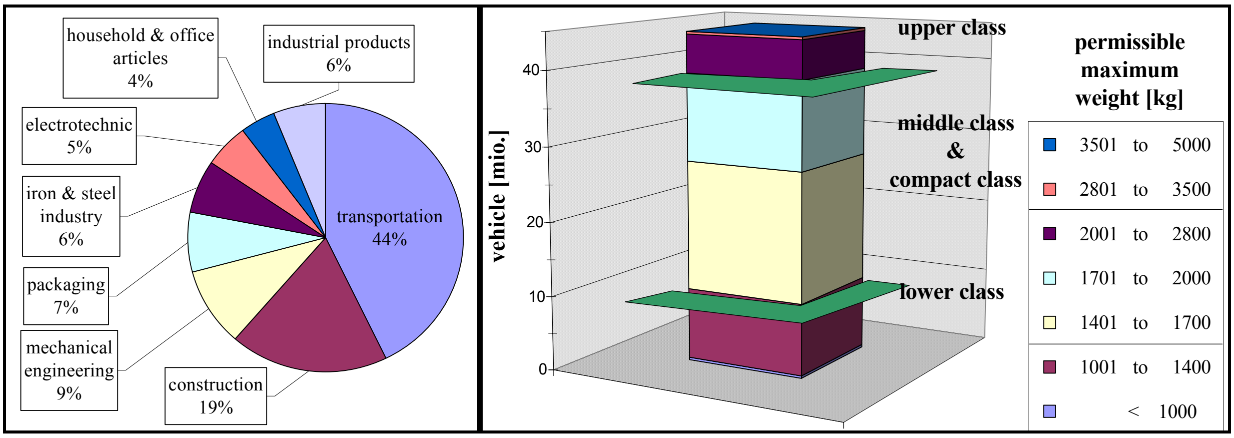


Figure 1: Distribution of the aluminium consumption to the industry sectors in Germany (2001)[1] (left) and rolling stock per permissible maximum weight [2](right)

The largest end-consumer market for aluminium has been the transportation sector already over a long period. About 44 % of the aluminium produced is captured here. Originally essential for lightweight applications in the aerospace industry, aluminium is now widely used in bicycles, cars, buses, coaches, lorries, trains, ships, ferries, and aircrafts.

The use of aluminium in vehicles rised continuously in the last years. Presently the average aluminium mass is approximately 80 kg per vehicle in Europe. The European Aluminium Association (EAA) estimates that this value will increase to approximately 160 kg per vehicle in the year 2008 (see figure 2). Several aluminium applications are already established in functional units like engine, drive train, and chassis (see table 1). While in the past aluminium is widely used in upperclass cars, at the present time car manufacturers became more interested for aluminium applications of the middle and compact class in order to reduce the car weight or at least to compensate the weight of new features in the cars.

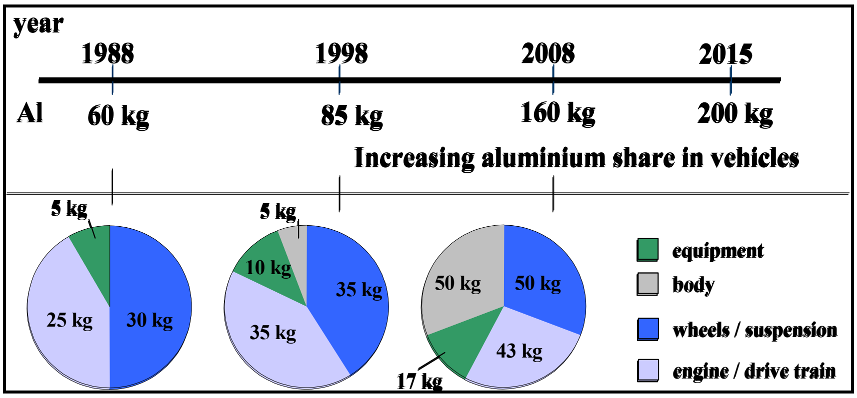


Figure 2: Aluminium use in car-components (estimated)[1][3][11][12]

In this report an analysis will be carried out on the environmental impacts which are connected with the use in individual traffic applications due to its lightweight potential in present and future vehicles. As a basis for the analysis a "state-of-the-art aluminium vehicle" (SAV) with 80 kg (2002) as the current average aluminium weight in vehicles is defined as a reference-car (2000). In a second step an estimation is made of the future average use of aluminium of 160 kg per vehicle (2008), respectively of 210 kg per vehicle (2015), whereas these vehicles are called "aluminium-intensive-vehicle" (AIV) respectively "aluminium-maximised vehicle" (AMV). This study covers the environmental impacts of primary weight savings as well as the potential for the so called secondary weight savings. A second view is given to the impact of the ressource requirements of individual use types (driving styles) compared with a "standard" consumer behaviour, which may superimpose any light-weight-advantage of Aluminium.

Table 1: Application of aluminium alloys (examples)

	Alloy	Application	
Wrought alloy	AlCuMg 2	▪ wheel baering ▪ transverse control arm	▪ crank and camshaft
	AlMgSi 1	▪ wheels	▪ profiles for the structure
	AlMg 2	▪ sheets for the car body	
	AlSi 17 CuNi	▪ piston (pressed)	
Casted alloy	G-AlSi 12	▪ crank case ▪ oil pan	▪ gear case
	G-AlSi 10 Mg	▪ crank case	▪ cylinder head (watercolded)
	GK-AlSi 12 CuNi	▪ casted piston	
	AlSi9Cu4	▪ general applicable	

2 Method

2.1 The integration of the use phase in the Aluminium mass flow

In order to reduce the environmental impacts of product components, products or a service as efficiently and effectively as possible, it is necessary to analyse the ressource requirements (e.g. energy consumption) of all process steps in of a "closed loop"- view from production to the disposal. For this a balance method is necessary, which seizes mass as well as energetic in- and outputs in an inventory. Throughout the requirements of mass- and energy preservation in the regarded system the completeness of the balance in the sense of an Holistic view has to be examined (see figure 3).

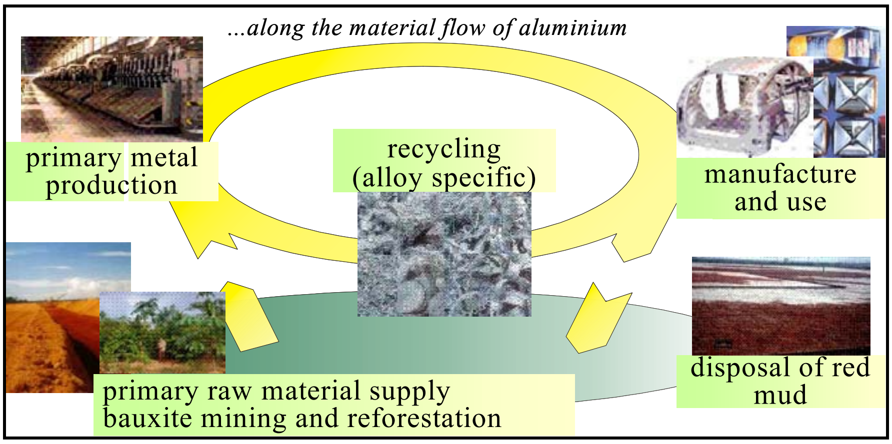


Figure 3: Life cycle of Aluminium

The inventory can be designed as a matrix, whereby the regarded processes along the life span are described in a vertical analysis and the categories of the in- and outputs of the respective subprocesses are described in a horizontal analysis. In this paper the subprocess “use phase” is investigated (see table 2).

Different investigations [6,7,8, 9] postulate that in the entire life cycle of a product the use phase has the highest environmental relevance so that a detailed view of the use phase is nessecary. In our model the use phase consists of five subphases (see figure 4), which have different relevance and intensity depending upon product. Generally the use of a product begins with the distribution to the final consumer (private or commercial consumer, service) and/or with its purchase and ends with the operation shut down and supply to the recycling cycle (collecting, sorting, processing) respectively to the waste utilization plant.

Table 2: Analysis matrix for the use phase (with examples)

status of vehicle	purchase *for selling*	operation startup *in state of trans-portation*	use *in state of going into action*	maintainence - repair *in state of service / repaired*	operation shut-down *in defect state*
input	Not investigated	detergents	fuel, oil, water	water, oil, battery, wheel, coolant	fuel
output		emissions, packaging	emissions	water, oil, battery, wheel	registration
working material		cleaning thinks		tools	tools
user profile			commuter, housewife	car owner engineer	
process management			commuter traffic weekend traffic		transportation to the graveyard
process surrounding			high way, motor-way, country road	garage	auto graveyard

The subphase "purchase" is determined primarily by more or less conservative, conscious acting of the buyer. This requires sense of responsibility, innovation strength and competence from both the buyer and the seller regarding ecological and socio-economic technique consequences and to avoide emissions. The "operation startup" of products can not be generalized. The start-up of a vehicle covers the filling with fuel, the removing from protection material and the inserting of additional equipments. This is quite different to other Aluminium applications as the start-up of a packing or can covers the packaging or filling, the distribution and the storage in the wholesale respectivley supermarket. The subphase "use" of a product represents the operational conditioning and the actual use of the product. This covers the application and consumption of products, the operation of a vehicle or a machine as well as the manufacturing of other products with the aluminium product.. The use of a product can be again subdevided into the phases preparation, use and aftertreatment. The maintenance of products takes place to a great extent according to fixed schemes. Here measures are carried out for keeping the function of the product in good condition. Repair measures are often not planned events, which are differently complex. In the subphase “operation shut down” the product is supplied accordingly to waste disposal decrees to waste utilization plants for paper, glass, plastics and to the recycling systems mainly for metals.

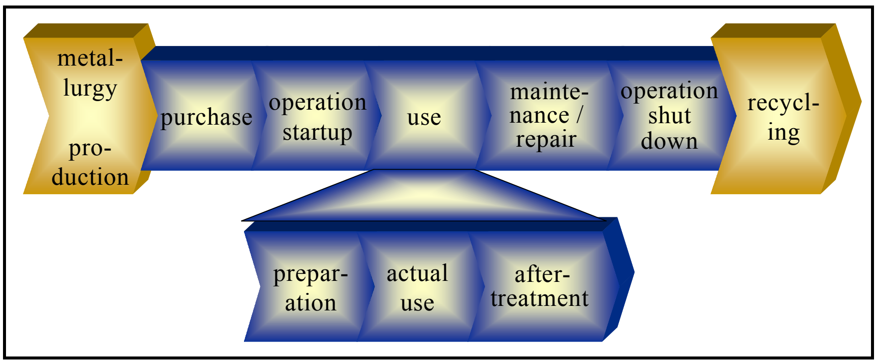


Figure 4: The use phase, devided into five sections, in the mass flow

2.2 Life-cycle-balances tool: GaBi

The software system GaBi [4] is a commercial tool to build up mass flow and life-cycle-balances. Its calculation possibilities are limited to productlife cycle analysis but GaBi illustrates quite good the life cycle in flow charts respectivley in Sankey diagrams, allowing a quick overview of mass, energy or even financial requirements. Some data is already contained in GaBi data bases and can be easily expanded and changed using the powerful datasource of the collaborative research center SFB525 in Aachen [10]. From the calculated mass flow analyses the results can be transferred to build ecobalances, which represents a combination of inventory and asseessment. For the evaluation using the "GaBi-analyst", variations of the parameter and scenario analyses have to be carried out. Thus the ecological effects (greenhouse effect etc.) and its changes due to different assumtions like SAV, AIV and AMV can be determined.

3 The future of the passenger vehicle as means of transport?

This question the pioneers of the passenger cars asked themselves such as Ford and Benz in the end of the 18th century. Hardly any product in our daily use, affected in such a manner the entire society over several generations in thinking, acting and planning. While the automobile became technically perfect, more comfortably as well as affordable for almost everyone, the economical, social and ecological problems will grows with the use of the automobile (world-wide 500 millions in the year 2001) (data for Germany see figure 5).

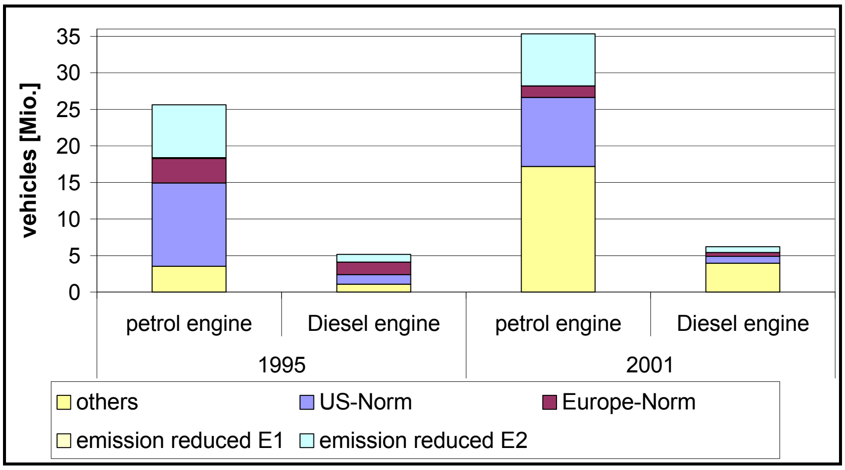


Figure 5: Rolling stock of emission reduced vehicles in Germany [2]

The individual traffic seems to become a victim of its own success and the further rising demand for mobility creates constantly new challenges, because still the social, economical and cultural progress is connected with the speed of mobility. The transportation sector plays a central role in the modern economy, because only the mobility of raw materials, semi and finished products as well as people (e.g. pupils, trainees, working persons, travelers, consumers) ensures the share of labour and wellfare in all sectors of the economy. In the background of the globalization the traffic sector becomes a constantly growing significance. Resource-requirements, land consumption and environmental pollutions induced by traffic as well as direct and indirect damage of humans and nature (e.g. by accidents) require a reorientation in production and recycling of vehicles. This is also in respect to traffice space and traffic management as well as driver training. In the last decades the weight of the vehicles increased continously (see figure 2 and 6). Safety measures, emission reduction measures, and claims for more comfort led directly and indirectly through adjustment of engine and chassis to an increasing weight of 1,600 kg of present vehicles in the previous 40 years.

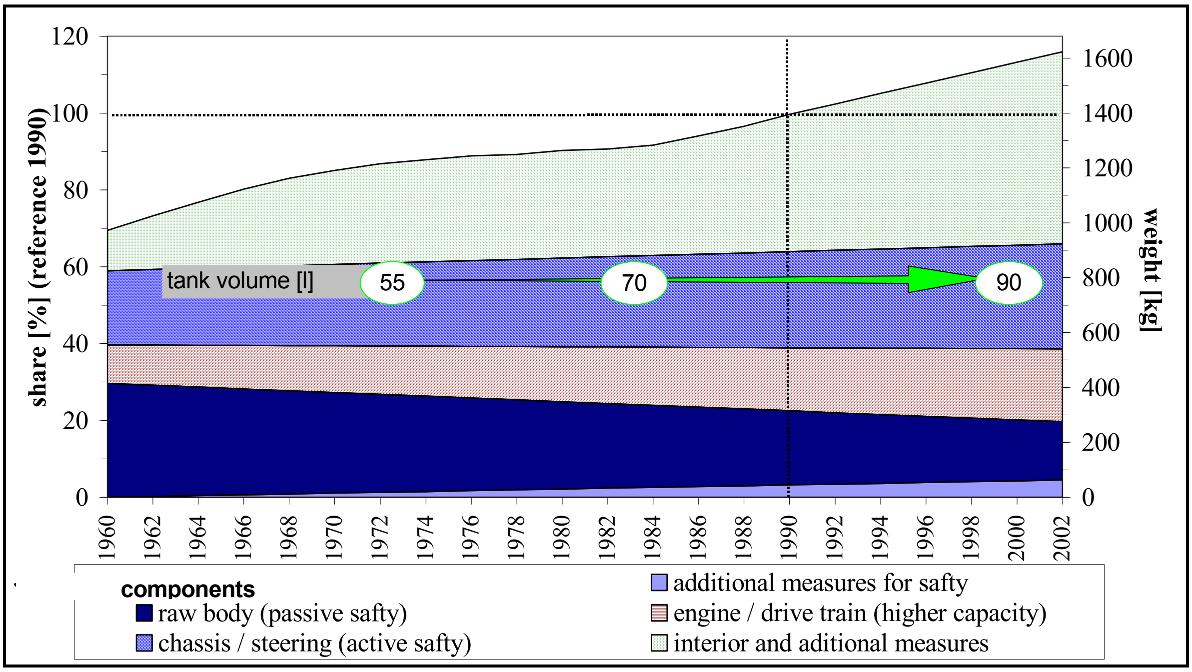


Figure 6: Development of the weight of an mid-class vehicle [4, modified]

3.1 Benefit and Potential of Weight Savings Using Aluminium in Cars

With the movement of the vehicle various driving resistances (the movement against work), which determine the fuel consumption as a function of the mass substantially. The total traction resistance F_w of a vehicle results from the sum of rolling resistance F_{Ro}, acsent resistance F_L, flow resistance and acceleration resistance F_A, whereby the single resistances operate not all at the same time (see figure 7 left).

The importance of the vehicle weight for a reduced fuel consumption is undisputed. Primary weight saving effects can be obtained through weight reduction of the body. The success of such measures is basis for further savings at other vehicle components. The light weight construction leads to downsized aggregates and components like engine or tank. They induce again further potential light weight construction, the so called secondary weight saving effects. Both the primary and secondary effects have to be considered when weight savings through the use of aluminium are determined and assessed. By replacing more components with current or new developed aluminium components a primary weight saving is realized. To determine the secondary weight saving the impact of this measure on the weight of the motor, chassis, body and drive-train have to be cosideres, as they can reduced by downscaling according to the new technique concept (see figure 7, right). For future vehicle generations the target for weight reduction is 30 - 35 %, which is equivalent to approx. 300 – 450 kg for a midclass vehicle. (see figure 8)[5].

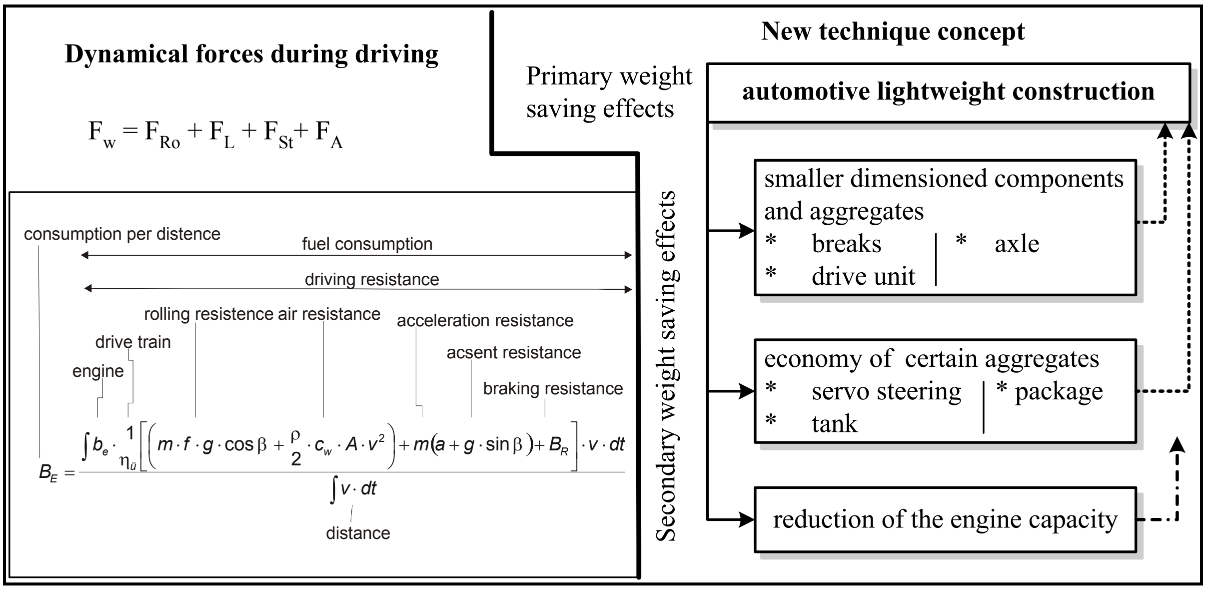


Figure 7: Dynamical forces during driving (left) [3] and primary and secondary effects of automotive light weight construction (right) [3][12]

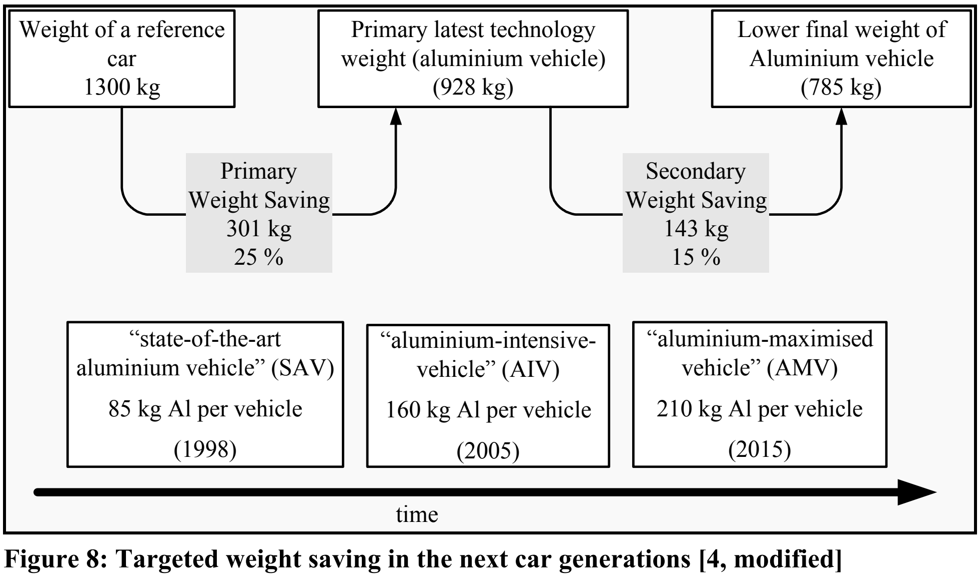


Figure 8: Targeted weight saving in the next car generations [4, modified]

4 Environmental Impact of the User Behaviour

Following the rule “To succed in an one-litre-vehicle it is nessecarry to have an one-litre-driver”, the behaviour of the car drivers has to be taken in account. Motor vehicles are subject to various

EEC-guidelines, where the requirements regarding active and passive vehicle safety as well as fuel consumption and thus CO_2-emissions of a vehicle are regulated. Consequently the definition of a “normal consumption” of a vehicle is vehicle specific and varies upon the class. Fuel can be saved not only with a low-consumption car, but also significantly with a foresighted and reserved driving method and last not bus least with a regularly maintained car. Driver trainings give helpful tips:

- "30-liter-vehicle"? – by frequent cold startings
- 1.5 - 2.7 % fuel saving with light oils
- aircondition is costly: approx. 0.3 - 0.7 l per hour
- power generation (e.g. music, navigation system) needs fuel: 0.5 l /100 km (average value)
- when the vehicle stops for more than 60 seconds - engine out
- drive in high gears / low rpm-values
- keep to the recommended speed on motorways

Almost each use of products leads to environmental impacts by the interaction “user – product – environment”. The user and his use behavior attain thereby special attention, because the extend of the environmental impact is directly dependent on the use behavior. The environmental impact of a use phase consists of user independend, so called technology-determined, individual and social determined effects (see figure 9, left).

The technology-determined environmental impacts are product intrinsic, which means that the user has no influence. Neglecting the influence of any user behavior this would be the expectable environmental effect from the outgoing product and thus represents the optimal behavior. The individual-determined impacts depends directly on the user behavior, since these are affected by various factors such as motivation, environmental interest, time and budget as well as by the social surrounding. The surplus of environmental impacts as a function of the number of persons in the vehicle can be related to social-determined effects, compared with the purpose to use a vehicle with full capacity. Individual-determined impacts results for e.g. from high speed or high accelerating drivers.

The “normal behavior” of an user is located somewhere between optimal behaviour and lapse depending on what kind of preference the user has regarding time, budget, or environmental interest (see figure 9 (right)). Altogether the consumer-dependent use behaviour always lead to failures, which are oftentimes multilayered.

In figure 9 (down) the CO_2-emissions is distributed to the individual subphases. The purchase phase is estimated because in this study this subphase is deeply investigated. The columns correspond to the environmental impacts, calculated with GaBi which vary upon the above described factors as well as climatic or regional parameters.

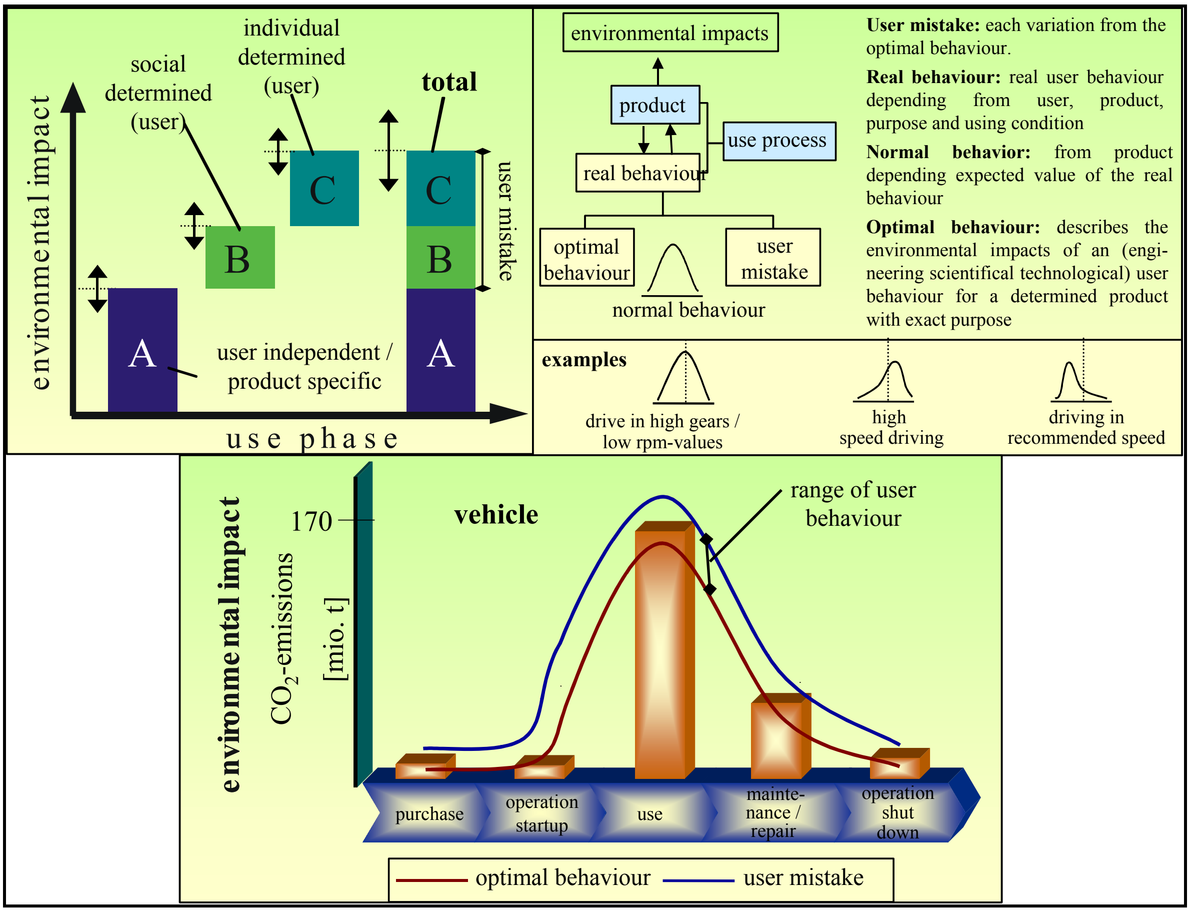
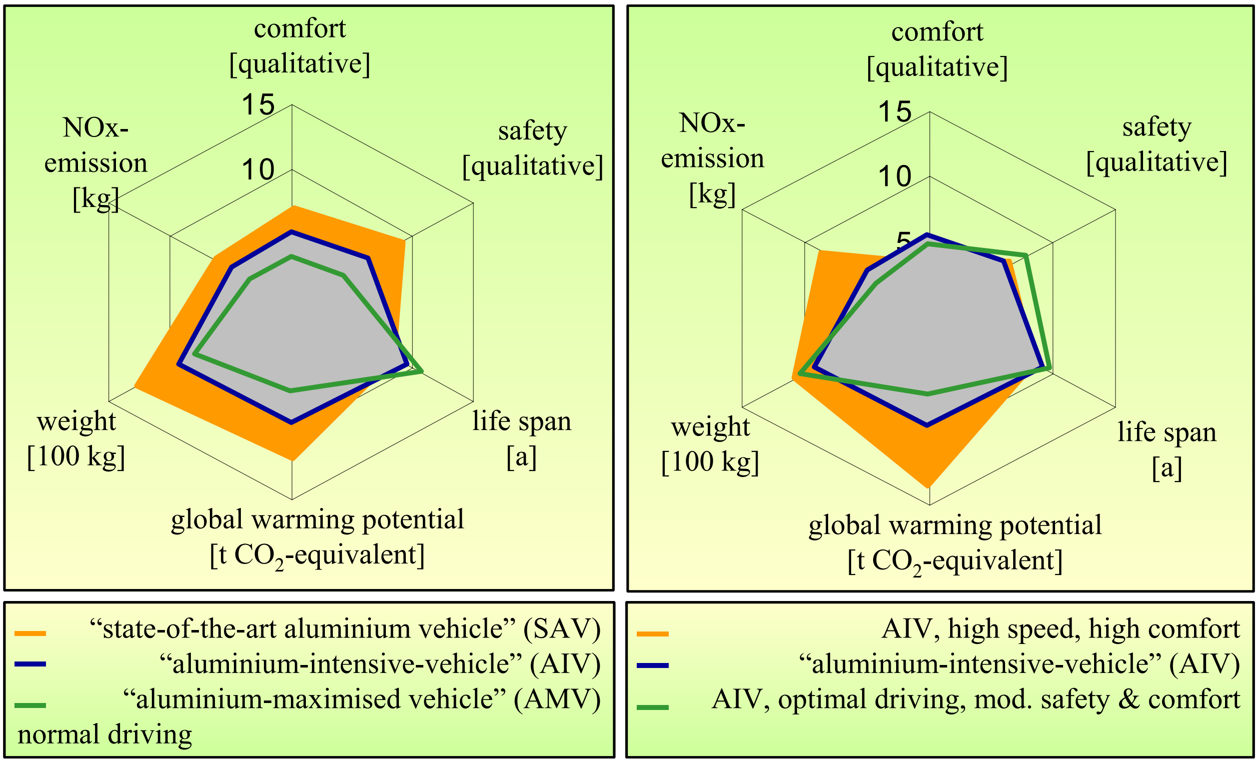


Figure 9: Classification of environmetal impact sources (left), describtion of the user behaviour (right), and influence of the user behaviour (own calculation)(down)

5 Results and Assessment

The environmental impact of the vehicle use phase is significant and the reasons are manifold and many parameters have to be considered simultaneously. Using a "spider chart" it is possible to illustrate qualitative as well as quantitative results and to give a summerized assessment of the use phase at the same time. The center of the cobwebs represents the optimum of all parameters, the outer edge of the cobweb stands for the worst case. The scale is linear in order to provide distorions.

Figure 10 (left) schows the GaBi calculated emission results of the three technologies using different shares of aluminium (SAV, AIV, AMV) together with improvments in safty, comfort, weight and life span. In view of the vehicle (user independent factors) the consumption of fuel can be reduced significant with which a reduction of emissions is obtained. For every 100 kg reduction of the weight, there is a decrease of 0.3 to 0.6 litres per 100 km in fuel consumption accompanied with a reduction of gas emissions up to 20% [3]. As schown in the spider chart the emissions of CO_2 and NO_x are obviousley lower for the aluminium-intensive-vehicles (AIV) and aluminium-maximised-vehicles (AMV) than for the state-of-the-art aluminium vehicle (SAV). Even safety improvements and life span extending measures can be realized without increasing emissions. Furthermore aluminium in vehicles increases safety directly through the new body concept or increasing energy absorbency during crash. Through the mass reduction there is the possibility to add more safety components without exceeding the actual car weight (indirect effect).



Legend	very high	high	medium	low	very low
	1	3	5	7	9

Figure 10: Environmental impact (left) and user influence (right) of the use phase of a aluminium vehicle (calculated)

The big share of drivers with non-optimal user behaviour lead to considerable environmental impacts. The user does have influence on fuel consumption on four levels (see figure 10):

1. selection of vehicle type (consumption, safety, extras,…)
2. driving reason and "beeing lazy" (especially: short distances)
3. driving style (speed, foresighted,…)
4. transportating of not actual needed material (empty waetr bottles,..)

The diagramm reflects three scenarios, alss based on the aluminium-intensive-vehivcle (AIV) (basis 2008). One scenario combines a highely equipped (heavy) vehicle, which is driven agressivly. A second scenario represents a moderate driver in a vehicle with moderate safety and comfort standard (no seat-heating, no navigation system, no extra hifi-equipment,…). The third scenario is the referece vehicle also used in figure 10 (left) (blue lines) equiped standard, but normal user behaviour.

6 Summary

These results summarized it can be schown that

1. emissions can be reduced significantly by using more aluminium in vehicles
2. A part of the weight reduction gained by aluminium use can be transferred to an improved safety and comfort level of the vehicles.
3. A slight improvement of the life span of the vehicle can be obtained by using aluminium components.
4. The user behaviour influences the emissions significantly. A high-speed driver compensates the advantages of an aluminium use by far.

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Thanks to the German Aluminium Association (GDA) and German Research Council (DFG) for financial support.

KRAFTSTOFFEINSPARUNG UND CO_2-REDUKTION DURCH ALUMINIUM-LEICHTBAU IN PERSONENKRAFTWAGEN*

(FUEL SAVING AND CO_2 REDUCTION BY MEANS OF ALUMINIUM LIGHTWEIGHT CONSTRUCTION IN PASSENGER CARS)

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ABSTRACT

The article deals with ecological aspects of aluminium light-weight potentials in the use phase of vehicles. Several studies have shown the unquestionable importance of the use phase e.g. in terms of fuel consumption and carbon dioxide emissions. Light-weight construction with aluminium is one option to reduce fuel consumption and related CO_2 emissions. This study considers different aluminium components in the body of new passenger cars and the resulting fuel saving and CO_2 reduction of the car fleets in Germany.

The methodological approach is based on two models and one scenario. The micro-model considers data of vehicle manufacturing and fuel consumption. It is used for the calculation of direct fuel saving and CO_2 reduction. The macro-model is an input-output-model that shows the interdependence of different industry sectors in an economy. It is used for the analysis of economy-wide effects of fuel saving and CO_2 reduction. The scenario-technique describes three possible situations of aluminium light-weight construction in passenger cars. As a result, between 71 and 435 million litre of fuel can be saved by the light-weight potential of aluminium in passenger car bodies.

KEYWORDS

Use phase, aluminium light-weight potential, fuel consumption, CO_2 emission, input-output-technique

* Source: STE- Preprint 45/2003

1 Einleitung

Die Nutzungsphase von Produkten kann aufgrund ihrer Umweltwirkungen eine wichtige Rolle im gesamten Lebenszyklus eines Produktes einnehmen. Die werkstoffliche Zusammensetzung, der technische Stand und die individuelle Nutzung des Produktes sind hierfür maßgeblich. Lebenszyklusanalysen von Personenkraftwagen haben gezeigt, dass die Nutzungsphase den gesamten Lebenszyklus mit Blick auf Energieaufwendungen, z. B. durch die Verbrennung von Diesel- und Benzinkraftstoff und damit zusammenhängende energiebedingte Emissionen, z. B. CO_2-Emissionen, dominiert. Seitens der Automobilindustrie werden verschiedene Aktivitäten unternommen, den Kraftstoffverbrauch der Pkw zu reduzieren. Darunter gehören Maßnahmen wie die Senkung des Luftwiderstandes, die Verbesserung von Motor und Antrieb sowie die Reduzierung der Fahrzeugmasse.

Ziel dieser Analyse ist es aufzuzeigen, welche mittelfristige Kraftstoffeinsparung und CO_2-Reduktion in der Nutzungsphase von Pkw durch unterschiedlich stark ausgeprägten Aluminium-Leichtbau in der Karosserie erzielt werden kann. Betrachtet wird der deutsche Pkw-Bestand ausgehend vom Basisjahr 1995 bis zum Zieljahr 2013. In der Analyse werden direkte und indirekte Effekte berücksichtigt. Beispielsweise erfolgt die erzielte CO_2-Reduktion zum einen direkt durch die vermiedene Verbrennung von Diesel- und Benzinkraftstoff und zum anderen indirekt durch die Vermeidung von Produktionsaktivitäten in der Mineralölwirtschaft sowie derer Zulieferindustrien, die an der Kraftstoffbereitstellung beteiligt sind. Beide Emissionsquellen werden in diesem Beitrag berücksichtigt.

In Kapitel 2 erfolgt eine Systembeschreibung. Das betrachtete System wird nur mit Blick auf die Nutzungsphase von Pkw betrachtet, andere Phasen des Lebenszyklus sind nicht Gegenstand der Analyse. Aufgezeigt wird, unter welchen Voraussetzungen Leichtbaumaßnahmen in der Karosserie der Nutzungsphase zugeschrieben werden können.

In Kapitel 3 wird der Modellansatz vorgestellt. Die Analyse baut methodisch auf zwei Modellen auf: erstens einem Pkw-Modell mit Daten zur Herstellung und Nutzung von Pkw und der Entwicklung des Pkw-Bestandes in Deutschland und zweitens einem volkswirtschaftlichen Input-Output Modell, das die deutsche Produktionsstruktur abbildet und durch physische Input-Output Tabellen, z. B. CO_2-Emissionen erweitert wird. Das Input-Output-Modell wird eingesetzt zur Analyse der Kraftstoffherstellung. Neben den beiden Modellen wird die Methode der Szenariotechnik eingeführt.

In Kapitel 4 wird ein Szenario mit Blick auf Struktur, Annahmen und Rahmendaten vorgestellt. Das Szenario wird strukturiert durch fallübergreifende und fallabhängige Annahmen und bildet die Bandbreite von drei möglichen Entwicklungen in der Zukunft ab. Zentrale fallübergreifende Annahmen bauen auf dem Shell Pkw-Szenario „One World“ auf, da es eine mögliche verkehrswirtschaftliche Entwicklung des motorisierten Individualverkehrs (MIV) in Deutschland abbildet. Darüber hinaus wird als fallübergreifende Szenarioannahme das grundsätzlich zu erwartende Potenzial des Aluminium-Leichtbaus im Pkw, abgeleitet aus verschiedenen Studien, definiert. In den fallabhängigen Annahmen werden die Neufahrzeuge in Bezug auf den Aluminiumeinsatz in der Karosserie und die damit zusammenhängende Gewichtseinsparung sowie die Antriebstechnik definiert. Zusätzlich werden Annahmen über den Aluminiumeinsatz und den Kraftstoffverbrauch im Restbestand getroffen. Das Kapitel schließt mit der Beschreibung von drei unterschiedlichen Fällen der Kraftstoffeinsparung und CO_2-Reduktion durch Aluminium-Leichtbaumaßnahmen in der Karosserie eines Pkw.

Kapitel 5 zeigt die Auswertungen und Ergebnisse der Szenariorechnung.

In Kapitel 6 erfolgt eine Zusammenfassung.

2 Systembeschreibung

Die Ökobilanz-Studie oder auch Lebenszyklusanalyse, ist eine wissenschaftlich fundierte Methode, die Umweltaspekte und mögliche Umweltwirkungen während der Herstellung, Nutzung und Entsorgung bzw. Wiederverwertung von Produkten untersucht. Sie kann dazu beitragen, Möglichkeiten zur Verbesserung von Umweltwirkungen in den einzelnen Lebenszyklusphasen eines Produktes aufzuzeigen.[1] Lebenszyklusanalysen haben gezeigt, dass der Nutzungsphase eine wesentliche Bedeutung im gesamten Lebenszyklus eines Produktes zukommen kann. Verschiedene Studien über Konsumgüter kommen zu dem Ergebnis, dass oftmals in dieser Lebensphase die höchsten Umweltauswirkungen anfallen.[2] In dieser Arbeit wird die Nutzungsphase[3] bzw. im besonderen die ‚Betriebsphase' eines Pkw betrachtet, da sie durch einen hohen Ressourcenverbrauch und damit zusammenhängende Emissionen gekennzeichnet ist. In Bezug auf den Energieaufwand des gesamten Lebenszyklus benötigt allein die Betriebsphase eines Pkw ca. 83 % des gesamten Energieaufwands. Mit Blick auf die anfallenden CO_2-Emissionen im Lebenszyklus, entstehen sie zu ca. 93 % in der Betriebsphase.[4] Der Energie- bzw. Kraftstoffverbrauch eines Fahrzeugs ist u.a. in hohem Maße vom Fahrzeuggewicht abhängig.[5] Eine Möglichkeit, Einsparungen beim Energie- bzw. Kraftstoffverbrauch in der Betriebsphase vorzunehmen, wird mit dem Leichtbau verfolgt. Aluminium ist ein geeigneter Werkstoff, um unterschiedliche Leichtbaumaßnahmen im Pkw durchzuführen. Voraussetzung für die Zurechnung der

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[1] International Organisation for Standardization (ISO): Umweltmanagement Ökobilanzen. Prinzipien und allgemeine Anforderungen 14040. Europäisches Komitee für Normung. Brüssel 1997, S. 2.

[2] Behrendt, S.: Anwendung von Ökobilanzen bei komplexen technischen Produkten am Beispiel von Fernsehgeräten. Produktbezogene Ökobilanzen IV. Berlin 1996, S. 119-138. Prins, J.: Design for environment in practice. In: Proceedings of the ICED'97. Vol. 3. Tampere (Finland) 1997, pp. 611-618. Schweimer, G.W./Schuckert, M: Sachbilanz eines Golf. In: Ganzheitliche Betrachtung im Automobilbau. Rohstoffe – Produktion – Nutzung – Verwertung. VDI Bericht Nr. 1307, Düsseldorf 1996, S. 235-255.

[3] In Dannheim, F./Birkhofer, H.: Die Bedeutung der Nutzungsphase für die Entwicklung umweltgerechter Produkte. In: Konstruktion. Nr. 50 (1998),Heft 3, S 27-29 wird eine Systematisierung der Nutzungsphase vorgenommen, um die Umweltauswirkung den einzelnen Teilphasen der Nutzung zuordnen zu können. Die Nutzungsphase kann dabei beispielsweise in die Phasen: Kauf, Inbetriebnahme, Betrieb, Reparatur und Ausserbetriebnahme unterteilt werden.

[4] Schäper, S./Haldenwanger, H.G./Rink, C/Sternau, H.: Materialrecycling von aluminiumintensiven Altfahrzeugen am Beispiel des AUDI A8. In: Neue Werkstoffe im Automobilbau. VDI Bericht Nr. 1235. Düsseldorf 1995, S. 249-266.

[5] Koewius, A.: Aluminium-Spaceframe-Technologie. Der Leichtbau des Serienautomobils erreicht eine neue Dimension. In: Aluminium. Jg. 70 (1994), Sonderdruck, S. 4-7.

Kraftstoffeinsparung für ein bestimmtes Bauteil ist, dass ein funktionaler Zusammenhang zwischen der Herstellungs- und Nutzungsphase in bezug auf das eingesetzte Material besteht. Dieser Zusammenhang wird unter der Annahme betrachtet, dass jeweils nur ein bestimmtes Bauteil, z. B. die Karosserie aus einem Leichtbauwerkstoff hergestellt wird, das in der Nutzungsphase zu einer Einsparung beim Treibstoffverbrauch führt. Da alle weiteren Bauteile des Fahrzeuges nicht verändert werden, kann der Kraftstoffminderverbrauch der Gewichtsveränderung des modifizierten Bauteils zugeordnet werden.[6]

Die Kraftstoffeinsparung und CO_2-Reduktion, die durch diese Leichtbaumaßnahme im Pkw erzielt wird, kann als direkte Einsparung bezeichnet werden. Unter diesem direkten Einsparungseffekt wird die unmittelbare Vermeidung der Kraftstoffverbrennung und CO_2-Emissionen verstanden. Darüber hinaus führt die Kraftstoffeinsparung zu einem Rückgang der Nachfrage nach Produkten der Mineralölwirtschaft sowie derer unmittelbaren Zulieferindustrien. Dieser Produktionszusammenhang wird bis zu einer bestimmten Grenze in konventionellen Lebenszyklusanalysen erfasst. Die vollständige Berücksichtigung von Produktionszusammenhängen – sowohl direkten als auch indirekten - kann durch volkswirtschaftliche Modelle erfolgen.[7] Das Zusammenspiel dieser verschiedenen Ansätze ermöglicht einer Quantifizierung von der durch Leichtbaumaßnahmen im Automobil ausgelösten Kraftstoffeinsparung und CO_2-Reduktion und darüber hinaus auch eine sektorale Aufschlüsselung dieser Effekte.

Für die Untersuchung von gesamtwirtschaftlichen Effekten der Kraftstoffeinsparung und daraus resultierenden CO_2-Reduktion werden die Ergebnisse über Ressourcenverbrauch und entstehende Emission aus Lebenszyklusanalysen von Pkw, die meist auf einer Einzelbetrachtungen beruhen, abstrahiert und auf den gesamten Pkw-Bestand übertragen.

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[6] Bubeck, D.: Life Cycle Costing (LCC) im Automobilbau. Hamburg 2002, S. 227. (= Quantitative Methoden in Forschung und Praxis, Bd. 1).

[7] Joshi, S.: Product Environmental Life-Cycle Assessment Using Input-Output-Techniques. In: Journal of Industrial Ecology. Vol. 3 (2000), No. 2-3, pp. 95-120.

3 Modellansatz

Der Modellansatz basiert auf zwei Modellen: Einem Pkw-Modell, das spezifische Daten zur Herstellung und Nutzung von Fahrzeugen beinhaltet sowie die Entwicklung des Pkw-Bestandes in Deutschland. Das zweite Modell ist ein volkswirtschaftliches Input-Output Modell, das die deutsche Produktionsstruktur abbildet und durch physische Input-Output Tabellen, z. B. CO_2-Emissionen, erweitert wird. Beide Modelle können unabhängig voneinander für eine Analyse herangezogen werden. In diesem Beitrag werden jedoch Ergebnisse aus dem Pkw-Modell für eine Input-Output-Analyse genutzt, wie in Abbildung 1 dargestellt. Das bedeutet, auf Basis der erzielten Kraftstoffeinsparung durch Aluminium-Leichtbau in der Karosserie eines Pkw wird eine Nachfrage quantifiziert, um gesamtwirtschaftliche Auswirkungen analysieren zu können. Die Verknüpfung der beiden Modelle erfolgt somit über die Aufstellung eines Nachfragevektors. Mit Hilfe der Szenariotechnik werden dann unterschiedliche Entwicklungen der Kraftstoffeinsparung und CO_2-Reduktion durch Aluminium-Leichtbau abgebildet.

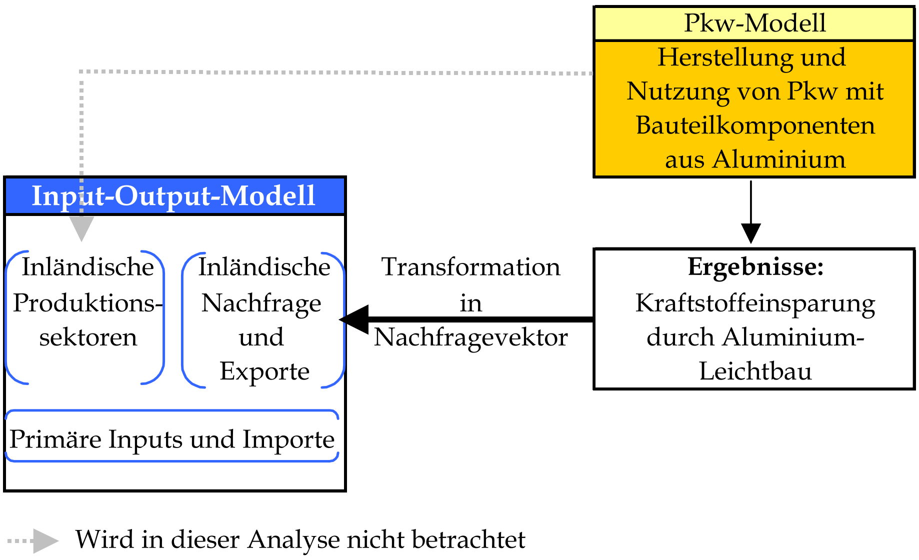

Abbildung 1: Modellansatz

3.1 *Das Pkw-Modell*

Das Pkw-Modell basiert auf einem Tabellen-Kalkulationsprogramm und wird für die Pkw-Bestandsbetrachtung herangezogen. Die grundlegende Entwicklung zeigt den motorisierten Individualverkehr (MIV) des Personenverkehrs auf. Das Pkw-Modell verfügt über Bestandsdaten, darunter Angaben über Löschungen und

Neuzulassungen. Die Neuzulassungen setzen sich zusammen aus Ersatzbedarf und Bestandszugang abzüglich der Altzulassungen. Die Bestandsdaten werden ergänzt durch statistische Angaben über die Altersstruktur des Pkw-Bestandes, aufgegliedert nach der Erstzulassung der Fahrzeuge. Auf diese Weise werden ebenfalls Daten über die Löschungen von Fahrzeugen ergänzt.[8] Die Altersstruktur im Bestand und in den gelöschten Fahrzeugen spielt eine Rolle hinsichtlich des durchschnittlichen Aluminiumeinsatzes der Fahrzeuge.

Im Pkw-Modell werden die unterschiedlichen Maßnahmen differenziert, die zu einem veränderten Kraftstoffverbrauch führen. So wird die Verbesserung der Antriebstechnik nach Benzin- und Dieselfahrzeugen berücksichtigt sowie die Entwicklung der jährlichen Laufleistung pro Fahrzeug. Der Kraftstoffverbrauch ist u.a. wesentlich vom Fahrzeuggewicht abhängig, d. h. der Kraftstoffverbrauchsfaktor (b) gibt den Kraftstoffverbrauch (ltr) in Abhängigkeit der Kilometerleistung (km) und des Gewichts (kg) an mit b = [ltr/(100 km x 100 kg)].[9]

Zusätzlich zu einer verbesserten Antriebstechnik und einem veränderten Mobilitätsverhalten können durch Leichtbaumaßnahmen weitere Kraftstoffeinsparungen erzielt werden. Im Pkw-Modell werden Aluminium-Leichtbaumaßnahmen in technischen Modellzyklen der Neufahrzeuge realisiert. Dabei werden die Fahrzeugtypen I – IV als Neufahrzeuge in den Bestand eingeführt, die sich durch verschiedene Aluminiumkomponenten in der Karosserie unterscheiden.

Auf der Grundlage des Pkw-Modell werden somit direkte Einsparung von Kraftstoff und CO_2-Emissionen berechnet, die durch Aluminium-Leichtbau in der Karosserie erzielt werden.

3.2 *Das ökonomische Input-Output-Modell*

Input-Output-Modelle werden für eine Reihe von unterschiedlichen wissenschaftlichen Fragestellungen eingesetzt. Der Einsatz reicht beispielsweise von Analysen über Konjunkturprogramme, den Technischen Fortschritt bis zu Stoffstromanalysen im Bereich der Energie- und Materialströme.[10]

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[8] Verband der Automobilindustrie (VDA): Tatsachen und Zahlen aus der Kraftverkehrswirtschaft. 62. Folge. Frankfurt 1998, S. 208, 249.

[9] Koewius, Aluminium-Spaceframe-Technologie, a.a.O., S. 5.

[10] Pan, X./Kraines, S.: Environmental Input-Output Models for Life-Cycle-Analysis. In: Environmental and Resource Economics. Vol. 20 (2001), pp. 61-72. Nathani, C.: Entwicklung eines Modellsystems zur Simulation der energiewirtschaftlichen und struktu-

3.2.1 Die Input-Output-Tabellen

Im Mittelpunkt eines Input-Output-Modells steht der Produktionsprozess, der als Transformationsprozess von Inputs in Outputs verstanden wird. Die Grundlage dieses Modells bilden Input-Output-Tabellen, die in Deutschland durch das Statistische Bundesamt aufgestellt werden.[11] Diese Tabellen haben die Aufgabe, die produktions- und gütermäßigen Verflechtungen zwischen den einzelnen Produktionssektoren einer Volkswirtschaft und der übrigen Welt abzubilden. Sie stellen die Entstehungs- und Verwendungsseite des Bruttoinlandsprodukts dar, d.h. die Produktion der Waren und Dienstleistungen und ihre Verwendung sowie die im Produktionsprozess entstandenen Einkommen. Die Input-Output Tabellen ermöglichen eine systematische und vollständige Beschreibung der Lieferbeziehungen zwischen den einzelnen Wirtschaftssektoren untereinander und dem Endnachfragebereich. Die Zeilen (Output) stellen die Lieferungen an die Abnehmersektoren dar, wobei zwischen der sogenannten Zwischennachfrage zur Weiterverarbeitung und der Endnachfrage, d. h. private Haushalte, Staat, Investitionen und Export, unterschieden wird. Die Spalten (Input) bilden den Inputbedarf der einzelnen Wirtschaftsbereiche für die eigene Produktionsaktivität ab. Dieser Vorleistungsbedarf lässt sich unterscheiden in Inputs aus dem eigenen und den übrigen Sektoren sowie den Bedarf an Importleistungen und primären Inputs. Letzterer umfasst die Bruttowertschöpfung, d. h. Abschreibungen, Steuern und Subventionen sowie Unternehmens- und Arbeitseinkommen.[12] Es werden monetäre und physische Tabellen aufgestellt. Die monetären Tabellen beruhen auf Wertangaben und werden in Deutschland in Euro angegeben. Die physischen Input-Output-Tabellen ermöglichen die Darstellung der Materialströme durch die Produktionsaktivitäten einer Volkswirtschaft über die Entnahme der Rohstoffe, den Durchfluss der Güter durch Produktion und Konsum sowie die Abgabe der Rest- und Schadstoffe, z.B. Luftschadstoffe, Abfall und Abwasser an die Natur.[13]

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rellen Veränderung einer verstärkten Kreislaufwirtschaft. Fraunhofer Institut ISI. Karlsruhe 2000. Hendrickson, C./Horvath, A./Joshi, S./Lave, L.: Economic Input-Output Models for Environmental Life Cycle Assessment. In: Environmental Science & Technology. April 1998, pp. 184A-191A.

[11] Statistisches Bundesamt: Volkwirtschaftliche Gesamtrechnung. Input-Output-Rechnung. Fachserie 18, Reihe 2, Wiesbaden 2000.

[12] Holub, H.W./Schnabel, H.: Input-Output Rechnung. Input-Output-Analyse. München 1994. Holub, H.W./Schnabel, H.: Input-Output Rechnung. Input-Output-Tabellen. München 1994a.

[13] Statistisches Bundesamt: Umwelt. Umweltökonomische Gesamtrechnung. Fachserie 19, Reihe 5, Wiesbaden 2002.

3.2.2 Mathematische Grundlagen des Input-Output-Modells

Das Modell basiert auf einer vorgegebenen volkswirtschaftlichen Produktionsstruktur, die sich über die Zeit nicht verändert. Voraussetzung für diese Annahme ist, dass nur ein bestimmtes Einsatzverhältnis der Produktionsfaktoren ökonomisch sinnvoll und technisch möglich ist. Die Grundgleichung dieses Modells erklärt die Abhängigkeit der sektoralen Outputs von der exogen vorgegebenen Endnachfrage. Eine zeilenweise Betrachtung der Input-Output-Tabelle ergibt die Summe der Lieferungen (Outputs) eines Sektors, die sich aus der Zwischennachfrage und die Endnachfrage zusammensetzt.

$$x_i = z_{i,j} + y_i \qquad (1)$$

mit $i, j = 1,\ldots,n$ Indizes der Input-Output Sektoren

x_j : Output von Sektor i

$z_{i,j}$: Güterlieferung von Sektor i an Sektor j

$y_i = \sum_k y_{i,k}$ Güterlieferung von Sektor i and die Endnachfrage

mit $k = 1,\ldots,K$: Index der Endnachfragebereiche der IO-Tabelle.

Die sektoralen Outputs x_i stellen je nach Tabellentyp Produktionswerte oder Güteraufkommen (einschließlich Importe) dar. Der Inputkoeffizient $a_{i,j}$ eines Sektors j gibt den Bedarf an Vorleistungen aus dem Sektor i zur Produktion einer Mengeneinheit des eigenen Outputs wieder und wird wie folgt definiert:

$$a_{i,j} = \frac{z_{i,j}}{x_j} \qquad (2)$$

mit $a_{i,j}$: Inputkoeffizienten von Sektor j für Vorleistungen aus Sektor i.

Mit der ($n \;\; x \;\; n$) Matrix der Inputkoeffizienten $A = (a_{i,j})$, dem Endnachfragevektor $y = (y_i)$ und dem Outputvektor $x = (x_i)$ lässt sich die Grundgleichung auch in Matrixnotation schreiben:

$$Ax + y = x \qquad (3)$$

Durch Auflösung der Gleichung (3) nach x erhält man

$$x = (I - A)^{-1} y \qquad (4)$$

mit I : Einheitsmatrix.

Die Matrix $C = (I - A)^{-1}$ wird auch als Leontief-Inverse bezeichnet. Die Elemente

$c_{i,j}$ geben an, um wie viele Einheiten der Output des Sektors i ansteigen muss, damit Sektor j eine zusätzliche Einheit für die Endnachfrage bereitstellen kann. Damit lassen sich die mit der Veränderung der Endnachfrage verbundenen direkten und auf vorgelagerte Produktionsstufen angestoßenen indirekten Produktionseffekte in der gesamten Volkswirtschaft ermitteln. Auf das Anwendungsbeispiel bezogen bedeutet dies, dass der Rückgang der Kraftstoffnachfrage in der Mineralölwirtschaft berücksichtigt wird und darüber hinaus auch noch in allen Zulieferindustrien, die durch die Bereitstellung von entsprechenden Gütern und Dienstleistungen mit der Herstellung von Mineralölprodukten verbunden sind.

Auf Basis des traditionellen ökonomiebezogenen Input-Output-Modells können durch entsprechende Erweiterungen mit Umweltdaten auch ökologische Fragestellungen untersucht werden. Material- und Energieflüsse können unmittelbar in Beziehung zu ökonomischen Aktivitäten gesetzt werden. Die Berücksichtigung von klimawirksamen Gasen und Schadstoffen (z.B. CO_2, SO_2, Abfälle) erfolgt durch Gleichung (5):

$$F\,C\,y = F\,(I - A)^{-1}\,y \tag{5}$$

wobei F eine Koeffizientenmatrix darstellt, die die Emissionen eines Produktionsbereiches in Relation zu dem dazugehörigen Produktionswert stellt.[14] Auf das Anwendungsbeispiel bezogen bedeutet dies, die Reduktion von CO_2-Emissionen aufgrund des nachfrageinduzierten Produktionsrückgangs in der Mineralölwirtschaft und seinen Zulieferindustrien.

3.3 Szenariotechnik

Mit der Szenariotechnik wird eine Methode eingesetzt, die es ermöglicht zukünftige Entwicklungen zu analysieren. Nach Gausemeier u.a. ist ein Szenario „eine allgemein verständliche Beschreibung einer möglichen Situation in der Zukunft, die auf einem komplexen Netz von Einflussfaktoren beruht. Ein Szenario kann darüber hinaus die Darstellung einer Entwicklung enthalten, die aus der Gegenwart zu dieser Situation führt“[15]. Die Szenariotechnik ist vor allem bei komplexen Systemen mit vielen Einflussfaktoren und hohen Unsicherheiten bezüglich der

[14] Leontief, W.: Environmental repercussions and the economic structure. An input-output approach. In: The review of economics and statistics. 52 (1970), 3, pp. 262-271.

[15] Vgl. Gausemeier, J./Fink, A./Schlake, O.: Szenario-Management. Planen und Führen mit Szenarien. München 1996, S. 35

zukünftigen Entwicklung anwendbar. Im Vergleich zu Prognosen wird dabei nicht der Versuch unternommen, wahrscheinliche Entwicklungen in der Zukunft vorherzusagen. Ein Szenario beschreibt durch seine Falldefinition nur eine mögliche Entwicklung in die Zukunft. Aus diesem Grund werden oftmals mehrere denkbare Fälle entworfen, um eine Bandbreite von unterschiedlichen Entwicklungen abzubilden. Das hier eingesetzte Szenario wird als exploratives Szenario bezeichnet, da es durch die Einführung von unterschiedlichen Maßnahmen (Aluminium-Leichtbau in der Karosserie eines Pkw) die Bandbreite der möglichen Auswirkung (Kraftstoffeinsparung und CO_2-Reduktion) in der Zukunft aufzeigt.

4 Szenario: Struktur, Annahmen und Rahmendaten

Das Szenario „Kraftstoffeinsparung und CO_2-Reduktion durch Aluminium-Leichtbau“ zeichnet vom Basisjahr 1995 ausgehend ab, welche Einsparung von Kraftstoff und CO_2-Emissionen im Zieljahr 2013 durch Aluminium-Leichtbau in der Karosserie von Pkw erzielt wird. Die verschiedenen Aluminium-Leichtbaumaßnahmen in der Karosserie werden in den Neufahrzeugen realisiert. Die Neufahrzeuge sind durch die Pkw-Typen I – IV definiert. Die Einführung dieser Neufahrzeuge in den Markt hängt von den definierten Fällen I – III ab, die eine Bandbreite von Entwicklungsmöglichkeiten abbilden. Im Szenario werden fallübergreifende und fallabhängige Szenarioannahmen unterschieden.

4.1 Fallübergreifende Szenarioannahmen

Die fallübergreifenden Szenarioannahmen sind bezogen auf bereits existierende Studien über die zukünftige Entwicklung des motorisierten Individualverkehrs (MIV) und den zukünftigen Einsatz von Aluminium in Personenkraftwagen. Diese grundlegenden Entwicklungstendenzen, ausgehend von einem steigenden MIV und Einsatz von Aluminium im Pkw, werden im Szenario entsprechend umgesetzt. Das Shell Pkw-Szenario „One World“ wird für die Entwicklung des MIV bis zum Jahr 2013 in Deutschland gewählt. Die wichtigsten Daten aus dieser Studie sind im folgenden Abschnitt zusammengefasst.

4.1.1 Shell Pkw-Studie “Mehr Autos – weniger Verkehr?”

Die von Shell publizierte Pkw-Studie basiert auf Welt-Szenarien, die von der Royal Dutch/Shell Gruppe entwickelt wurden.[16] Darin wird in Abhängigkeit von variierenden wirtschaftlichen Rahmenbedingungen die Entwicklung der Motorisierung in Deutschland bis 2020 mit zwei unterschiedlichen Szenarien beschrieben. Shell konzentriert sich dabei auf das Verkehrssegment „motorisierter Individualverkehr“ (MIV). Die Entwicklung anderer Verkehrsträger wird nicht betrachtet. Ergebnisse der Szenariorechnungen sind: Bestand an Pkw, die Verteilung auf Antriebsart (Otto/Diesel/Alternativ), die Pkw-Dichte, der Kraftstoffverbrauch pro Fahrzeug sowie die jährliche Kilometerleistung pro Fahrzeug. Die Fahrleistung wird über die Projek-

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[16] Shell Pkw-Szenarien: Mehr Autos – weniger Verkehr? Deutsche Shell GmbH, Hamburg 2001.

tion des Pkw-Bestandes und der pro Pkw erbrachten Fahrleistung ermittelt. Daraus ergibt sich unter Berücksichtigung von spezifischen Kraftstoffverbrauchsdaten/-annahmen der Energieverbrauch und damit zusammenhängende Emissionen.

Mit den beiden Szenarien gehen die Autoren auf das Spannungsfeld ein, das sich durch Liberalisierung, Globalisierung und technische Weiterentwicklung nahezu weltweit entwickelt hat. Im Szenario "One World" wird die weitere Entwicklung von US-amerikanischen Wertvorstellungen und Prinzipien bestimmt, dagegen wird im Szenario „Kaleidoskop" die Entwicklung vor dem Hintergrund nationaler Werte und Traditionen abgebildet. Da auch in anderen Verkehrsprognosen meist von einem Anstieg des MIV in Zukunft ausgegangen wird (s. Synopse von Birnbaum u.a.[17]), wurde für diese Analyse das Szenario „One World" als grundlegende Entwicklung für diesen Bereich der Verkehrswirtschaft gewählt.

Im Szenario „One World" wird für die deutsche Wirtschaft ein durchschnittliches Wachstum von 1,8 % pro Jahr angenommen. Die Verkehrsinfrastruktur wird mit Hilfe von privaten Betreibern weiter ausgebaut. Fahrzeugemissionen werden kurzfristig verringert durch die Potenziale technischer Effizienzverbesserungen konventioneller Fahrzeuge und langfristig durch die Marktpenetration alternativer Antriebstechnologien. Es wird angenommen, dass die Kosten für Autofahrer weiter ansteigen, beispielsweise durch einen Anstieg der Kraftfahrzeugsteuer oder durch Mautgebühren. Es sind keine verkehrspolitischen Maßnahmen zur Steuerung der Verkehrsentwicklung geplant

Die **Bevölkerungsentwicklung** wird in der Bundesrepublik Deutschland nach Auffassung des Bundesministerium des Inneren wegen der niedrigen Geburtenraten einerseits und der steigenden Lebenserwartung andererseits durch die Zuwanderung bzw. Abwanderung von Ausländern spürbar mitbestimmt. Im Shell-Szenario steigt die jährliche Zuwanderung so weit an, dass die Bevölkerungszahl in 2020 mit 81,8 Millionen das heutige Niveau hält. Jedoch verschiebt sich die Altersstruktur, was dazu führt, dass sich die Anzahl der Personen im arbeitsfähigen Alter um 2,5 Millionen verringert.

Die künftige Entwicklung des **Pkw-Bestandes** und der **Neuzulassungen** wird aus den Kenngrößen „Anzahl der Erwachsenen" (hier nur die Gruppe über 18 Jahre) und „Pkw-Dichte" (Anzahl Pkw/1000 Erwachsene) hergeleitet. Da zwar die Gruppe der „Senioren" ansteigt, sie aber zukünftig einen höheren Motorisierungsgrad errei-

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[17] Birnbaum, K.U./Linßen, J./Walbeck, M.: Synoptische Analyse vorliegender Studien in Bezug auf den Trend bzw. die Reduktionspotentiale von CO2-Emissionen im Verkehr. Berlin 2002, S. 12-13

chen, wird sich die Pkw-Dichte zukünftig weiter erhöhen, ohne dass es vorerst zu einer Sättigung kommt (vgl. Tabelle 1).

Tabelle 1: Kennzahlen Shell Pkw-Szenario „One World“

	One World		
	2000	2010	2020
Pkw-Bestand in Mill. Fz.	42,8	49	52,3
- davon Diesel	6	12,5	15,7
- davon alternative Antriebe	0	0,4	5,2
Verbrauch Benzin- und Diesel-Pkw l/100 km			
- davon Bestand	8,5	7,2	5,8
- davon Neuzulassungen	7,7	5,7	4,3
Fahrleistung pro Jahr in km	12300	11900	11300
Gesamtfahrleistung in Mrd. km	528	581	591
Kraftstoffkonsum Benzin- und Diesel-Pkw in Mill. Tonnen	33,9	31,7	24,5

Die angenommenen Haushaltseinkommen sowie der Mobilitätsbedarf für Familien führen zu einem Anstieg des Pkw-Bestands bis zum Jahr 2020. Fahrzeuge mit alternativen Antriebskonzepten werden auf dem Markt angeboten und erreichen einen Anteil von 10 % am Gesamtbestand im Jahr 2020. Konventionelle Fahrzeuge bzw. Antriebe werden im gleichen Zeitraum weitere Effizienzfortschritte machen, so dass die Neufahrzeuge 44 % weniger Kraftstoff verbrauchen als 2000; im Durchschnitt knapp vier Liter pro 100 Kilometer. Diese Kraftstoffeinsparung ist auf die verbesserte Antriebstechnik zurückzuführen. Der Durchschnittsverbrauch der gesamten Pkw-Flotte reduziert sich in dieser Zeit um ein Drittel. Auch die **durchschnittliche, jährliche Fahrleistung** pro Fahrzeug sinkt. Für das Szenario „One World“ ergibt sich daraus trotz steigender Gesamtfahrleistung von 528 Mrd. km in 2000 auf 591 Mrd. km in 2020 eine Kraftstoffeinsparung von 9,4 Mill. Tonnen.

In Bezug auf **Kohlendioxidemissionen** gibt das Szenario Auskünfte in der Weise, dass die CO_2-Emissionen insbesondere wegen der Effizienzsteigerungen in der Motorentechnik und durch den steigenden Anteil sparsamerer Diesel-Pkw proportional zum Kraftstoffverbrauch um 30 % zurückgehen. Bei der Angabe der Abgasemissionen für Benzol, Kohlenwasserstoff, Kohlenmonoxid, Stickoxid und Dieselpartikel bezieht sich Shell auf eine Auftragsstudie von IFEU. Diese nutzen das

Modellinstrumentarium „TREMOD" für Emissionsberechnungen des gesamten Straßenverkehrs.[18]

4.1.2 Aluminium-Leichtbau in Personenkraftwagen

Vom Jahr 1990 ausgehend hat sich die Automobilindustrie verpflichtet, den durchschnittlichen Kraftstoffverbrauch aller neuzugelassener Personenkraftwagen bis zum Jahre 2005 um 25% zu reduzieren. Diese Verpflichtung zwingt die Automobilindustrie zur Herstellung verbrauchsärmerer Fahrzeuge. Für Innovationen stehen z. B. die Senkung des Luftwiderstandes, die Verbesserung des Wirkungsgrades von Motor und Antrieb und die Reduzierung der Fahrzeugmasse zur Verfügung. Die Reduzierung der Fahrzeugmasse kann neben der Verbesserung von Motor und Antrieb einen erheblichen Anteil an den Potenzialen zur Verbrauchssenkung ausmachen.[19] Die Entwicklung des Leergewichtes über Fahrzeuggenerationen hinweg zeigt, dass die Fahrzeuge durch Zusatzaggregate im Bereich Sicherheit und Komfort schwerer geworden sind.[20] An der gesamten Fahrzeugmasse hat die Karosserie einen Gewichtsanteil von ca. 20-25 %[21] und auch sie ist über die Jahre hinweg schwerer geworden. Ein Grund dafür ist der Trend zu größeren Fahrzeugen und damit auch größeren Karosserien, die jedoch in ihrer Funktionalität sicherer und steifer geworden sind.[22] Eine Möglichkeit, Einsparungen beim Kraftstoffverbrauch in der Betriebsphase vorzunehmen, wird mit der Leichtbauweise verfolgt. Unter Leichtbau versteht man die Verringerung des Fahrzeug-Leergewichts durch den Einsatz von spezifisch leichteren Konstruktionswerkstoffen. Leichtbau durch Werkstoffsubstitution ist i.d.R. teurer als konventioneller Fahrzeugbau und deshalb aufgrund der Kostensituation nur begrenzt möglich. Daraus folgt, dass im Fahrzeugbau nur dann Werkstoffe durch spezifisch leichtere Konstruktionswerkstoffe substituiert werden, wenn eine bestimmte Grenze an Mehrkosten nicht

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[18] Shell Pkw-Szenarien: Mehr Autos – weniger Verkehr? a.a.O., S. 3-6, 13-16, 21-22, 31-32, 35-37.

[19] Anderseck, R.: Karosserie Leichtbau in Klein- und Großserien. Welche Einflüsse bestimmen die Materialauswahl? In: Tagungsband Technischer Kongress. Verband der Automobilindustrie (VDA), Bad Homburg v. d. Höhe 2001, S. 293.

[20] Altmann, M./Blandow, V/Niebauer, P./Schindler, J./Schurig, V./Weindorf, W./Wurster, R./Zittel, W.: Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung. Studie im Auftrag des Bayerischen Staatsministeriums für Landesentwicklung und Umweltfragen. L-B-Systemtechnik GmbH, Ottobrunn 2002, Abschnitt 5.1.1 – keine Seitenangaben!

[21] Anderseck, Karosserie Leichtbau in Klein- und Großserien, a.a.O., S. 296.

überschritten wird. Das bedeutet, dass das ‚technische Potenzial' möglicher Gewichtseinsparungen aus Kostengründen nicht, oder nicht vollständig realisiert wird. Gründe dafür sind z. B. fehlende, auf den jeweiligen Substitutionswerkstoff ausgerichtete, Fertigungstechniken, die es ermöglichen, die höheren Werkstoffkosten zu kompensieren.[23] Innovativer Karosseriebau ist daher geprägt von dem Ziel, Kosten und Gewicht bei verbesserter Funktionalität zu senken. Jedoch zeichnet sich ab, dass ein einziger Werkstoff diese Anforderung nicht erfüllen kann. Der Einsatz von verschiedenen Leichtbaumaterialien wie Kunststoff, Aluminium und Magnesium wird in Zukunft an Bedeutung gewinnen, letztere vor allem durch intensive Entwicklung neuer Legierungen.[24]

Im folgenden wird anhand von verschiedenen Studien aufgezeigt, wie sich der durchschnittliche Aluminiumeinsatz im Pkw in der Vergangenheit entwickelt hat und welche Potenziale mit der Aluminium-Leichtbauweise in Zukunft verbunden werden. Nach Jones[25] entwickelte sich in Westeuropa der Einsatz von Aluminium im Fahrzeugbestand von 1960 bis 1980 kontinuierlich von 20 kg auf 43 kg pro Fahrzeug und steigt dann stark bis zum Ende der 90er Jahren auf 99 kg pro Fahrzeug an (Abb. 2). Jones gibt eine Abschätzung des Aluminiumeinsatzes bis zum Jahr 2009 an, die sich mit ähnlichen Erwartungen bis zum Jahr 2010 in diesem Bereich deckt.[26]

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22 Hillmann, J./Morsch, D./Welsch, F.: Der schwierige Weg zum Leichtbau. In: Entwicklungen im Karosseriebau. VDI Bericht Nr. 1264. Düsseldorf 1996, S 457-475.

23 Koewius, Aluminium-Spaceframe-Technologie, a.a.O., S. 4-7

24 Friedrich, H.E./Haldenwanger, H.-G.: Leichtbaustrategien und Trends. In: Tagungsband Technischer Kongress, Verband der Automobilindustrie (VDA), Bad Homburg v. d. Höhe 2001, S 311-316.

25 Jones, R.: The growing use of aluminium in the automotive Industry. In: The 10th International Arab Aluminium Conference, Dubai 2001.

26 McKinsey & Company: Serving Automotive Industry. Attractive Option or Significant Risk? Düsseldorf 2001,p. 28, unpublished. Gélas de, B.: Automotive Aluminium Recycling. European Aluminium Association (EAA). Brussels 1999, p. 5. Stelzer, W.A.: Promising future ahead for aluminium in automobile design and construction. Challenges for application and recycling. In : The 6th International Secondary Aluminium Congress of the OEA. Cannes 2001 – keine Seitenangaben. Automobil Entwicklung. Keine Monokultur, September 2001, S. 130.

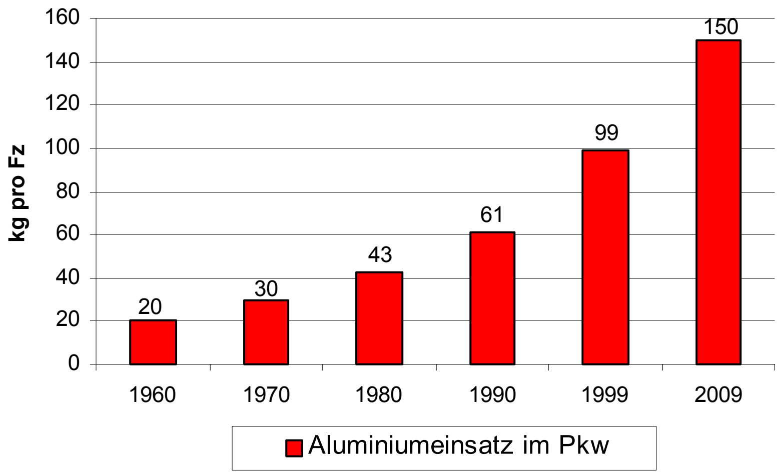

Abbildung 2: Aluminiumeinsatz im Pkw in Westeuropa nach Jones

Um den in Deutschland eingesetzten Aluminiumanteil in Personenkraftwagen genauer angeben zu können, wurde Anfang der 90er Jahre eine Untersuchung mit sieben großen Automobilfirmen durchgeführt.[27] Die Anwendung von Komponenten und Bauteilen aus Aluminium im Fahrzeug ist vielseitig und hauptsächlich von der Fahrzeugklasse abhängig. In der Studie wurden nur die Fahrzeugbauteile betrachtet, in denen Aluminium verbaut wird. Das sind: Karosserie, Ausstattung, Fahrwerk und Antrieb. Einige Automobilhersteller waren in der Lage, detaillierte Angaben über den Aluminiumeinsatz in ihren Fahrzeugen zu machen, bei anderen Herstellern wurden plausible Schätzungen vorgenommen. Der so errechnete Aluminiumanteil in den untersuchten Fahrzeugklassen wurde auf die in Deutschland produzierten Fahrzeuge im Jahr 1992 übertragen. In der Studie wurde somit ein durchschnittlicher Aluminiumeinsatz von 53 kg pro Fahrzeug berechnet, ohne Berücksichtigung der Aluminiumräder, die einen zusätzlichen Anteil von 5,17 kg pro Fahrzeug ausmachen. Diese errechneten Werte weichen nicht erheblich von den oben aufgeführten Angaben für Westeuropa nach Jones ab. Zusätzlich wurde in der Studie von Rink unterschieden, ob Aluminium als Guss- oder Knetlegierung im Fahrzeug verbaut wurde. Es wurde deutlich, dass Gusslegierung mit ca. 80% und Knetlegierungen mit ca. 20 % in den Bauteilen vertreten waren. Mit Blick auf die größte Durchdringung der Bauteile mit Aluminium wurde festgestellt, dass der Antriebsbereich das Haupteinsatzgebiet darstellte. Im Antriebsbereich sind Gussteile zahlreich vertreten, woraus sich ableiten lässt, dass Stahlgussbauteile

[27] Rink, C.: Aluminium, Automobil und Recycling. Institut für Kraftfahrwesen Hannover. Forschungsbericht Nr. 515. Düsseldorf 1994, S. 40-62.

stärker durch Aluminiumgussteile substituiert wurden als Bauteile aus Knetwerkstoffen. Rink weist in seiner Studie darauf hin, dass ein hohes Substitutionspotenzial bezüglich Aluminiumknetbauteilen in den Bereichen Karosserie und Fahrwerk vorhanden ist, welches im Hinblick auf Gewichtseinsparung im Automobil genutzt werden könnte. Seiner Einschätzung nach bietet die Karosserie das größte Substitutionspotenzial durch Aluminium, gefolgt vom Fahrwerks- und Antriebsbereich, was zu einem steigenden Anteil von Knetlegierungen in der Zukunft führen wird.

Die Einschätzung, dass im Bauteil Karosserie in Zukunft mehr Aluminium eingesetzt wird, bestätigen auch andere Studien.[28] In Abbildung 3 steigt der Einsatz von Aluminium allein im Bauteil Karosserie auf 50 kg pro Fahrzeug bis zum Jahr 2008. Dieser Anteil bezieht sich auf einzelne Komponenten in der Karosserie, wie z. B. Tür, Motorhaube oder Kotflügel.

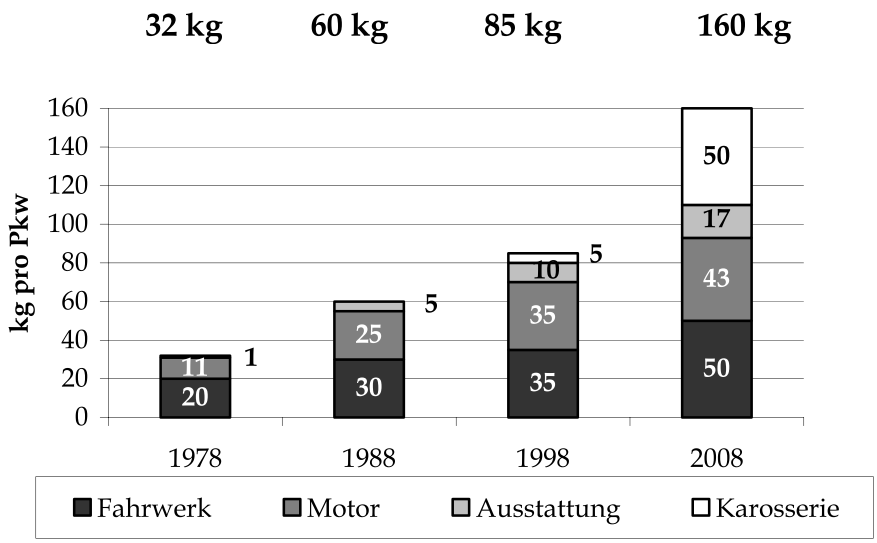

Abbildung 3:Aluminiumeinsatz im Pkw nach GDA

Grundsätzlich ist davon auszugehen, dass der Einsatz von reinen Aluminiumkarosserien auch in Zukunft auf kleine Stückzahlen, z. B. sparsame Kleinwagen, Oberklassewagen und einige Sportwagen beschränkt bleibt aufgrund der hohen Werkstoff- und Fertigungskosten.[29]

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[28] McKinsey & Company, Serving Automotive Industry, a.a.O., pp. 19,23. Automobil Entwicklung, a.a.O., S. 130

[29] Wallentowitz, u.a., Technologie-Trends in der Automobilindustrie, a.a.O., S. 231-232. McKinsey & Company, Serving Automotive Industry, a.a.O., pp. 23-24.

4.2 *Fallabhängige Szenarioannahmen*

Für das Szenario „Kraftstoffeinsparung und CO_2-Reduktion durch Aluminium-Leichtbau“ wird davon ausgegangen, dass für die Erzielung einer Kraftstoffeinsparung und CO_2-Reduktion für den MIV unterschiedliche Aluminium-Leichtbaumaßnahmen in den Neufahrzeugen bis zum Zieljahr 2013 durchgeführt werden. Es werden nur Personenkraftwagen betrachtet und die Leichtbaumaßnahmen sind in dieser Arbeit auf das Bauteil ‚Karosserie' beschränkt. Dies bedeutet, dass Komponenten, die ursprünglich aus Stahl gefertigt wurden, durch Aluminium-Komponenten substituiert werden.

Die Bestandsentwicklung baut auf dem Shell Pkw-Szenario „One World“ auf. Die Neufahrzeuge ab dem Basisjahr 1995 werden bis zum Zieljahr 2013 definiert über die Pkw-Typen I – IV (siehe nächster Abschnitt). Der Pkw-Bestand setzt sich somit aus den Neufahrzeugen der Pkw-Typen I – IV plus dem jeweiligen Restbestand zusammen.

4.2.1 Annahmen Neufahrzeuge

<u>Aluminiumeinsatz in Neufahrzeugen</u>

Im Szenario werden die Neufahrzeuge in vier Pkw-Typen unterschieden. Tabelle 2 zeigt die Pkw-Typen I – IV mit ihrem durchschnittlichen Aluminiumeinsatz. Im Basisjahr 1995 hat das Referenzfahrzeug Typ I durchschnittlich 70 kg Aluminium verbaut, diese sind nach der Rink Studie (s. Abschnitt 4.1.2) überwiegend in den Bauteilen Antrieb und Fahrwerk zu finden. Dieser durchschnittliche Anteil von 70 kg Aluminium bleibt über die Pkw-Typen II bis IV konstant. Mögliche Aluminium Leichtbaumaßnahmen in den Bauteilen Antrieb und Fahrwerk werden in dieser Analyse nicht betrachtet. Im Bauteil Karosserie werden in den Pkw-Typen II bis IV verschiedene Komponenten aus Aluminium zugebaut, die als Leichtbaumaßnahme zu einer Kraftstoffeinsparung führen. Es handelt sich bei den hier betrachteten Pkw, um auf die Untersuchung zugeschnittene Fahrzeuge. Die Pkw werden der Mittelklasse zugeordnet. Die Mittelklasse wurde ausgewählt, da jeder dritte neu hergestellte Personenkraftwagen in Deutschland im Zeitraum 1996 bis 2001 diesem Segment zugehörig war. Die Neuzulassungen werden ebenfalls durch dieses Segment dominiert.[30] Die Annahmen über den zukünftigen Aluminiumeinsatz in dieser Klasse wurden einer Studie von McKinsey entnommen. Grundlage dieser Studie war eine Untersuchung über den potenziellen Einsatz von Aluminium in der Mittelklasse bis zum Jahr 2010. Die Studie kommt zu der Einschätzung, dass der Einsatz von ca. 10 kg bis 35 kg Aluminium in der Karosserie für diese Klasse möglich wäre.[31] Der Aluminiumeinsatz der Pkw-Typen II und III wurde auf dieser Grundlage aufgebaut. Der Aluminiumeinsatz des Typs IV wurde der Studie von Altmann u.a. entnommen, in der die konventionelle Stahlkarosserie eines Golfs durch eine Aluminiumkarosserie substituiert wird. Für die Aluminiumkarosserie wurde ein Gewichtsreduktionsfaktor von 40 % gegenüber Stahl angenommen, d. h. die Aluminiumkarosserie ist um diesen Faktor leichter als die Stahlvariante.[32] Diese Annahme wird auch für die Gewichtseinsparung der Typen I – III genutzt. Mit dem Pkw-Typ IV ist der höchste Aluminiumeinsatz erreicht. Diese Annahme beruht auf dem technisch machbaren und nicht dem wirtschaftlich durchsetzbaren Potenzial der Aluminium-Bauweise in der Karosserie. Die Pkw-Typen II bis IV werden in technischen Modellzyklen von jeweils 6 Jahren produziert und als Neufahrzeuge in den Bestand aufgenommen.

Tabelle 2: Aluminiumeinsatz in Neufahrzeugen nach McKinsey u. Altmann u.a.

	Pkw-Typ I 1995	Pkw-Typ II 1996-2001	Pkw-Typ III 2002-2007	Pkw-Typ IV 2008-2013
Bauteil unspezifisch in kg	70	70	70	70
+ Motorhaube in kg	-	10	10	10
+ 2 Türen in kg	-	-	25	25
+ Aluminium-Karosserie in kg	-	-	-	192
Insgesamt in kg	70	80	105	297

Verbrauchseinsparung für Diesel- und Benzinfahrzeuge

Die Kraftstoffverbrauchsdaten für Diesel- und Benzinfahrzeuge sind aus Altmann u.a. entnommen. Darin wird die Golf-Klasse durch die Referenzfahrzeuge Golf IV,

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30 Verband der Automobilindustrie (VDA): Jahresbericht. Frankfurt 2002, S. 40- 43. In diesem Jahresbericht werden die Fahrzeuge der Segmente untere Mittelklasse, Mittelklasse und obere Mittelklasse addiert und mit dem Begriff ‚Mittelklasse' bezeichnet.

31 McKinsey & Company, Serving Automotive Industry, a.a.O., pp. 21, 28

32 Altmann u.a., Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung, a.a.O., Abschnitt 5.1.4.1 – keine Seitenangaben!

Opel Astra und Audi A3 definiert.[33] In dieser Studie ist die Verbesserung der Antriebstechnik in der Zukunft auf die technische Effizienzsteigerung zurückzuführen und nicht auf eine Gewichtsreduktion der Fahrzeuge (siehe Tabelle 3).[34] Dies ist eine wichtige Annahme, um die unterschiedlichen Maßnahmen zur Kraftstoffeinsparung getrennt voneinander untersuchen zu können.

Tabelle 3: Verbrauchsdaten für Diesel und Benziner nach Altmann u.a.

	Einheit	**Golf-Klasse**
Verbrauch **heutiger** Benziner mit Verbrennungsmotor	l/100 km	8,29 ± 2,38
Verbrauch **zukünftiger** Benziner mit Verbrennungsmotor	l/100 km	5,73 ± 1,70
Verbrauch **heutiger** Diesel mit Verbrennungsmotor	l/100 km	5,76 ± 1,31
Verbrauch **zukünftiger** Diesel mit Verbrennungsmotor	l/100 km	4,95 ± 1,18

Die Berechnung der Kraftstoffeinsparung wird an dem Benzinfahrzeug (heute) beispielhaft in Tabelle 4 aufgeführt. In der Golf-Klasse wird z. B. bei dem Golf IV (Fahrzeuggewicht 1049 kg) die Stahlkarosserie von ca. 317 kg durch eine Aluminiumkarosserie mit 192 kg ersetzt (vgl. Pkw-Typ IV in Tab. 2). Dies entspricht einer Gewichtsreduktion von 40 %.[35]

Tabelle 4: Kraftstoffeinsparung durch Gewichtsreduktion nach Altmann u.a.

	Einheit	Golf-Klasse
Kraftstoffverbrauch **heutiger** Benziner mit Verbrennungsm.	l/100 km	8,29 ± 2,38
Gewichtseinsparung durch Aluminiumeinsatz in Karosserie	kg	125
Verbrauchseinsparung durch Gewichtsreduktion	l/100 km	0,29 ± 0,09
Einsparung bezogen auf **ein Kilo** Gewichtsreduktion	l/100 km	0,00232 ± 0,00072

Nach Altmann u.a. wird durch diesen Aluminiumeinsatz in der Karosserie eine durchschnittliche Verbrauchseinsparung von 3,5 % des Kraftstoffverbrauchs für das heutige Benzinfahrzeug erzielt.[36] Diese Verbrauchsseinsparung von 3,5 % (für

33 Altmann u.a., Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung, a.a.O., Abschnitt 1.2.1 – keine Seitenangaben!

34 Altmann u.a., Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung, a.a.O., Abschnitt 5.2.1.1 und 5.2.1.3 – keine Seitenangaben!

35 Altmann u.a., Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung, a.a.O., Abschnitt 5.1.4.1 – keine Seitenangaben

36 Altmann u.a., Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung, a.a.O., Abschnitt 5.2.1.12 – keine Seitenangaben

125 kg Gewichtseinsparung) wird für das weitere Vorgehen konstant gehalten und in Abhängigkeit der verbesserten Antriebstechnik der Benzin- und Dieselfahrzeuge (vgl. Tab. 5) auf ein Kilo ‚Gewichtseinsparung' umgerechnet und auf die Pkw-Typen I bis IV übertragen. Zusätzlich wird der Verbrauch heutiger Pkw auf das Jahr 2000 und der zukünftige Verbrauch auf das Jahr 2010 festgelegt. An dieser Stelle sei darauf hingewiesen, dass die Pkw-Typen I – IV den Aluminiumeinsatz in der Karosserie definieren und nicht die Antriebstechnik. Die verbesserte Antriebstechnik hat einen Einfluss auf die Kraftstoffeinsparung, was in Tabelle 5 durch die Angaben pro kg Gewichtseinsparung deutlich wird (vgl. Spalte 2 und 4). Bei einer Variation der Pkw-Typen I – IV in der späteren Szenariotechnik wird die Kraftstoffeinsparung durch Aluminium-Leichtbau in der Karosserie jeweils in Abhängigkeit der Antriebstechnik berücksichtigt. Für die Berechnung der absoluten Kraftstoffeinsparung von l/100 km der Pkw-Typen I – IV muss nur noch die Einsparung pro kg der Benzin- und Dieselfahrzeuge mit der Gewichtsreduktion multipliziert werden. Es handelt sich bei der Verbrauchseinsparung immer um einen Mittelwert, der in einer Bandbreite von ± 31 % liegen kann (vgl. Tab. 4).

Tabelle 5: Kraftstoffeinsparung der Typen I – IV pro kg Gewichtsreduktion

	Kraftstoff-verbrauch Benziner l/100 km	Einsparung Benziner l/100 km pro kg Gew.-reduktion	Kraftstoff-verbrauch Diesel l/100 km	Einsparung Diesel l/100 km pro kg Gew.-reduktion	Gewichts-reduktion kg
Typ I	8,50	0,00238	6,10	0,00171	6,8*
Typ II	8,29	0,00232	5,76	0,00161	4
Typ III	7,01	0,00196	5,36	0,00150	14
Typ IV	5,73	0,00160	4,95	0,00139	91

* gegen Restbestand gerechnet und nicht durch Bauteil definiert

4.2.2 Annahmen Restbestand

Aluminiumeinsatz im Restbestand

Der Restbestand wird nicht weiter nach Typenklassen oder Segmentzugehörigkeit definiert. Es handelt sich dabei um Altfahrzeuge die vor 1995 hergestellt wurden. Für den Aluminiumeinsatz im Restbestand wird auf die Untersuchung von Rink zurückgegriffen und ein durchschnittlicher Aluminiumeinsatz von 53 kg pro Restfahrzeug definiert. Für den Restbestand wird dieser Wert bis zum Zieljahr 2013 konstant gehalten.

Kraftstoffverbrauchsdaten Restbestand

Angaben über den durchschnittlichen Kraftstoffverbrauch im Bestand sind nach Shell immer in einer Summe auf Diesel- und Benzinfahrzeug bezogen.[37] Der Durchschnittsverbrauch des Bestandes verbessert sich im betrachteten Zeitraum durch das Ausscheiden alter Fahrzeuge und die Einführung neuer Fahrzeuge mit verbesserter Antriebstechnik. Diese Verbrauchsdaten wurden für den Restbestand übernommen, obwohl keine Neufahrzeuge in den Restbestand gelangen, jedoch durch das Ausscheiden älterer Fahrzeuge von einer Verbesserung des Durchschnittsverbrauchs ausgegangen werden kann.

4.2.3 Überblick Szenario-Rahmendaten

In Tabelle 6 ist zusammenfassend ein Überblick über die Szenario-Rahmendaten gegeben. Ausgehend vom Basisjahr 1995 bis zum Zieljahr 2013 werden zusätzlich die Daten der Jahre 2001 und 2007 aufgeführt, da mit Ausnahme des Pkw-Typs I die Neufahrzeuge in technischen Modellzyklen von 6 Jahren in den Bestand eingeführt werden. Die Daten für Neuzulassungen, Löschungen sowie die Entwicklung des Gesamtbestandes und der Laufleistung sind der Shell-Studie „One World“ entnommen. Der prozentuale Anteil der Dieselfahrzeuge an den Neuzulassungen basiert auf einer VDA Statistik, die für die Automobilwoche[38] aufbereitet wurde. Die Daten über die Entwicklung der Dieselfahrzeuge am Gesamtbestand weichen im Vergleich zu den Annahmen in Shell ab und führen zu einem höheren Bestand an Dieselfahrzeugen in Zukunft. Im Jahr 2002 erreichen die Dieselfahrzeuge einen Anteil von 38 % an den Neuzulassungen. Diese positive Entwicklung wird mit einer Wachstumsrate von 0.64 % p. a. fortgeschrieben und führt im Vergleich zu den Annahmen in Shell zu einem Dieselbestand von 15,7 Mill. Fahrzeugen im Jahr 2010. Dieser Dieselbestand wird nach Shell erst im Jahr 2020 erreicht. Die Annahmen über den Aluminiumeinsatz in den Neufahrzeugen und dem Restbestand sowie die Kraftstoffverbrauchsdaten wurden in den vorhergehenden Abschnitten ausführlich beschrieben.

[37] Shell Pkw-Szenarien, Mehr Autos – weniger Verkehr? a.a.O., S. 4

[38] Automobilwoche: Marktanteile von neu zugelassenen Pkw mit Dieselmotor in westeuropäischen Ländern. Nr. 10, v. 12.05.2003

Tabelle 6: Szenario-Rahmendaten nach Shell, McKinsey und Altmann u.a.

		Basisjahr			Zieljahr
	Einheit	1995	2001	2007	2013
Neuzulassungen	Mill. Fz.	3,3	3,3	4	4,1
-davon Dieselfahrzeuge	%	14,5	34,6	42	45
Löschungen	Mill. Fz.	2,9	3	3,6	3,8
Pkw-Bestand	Mill. Fz.	41	44	48	50
-davon 'Pkw-Typen I - IV'	Mill. Fz.	3,3	23	38,6	46,7
Ø Aluminiumeinsatz Neufahrzeuge	kg/Fz.	70	80	105	297
Ø Aluminiumeinsatz Restbestand	kg/Fz.	53	53	53	53
Laufleistung p.a.	Tsd. km	12,5	12,26	12,02	11,78
Ø Kraftstoffverbrauch Restbestand	l/100 km	9,15	8,37	7,59	6,81
Ø Benzinverbrauch 'Neufahrzeuge'*	l/100 km	8,50	8,29	7,01	5,73
Ø Dieselverbrauch 'Neufahrzeuge'*	l/100 km	6,10	5,76	5,36	4,95

*ohne Leichtbau

4.3 Annahmen zur Fallentwicklung I – III

Als weiterer Bestandteil des Szenarios werden im folgenden drei Fälle eingeführt, die durch die unterschiedliche Realisierung von Aluminium-Leichtbaumaßnahmen bzw. Einführung der Pkw-Typen I – IV gekennzeichnet sind.

- Fall I: Basisentwicklung

In der Basisentwicklung wird das Basisjahr 1995 dem Zieljahr 2013 gegenübergestellt. In diesen beiden Jahren werden nur die Neufahrzeuge des Typs I mit einem durchschnittlichen Aluminiumeinsatz von 70 kg pro Pkw und der entsprechende Restbestand aus Altfahrzeugen, die vor 1995 hergestellt wurden, mit einem durchschnittlichen Aluminiumeinsatz von 53 kg pro Pkw eingesetzt. Der Gesamtbestand entwickelt sich bis zum Jahr 2013 entsprechend der Vorgaben nach Shell „One World“. In der Basisentwicklung wird die verbesserte Antriebstechnik der Neufahrzeuge sowie das Absinken des Durchschnittsverbrauchs des Restbestandes berücksichtigt. Die werkstoffbedingte Kraftstoffeinsparung ergibt sich aus dem höheren Aluminiumeinsatz im Pkw-Typ I gegenüber dem Restbestand.

- Fall II: Aluminium-Leichtbau

Im Fall II werden alle Leichtbaumaßnahmen aus Aluminium in der Karosserie bis zum Zieljahr 2013 realisiert, d. h. im Bestand existiert eine Mischung aus dem Restbestand und den Pkw-Typen I – IV, bei dem der Typ IV den höchsten Anteil am Bestand erzielt. Die Kraftstoffeinsparung durch Aluminium-Leichtbau ergibt sich ausgehend vom Typ I (Referenzfahrzeug) mit einem höheren Aluminiumeinsatz gegenüber dem Restbestand und zusätzlich durch die in den Typen II – IV eingebauten Komponenten aus Aluminium in der Karosserie.

- Fall III: Veränderte Modellzyklen

Im Fall III werden lediglich die Leichtbaumaßnahmen der Pkw-Typen I – III bis zum Jahr 2013 realisiert, d. h. im Bestand gibt es eine Mischung aus den Typen I – III und dem Restbestand, bei dem der Typ III den höchsten Anteil am Bestand erzielt. Der Pkw-Typ IV mit dem höchsten Aluminium-Leichtbaupotential wird nicht marktrelevant und der durchschnittliche Aluminiumeinsatz bleibt konstant bei 105 kg pro Fahrzeug. In dieser Fallbetrachtung werden entsprechend den Annahmen nach McKinsey in der Karosserie nur wenige Komponenten, wie die Motorhaube und Türen, aus Aluminium gefertigt. Der Bestand, die Laufleistung und die Antriebstechnik entwickeln sich entsprechend der Fälle I und II. Die Kraftstoffeinsparung durch Aluminium-Leichtbau ergibt sich ausgehend vom Typ I (Referenzfahrzeug) mit einem höheren Aluminiumeinsatz gegenüber dem Restbestand und zusätzlich durch die in den Pkw-Typen II – III eingebauten Komponenten aus Aluminium in der Karosserie.

5 Auswertung und Ergebnisse der Szenariorechnung

5.1 *Ergebnisse der Kraftstoffeinsparung im Pkw*

Zuerst wird die Entwicklung des Pkw-Bestandes von 1995 bis 2013 beispielhaft an Fall II in Abbildung 4 dargestellt. Der Fall II wurde gewählt, da alle Pkw-Typen I – IV in den Bestand eingeführt werden und sich anschaulich der Auf- und Abbau der einzelnen Bestände erkennen lässt. Im Basisjahr 1995 belief sich der deutsche Pkw-Bestand auf 40,4 Mill. Fahrzeuge, der bis zum Zieljahr 2013 abgeleitet aus Shell „One World“ auf 50,3 Mill. Fahrzeuge ansteigt. Im Bestand des Jahres 1995 sind 3,3 Mill. Neufahrzeuge ausschließlich des Typs I vertreten. Bis zum Jahr 2013 werden alle Typen I – IV eingeführt und erreichen insgesamt 46,7 Mill. Fahrzeuge, die einen Anteil von 93 % am Gesamtbestand ausmachen.

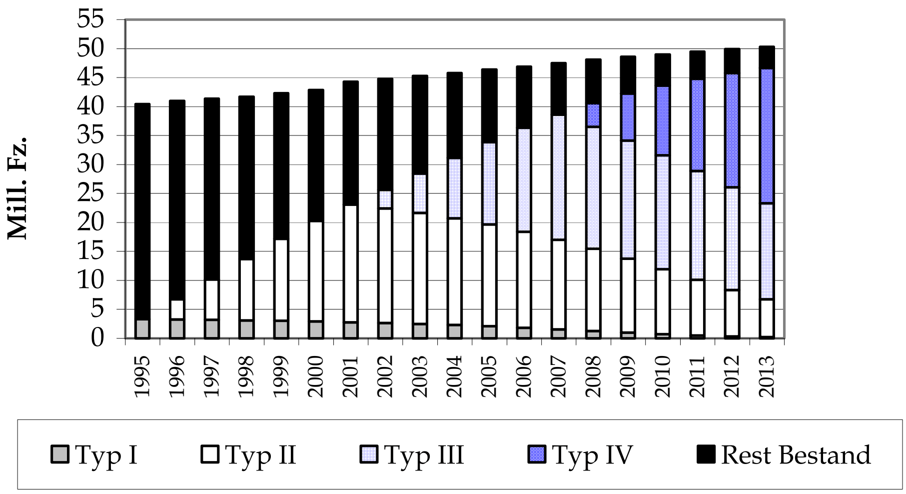

Abbildung 4: Entwicklung des Pkw-Bestands bis 2013

In Abbildung 5 ist die Struktur des Pkw-Bestandes für das Zieljahr 2013 je nach Fall I – III dargestellt. Die Einführung der Pkw-Typen I – IV erreicht unabhängig von der Fallbetrachtung im Jahr 2013 immer die Höhe von 46,7 Mill. Fahrzeugen, wobei sich der Restbestand auf 3,6 Mill. Fahrzeuge beläuft. Im Basisfall I, wird nur der Typ I in den Pkw-Bestand eingeführt. Der Fall II ist durch die Einführung aller Typen I – IV gekennzeichnet und der Fall III unterscheidet sich vom Fall II lediglich durch den Ausfall des Typs IV, der durch den Typ III substituiert wird.

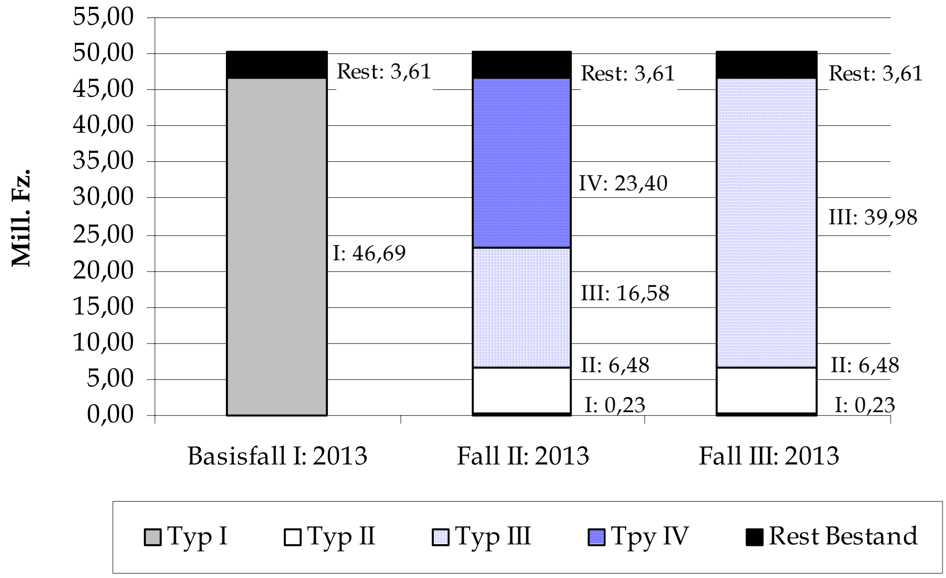

Abbildung 5: Struktur des Pkw-Bestandes im Zieljahr 2013

In Tabelle 7 ist der Kraftstoffverbrauch aufgeführt. Der gesamte Pkw-Bestand benötigt im Basisjahr 1995 ca. 46 Mrd. Liter Benzin- und Dieselkraftstoff ohne die Berücksichtigung von Aluminium-Leichtbaumaßnahmen. Dieser Kraftstoffverbrauch reduziert sich im Zieljahr 2013 um 9,6 Mrd. Liter auf 36,2 Mrd. Liter, obwohl der Pkw-Bestand um 24,5 % ansteigt (vgl. Abb. 4). Gründe für die Reduzierung des Kraftstoffverbrauchs sind in der niedrigeren jährlichen Laufleistung pro Fahrzeug, dem Rückgang des durchschnittlichen Kraftstoffverbrauchs des Restbestandes und in der effizienteren Antriebstechnik der bis zum Jahr 2013 eingeführten Neufahrzeuge zu finden.

Tabelle 7: Kraftstoffverbrauch Pkw-Bestand

	Basisjahr 1995	Fall I - III 2013
Kraftstoffverbrauch ohne Leichtbau in Mill. Liter	45.800	36.203

In Tabelle 8 ist die zusätzliche Kraftstoffeinsparung durch Gewichtsreduktion aufgeführt, die durch die Einführung der einzelnen Pkw-Typen I – IV erzielt werden. Diese Pkw erreichen im Jahr 2013 insgesamt 46,7 Mill. Fahrzeuge und haben einen Anteil von 93 % am Gesamtbestand. Mit Blick auf das Zieljahr 2013 wird deutlich, dass der realisierte Aluminium-Leichtbau zu einer Kraftstoffeinsparung durch Gewichtsreduktion in einer Größenordung von 0,2 – 1,2 % vom Gesamtkraftstoffverbrauch führt (vgl. Tabelle 7). Die unterschiedliche Höhe der Kraftstoffeinsparung ist abhängig von der Einführung der Typen I bis IV, die in Abschnitt

4.3 durch die Fälle I bis III definiert wurden. Die geringste Kraftstoffeinsparung im Jahr 2013 ist mit dem Basisfall I verbunden, in dem jeweils nur der Typ I als Neufahrzeug in den Bestand eingeführt wird. Die höchste Kraftstoffeinsparung wird durch den Fall II erzielt. In diesem Fall sind alle Pkw-Typen I bis IV im Bestand des Jahres 2013 vorhanden. Der Typ IV erzielt im Vergleich zu den anderen Pkw-Typen die höchste Kraftstoffeinsparung mit einem Anteil von 87 % an der gesamten Kraftstoffeinsparung. Im Fall III wird eine Kraftstoffeinsparung von 0,3 % des gesamten Kraftstoffbedarfs erzielt (vgl. Tab. 7). Dies erfolgt durch die Einführung der Typen I bis III in den Pkw-Bestand bis zum Jahr 2013. Der Typ IV wird nicht marktwirksam und durch den Typ III substituiert. Welchen Stellenwert Typ IV durch sein hohes Leichtbaupotenzial bei der Erzielung der Kraftstoffeinsparung einnimmt, wird hier im Vergleich zu Fall II deutlich. Zusammenfassend ist aus Tabelle 8 zu erkennen, dass ein verstärkter Einsatz von Aluminium in der Karosserie eines Fahrzeugs notwendig ist, um eine höhere Kraftstoffeinsparung durch Aluminium-Leichtbau sichtbar zu machen.

Tabelle 8: Kraftstoffeinsparung durch Aluminium-Leichtbau

	Basisfall I 2013	Fall II 2013	Fall III 2013
Kraftstoffeinsparung: Typ I in Mill. Liter	71	0	0
Kraftstoffeinsparung: Typ II in Mill. Liter	-	7	7
Kraftstoffeinsparung: Typ III in Mill. Liter	-	49	107
Kraftstoffeinsparung: Typ IV in Mill. Liter	-	379	-
Gesamte Kraftstoffeinsparung in Mill. Liter	71	435	114

Aus Tabelle 8 ist zu erkennen, dass durch den Vergleich der Szenariofälle II und III mit dem Basisfall I die Realisierung unterschiedlicher Aluminium-Leichtbaumaßnahmen in der Karosserie bis zum Jahr 2013 eine um den Faktor 1,6 bis 6 mal höhere Kraftstoffeinsparung erzielt werden kann, letztere nur durch den Einsatz von Aluminium in einer Größenordnung von ca. 230 kg pro Fahrzeug, wie im Pkw-Typ IV, durch die Karosserie in Aluminium-Bauweise.

Tabelle 9 zeigt die eingesparten CO_2-Emissionen, die in den Fällen I bis III durch die vermiedene Verbrennung von Kraftstoffen erzielt werden (vgl. Tab. 8). Die Dieselfahrzeuge haben einen Anteil von ca. 39 % an der Kraftstoffeinsparung und erzeugen bei der Verbrennung von Dieselkraftstoff 2,58 kg CO_2 pro Liter. Benzinfahrzeuge erzeugen bei der Verbrennung von Benzinkraftstoff 2,28 kg CO_2 pro Liter (Birnbaum, 1993).[39]

Tabelle 9: Reduktion CO_2-Emissionen durch Aluminium-Leichtbau

	Basisfall I 2013	Fall II 2013	Fall III 2013
Summe CO_2-Reduktion durch Typen I - IV in 1000 t	170	1043	273

Tabelle 9 kann analog zu Tabelle 8 den Vergleich der Szenariofälle II und III mit dem Basisfall I aufzeigen, der je nach Umsetzung der Aluminium-Leichtbaumaßnahmen in der Karosserie eine um den Faktor 1,6 bis 6 mal höhere CO_2-Reduktion erzielt.

5.2 *Ergebnisse der gesamtwirtschaftlichen Analyse*

Auf der Grundlage der absoluten Kraftstoffeinsparung der Fälle I – III (vgl. Tab. 8) wird nun im folgenden Abschnitt die gesamtwirtschaftliche Auswirkung der Kraftstoffreduktion auf der Basis einer Input-Output-Analyse aufgezeigt. Dafür wird in einem ersten Schritt die physische Kraftstoffeinsparung (Mill. Liter) in einen monetären Wert umgerechnet, um die ausgefallene Kraftstoffnachfrage zu quantifizieren. Ausgangslage für die Bewertung in monetären Einheiten ist der reale Produktionspreis von Benzin- und Dieselkraftstoff vor Steuer, ausgehend vom Basisjahr 1995. Die Preisentwicklung für Benzin- und Dieselkraftstoffe ist der LfU Studie (2002) entnommen, in der die Entwicklung der nominalen und realen Kraftstoffpreise in Deutschland von 1981 bis 2001 abgebildet wird. Die realen Benzin- und Dieselpreise im Zieljahr 2013 wurden entsprechend der Annahme über die Entwicklung der nominalen Rohölpreise bis zum Jahr 2015 nach Prognos (1999) abgeschätzt und umgerechnet. Daraus ergibt sich für einen Liter Benzin vor Steuer ca. 0,25 € (48 Pf) und für einen Liter Diesel vor Steuer ca. 0,28 € (54 Pf). Diese Preise werden für die Quantifizierung der verminderten Kraftstoffnachfrage durch Aluminium-Leichtbau herangezogen. Hier sei noch einmal der Hinweis gegeben, dass die Dieselfahrzeuge mit einem Anteil von 39% an der Einsparung beteiligt sind.

[39] Birnbaum, K.U.: Fossile Energieträger und Kohlendioxidemissionen. In: GASWÄRME International. Nr. 42 (1993), Heft 4, S.166.

Die Analyse auf Basis einer Input-Output Rechnung berücksichtigt nicht nur die verminderte Kraftstoffnachfrage in der Mineralölwirtschaft (vgl. Spalte 2 in Tab. 10), sondern auch die Branchen, die Zulieferleistungen für die Mineralölwirtschaft bereitstellen, wodurch es zu einem kumulierten Produktionsrückgang kommt (vgl. Spalte 3). In gleicher Weise ist nicht nur die Mineralölwirtschaft an einer CO_2-Reduktion beteiligt, sondern auch die Industrien, die vorgelagert Güter und Dienstleistungen für diesen Wirtschaftszweig zur Verfügung stellen (vgl. Spalte 4). Da die Emissionsrechung an die monetäre Produktionsrechnung gekoppelt ist, wurden die CO_2-Emissionen entsprechend der realen Preisentwicklung für Kraftstoffe im Jahr 2013 auf das Basisjahr 1995 (= 100 %) korrigiert, so dass die Produktion von einem Liter Kraftstoff in 1995 und 2013 mit den gleichen durchschnittlichen CO_2-Emissionen verbunden ist. Aus dem Vergleich der Ergebnisse in Spalte 2 und 3 wird deutlich, dass zwischen der verminderten Kraftstoffnachfrage und dem kumulierten Produktionsrückgang für die Fälle I – III ein Faktor von 1,8 liegt. In entsprechender Weise liegt zwischen dem kumulierten Produktionsrückgang und den angehängten CO_2-Emissionen ein Faktor von 1,06.

Tabelle 10: Gesamtwirtschaftliche Ergebnisse für Kraftstoffeinsparung in 2013

	Kraftstoffeinsparung		Kumulierter Produktionsrückgang	Kumulierte CO_2-Reduktion
	Mill. Liter	Mill. €	Mill. €	1000 t
Basisfall I	71	18	33	35
Fall II	435	112	201	204
Fall III	114	29	52	54

Mit Hilfe der Input-Output-Analyse wird deutlich, welche Produktionssektoren von einem Rückgang der Kraftstoffnachfrage betroffen sind und in welchen Sektoren CO_2-Emissionen eingespart werden. Im folgenden wird nicht mehr zwischen den Fällen I bis III unterschieden, da die Ergebnisstruktur der Input-Output-Analyse aufgrund der linearen Produktionsfunktion gleich ist. Abbildung 6 gibt einen Überblick über den Anteil der Sektoren, die durch Zulieferleistungen an die Mineralölwirtschaft von einem Rückgang der Kraftstoffproduktion betroffen sind. Das ist in erster Linie die Mineralölwirtschaft selbst, die mit dem größten prozentualen Anteil den Ausfall der Kraftstoffnachfrage spürt. Dann folgen unmittelbar die Sektoren der Grundstoffindustrie, wie die Herstellung von Kohle, Erdöl und Erdölgas sowie Sektoren im Dienstleistungsbereich, wie z. B. die Unternehmensbezogenen Dienstleistungen und Dienstleistungen der Kreditinstitute.

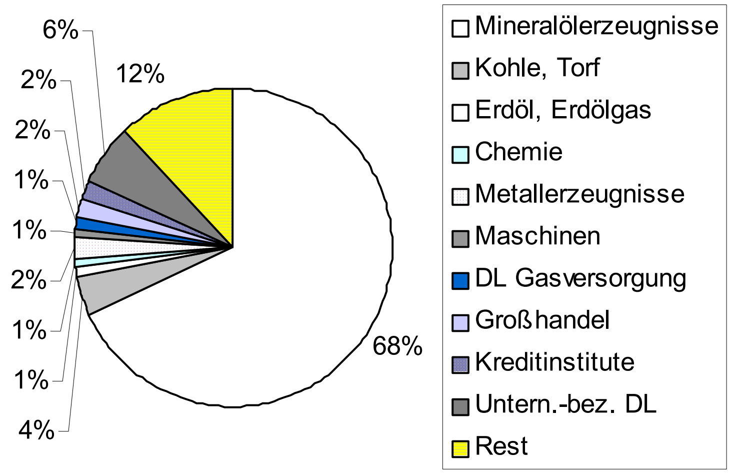

Abbildung 6: Anteil der Sektoren an den kumulierten Produktionseffekten

Abbildung 7 zeigt die Sektoren, die bei der Einsparung von CO_2-Emissionen eine Rolle spielen. Die Abbildung 7 zeigt im Vergleich zu Abbildung 6 eine andere Zusammenstellung der betroffenen Sektoren und der prozentualen Anteile. Auch hier trägt die Mineralölwirtschaft am stärksten zu einem Rückgang der CO_2-Emissionen bei. Wie zuvor bei den Produktionseffekten tragen die Sektoren der Grundstoffindustrie, wie die Herstellung von Kohle, zu einem geringen Anteil zur CO_2-Reduktion bei. Auffällig an der Ergebnisstruktur ist, dass die Elektrizitätswirtschaft als zweitwichtigster Sektor mit einem Anteil von 6 % zur CO_2-Reduktion beiträgt. Gründe für eine von der Struktur der Produktionseffekte abweichende Struktur der CO_2-Emissionseffekte liegen in den spezifischen CO_2-Emissionskoeffizienten der einzelnen Sektoren. Diese sind für einzelne Sektoren unterdurchschnittlich, wie z. B. Dienstleistungen, für andere überdurchschnittlich, wie z. B. Mineralölerzeugnisse. Die Produktion von Elektrizität ist ebenfalls mit einem überdurchschnittlich hohen CO_2-Emissionskoeffizienten versehen.

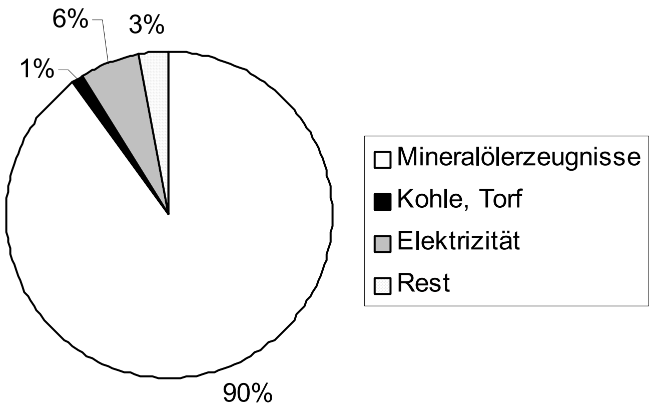

Abbildung 7: Anteil der Sektoren an der kumulierten CO_2-Reduktion

5.3 *Übersicht Ergebnisse für CO_2-Emissionen*

In Tabelle 11 sind die Ergebnisse der CO_2-Reduktion (vgl. Tab. 9 und 10) zusammengefasst. Die vermiedene Verbrennung von Benzin- und Dieselkraftstoff im Motor kann als direkte CO_2-Einsparung bezeichnet werden, wogegen die Vermeidung der Produktion für die Bereitstellung von Kraftstoffen als indirekte CO_2-Einsparung bezeichnet wird. Die CO_2-Einsparungen aus den unterschiedlichen Emissionsquellen werden dann addiert. Aus der Tabelle 11 ist ersichtlich, dass die Vermeidung der Kraftstoffproduktion ca. 20 % der vermiedenen Kraftstoffverbrennung ausmacht. Im Fall II werden somit direkt und indirekt ca. 1,3 Millionen Tonnen CO_2 eingespart, die dem aluminiumbedingten Leichtbau bei Pkw zuzurechnen sind.

Tabelle 11: Direkt und indirekt eingesparte CO_2-Emissionen

	Basisfall I	Fall II	Fall III
	2013	2013	2013
Vermeidung Produktion (indirekt) in 1000 t	35	204	54
Vermeidung Kraftstoffverbrennung (direkt) in 1000 t	170	1043	273
Einsparung insgesamt in 1000 t	205	1247	327

6 Zusammenfassung

Der Lebenszyklus eines Pkw wird dominiert durch die Nutzungs- bzw. Betriebsphase aufgrund des Ressourcenverbrauchs und der damit zusammenhängende Emissionen. Studien haben gezeigt, dass ein Pkw beispielsweise ca. 83 % des gesamten Energieaufwands allein in der Betriebsphase durch die Verbrennung von Kraftstoffen benötigt. Die bei der Kraftstoffverbrennung entstehenden CO_2-Emissionen der Betriebsphase machen sogar ca. 93 % der gesamten CO_2-Emissionen im Lebenszyklus eines Pkw aus. Es existieren verschiedene Möglichkeiten den Kraftstoffverbrauch eines Pkw zu reduzieren. Dazu zählen die Senkung des Luftwiderstandes, die Verbesserung von Motor und Antrieb und die Reduzierung der Fahrzeugmasse.

Im Mittelpunkt dieser Untersuchung steht die Einsparung von Kraftstoff durch die Reduzierung der Fahrzeugmasse bzw. durch Leichtbaumaßnahmen mit dem Werkstoff Aluminium. Verschiedene Studien weisen darauf hin, dass der Einsatz von Aluminium im Pkw in Zukunft an Bedeutung gewinnen wird. Experten erwarten, dass das größte Einsatzpotenzial von Aluminium im Bauteil Karosserie sein wird, gefolgt vom Fahrwerks- und Antriebsbereich. Aus diesem Grund gilt das Hauptaugenmerk dieser Arbeit dem Einsatz von Aluminium in der Karosserie. Zu diesem Zweck werden vier verschiedene Pkw-Typen definiert, die dem Segment der Mittelklasse zuzuordnen sind. Diese Pkw-Typen I – IV unterscheiden sich lediglich durch verschiedene Aluminium-Leichtbaumaßnahmen in der Karosserie. Dazu gehört die Fertigung der Motorhaube und Türen aus Aluminium sowie die Herstellung der Karosserie in Aluminium-Bauweise.

Methodisch baut die Untersuchung auf zwei verschiedenen Modellen und der Szenariotechnik auf. Das Pkw-Modell basiert auf Daten zur Herstellung und Nutzung von Fahrzeugen sowie der Entwicklung des Pkw-Bestandes in Deutschland. Es wird herangezogen für die Pkw-Bestandsbetrachtung vom Basisjahr 1995 bis zum Zieljahr 2013. Dabei werden die Pkw-Typen I – IV jeweils als Neufahrzeuge in den Bestand eingeführt und sorgen für eine Kraftstoffeinsparung und CO_2-Reduktion durch die realisierten Aluminium-Leichtbaumaßnahmen in der Karosserie. Auf der Grundlage des Pkw-Modells wird somit eine direkte Einsparung von Kraftstoff und CO_2-Emissionen berechnet, die aus der unmittelbaren Vermeidung der Kraftstoffverbrennung im Motor resultiert. Das zweite Modell ist ein volkswirtschaftliches Input-Output-Modell, das die deutsche Produktionsstruktur abbildet und durch umweltökonomische Daten, z. B. CO_2-Emissionen, erweitert werden kann. Die Kraftstoffeinsparung führt zu einem Rückgang der Nachfrage nach Produkten in der Mineralölwirtschaft sowie derer Zulieferindustrien. Dieser produktionsseitige Effekt der Kraftstoffeinsparung wird mit dem Input-Output-Modell berechnet. Auf der Basis dieses Modells ist es möglich, direkte und indirekte Produktionseffekte und CO_2-Reduktionen zu analysieren, die durch den Rückgang der Kraftstoffnachfrage ausgelöst werden. Mit Hilfe der Szenariotechnik werden drei Entwicklungsfälle definiert, die in Abhängigkeit der Einführung der Pkw-Typen I – IV eine unterschiedliche Kraftstoffeinsparung durch Aluminium-Leichtbau in der Karosserie bis zum Jahr 2013 aufzeigen.

Die Ergebnisse der Szenarioanalyse zeigen, dass je nach Szenariofall eine direkte Kraftstoffeinsparung durch Aluminium-Leichtbaumaßnahmen in der Karosserie in der Größenordnung von 0,2 – 1,2 % des gesamten Kraftstoffbedarfs des Pkw-Bestandes im Jahr 2013 liegt. In absoluten Zahlen liegt die Kraftstoffeinsparung zwischen 71 – 435 Mill. Liter Benzin- und Dieselkraftstoff. Die damit zusammenhängende CO_2-Reduktion durch die vermiedene Kraftstoffverbrennung liegt zwischen 0,17 Mill. Tonnen und einer Millionen Tonnen. Die große Bandbreite erklärt sich aus unterschiedlichen Annahmen bezüglich der Marktpenetration von Leichtbaufahrzeugen. Die CO_2-Reduktion erhöht sich noch einmal um 20 %, wenn zusätzlich produktionsseitige Effekte bzw. die direkt und indirekt vermiedene Produktion der Mineralölwirtschaft und derer Zulieferbetriebe durch die Kraftstoffeinsparung in die Analyse einbezogen wird. Auf diese Weise werden beide CO_2-Emissionsquellen in diesem Beitrag berücksichtigt.

Die mit Abstand größte Einsparung wird durch den Pkw-Typ IV realisiert, da es sich hierbei um das Fahrzeug mit dem höchsten Aluminiumeinsatz in der Karosserie handelt. Aus den Szenarioergebnissen wird deutlich, dass ein verstärkter Einsatz von Aluminium notwendig ist, um einen höheren Einsparungseffekt in bezug auf Kraftstoffe und CO_2-Emissionen durch Aluminium-Leichtbau in der Nutzungsphase sichtbar zu machen. Dafür sind zwei Gründe maßgeblich. Im Rahmen des hier durchgeführten Szenarios erzielen die Aluminium-Leichtbaumaßnahmen im Bauteil Karosserie eine Gewichtseinsparung von 40% gegenüber der konventionellen Stahlbauweise. Aufgrund verbesserter Antriebstechnik sinkt die Kraftstoffeinsparung pro kg Gewichtseinsparung auf 100 km.

7 Inhaltszusammenfassung

Der Beitrag handelt von ökologischen Aspekten der Aluminium-Leichtbau Potenziale in der Nutzungsphase von Fahrzeugen. Verschiedene Studien haben die herausragende Bedeutung der Nutzungsphase in bezug auf Kraftstoffverbrauch und damit zusammenhängende CO_2-Emissionen aufgezeigt. Leichtbaumaßnahmen mit Aluminium ist eine Möglichkeit Kraftstoffverbrauch und CO_2-Emissionen zu reduzieren. In diesem Beitrag werden verschiedene Komponenten aus Aluminium in der Karosserie von Personenkraftwagen berücksichtigt und auf den Pkw-Bestand in Deutschland übertragen. Gegenstand der Analyse ist die aufgrund von Aluminium-Leichtbau resultierende Reduktion von Kraftstoffen und CO_2-Emissionen.

Der methodische Ansatz basiert auf zwei Modellen und einem Szenario. Das Pkw-Modell berücksichtigt Daten zur Herstellung und Nutzung von Pkw und wird eingesetzt für die direkte Berechnung der Kraftstoffeinsparung und CO_2-Reduktion. Das zweite Modell ist ein volkswirtschaftliches Input-Output-Modell, dass die Verflechtung der deutschen Produktionsstruktur abbildet. Dieses Modell wird für eine gesamtwirtschaftliche Analyse der Kraftstoffeinsparung und CO_2-Reduktion herangezogen. Mit Hilfe der Szenariotechnik werden drei mögliche Entwicklungen des Aluminium-Leichtbaus in Pkw abgebildet. Das Szenario zeigt auf, dass durch Aluminium-Leichtbaumaßnahmen in der Karosserie von Pkw zwischen 71 und 435 Millionen Liter Kraftstoff eingespart werden können.

Summary

The article deals with ecological aspects of aluminium light-weight potentials in the use phase of vehicles. Several studies have shown the unquestionable importance of the use phase e.g. in terms of fuel consumption and related carbon dioxide emissions. Light-weight construction with aluminium is one option to reduce fuel consumption and CO_2 emissions. This study considers different aluminium components in the body of new passenger cars and the resulting fuel saving and CO_2 reduction of the car fleets in Germany.

The methodological approach is based on two models and one scenario. The micro-model considers data of vehicle manufacturing and fuel consumption. It is used for the calculation of direct fuel saving and CO_2 reduction. The macro-model is an input-output-model that shows the interdependence of different

industry sectors in an economy. It is used for the analysis of economy-wide effects of fuel saving and CO_2 reduction. The scenario-technique describes three possible situations of aluminium light-weight construction in passenger cars. As a result, between 71 and 435 million litre of fuel can be saved by the light-weight potential of aluminium in passenger car bodies.

8 Danksagung

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ALUMINIUM-EINSATZ IM VERKEHRSSEKTOR*

(UTILIZATION OF ALUMINIUM FOR TRANSPORTATION)

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ABSTRACT

With a total consumption of more than 2.5 million metric tons in 1997, Germany is the largest consumer of aluminium in Europe. The largest share of aluminium products is used by the transport sector.

The following article will provide a quantitative overview of the total amount of aluminium used in the transport sector, which exceeds the amount used for car production alone.

Approximately 420.000 metric tons are processed in this field, 320.000 metric tons being cast-aluminium products. With an overall production of 4,36 million cars in 1996, most of the aluminium is naturally used in this area (82%). Another 9% are needed for the production of commercial vehicles. The remaining 9% are being divided by the following: rail-, sea- and air-transportation as well as the production of bicycles, motor-bikes, containers, transport pallet and special vehicles.

According to an estimate of the aluminium industry, the trend of a rising demand will further increase. One plausible scenario assumes that in 2008 a quarter of all cars are built of aluminium body. This will result in a doubling of today's aluminium demand in Germany.

KEYWORDS
Aluminium, Vehicles, Practical Application, Transport, Use Quantity

* Source: Erzmetall 52 (1999), Nr. 7/8, S. 411-418

„Aluminium – Ein Leichtmetall mit Schwergewicht"

1 Einleitung

Von den NE-Metallen ist Aluminium mit einer Hüttenproduktion von fast 22 Millionen Tonnen weltweit 1997 das mengenmäßig wichtigste Gebrauchsmetall (auf Platz 2 Hüttenproduktion von Kupfer: 10 Millionen Tonnen). In den meisten Statistiken und Veröffentlichungen wird überwiegend der Terminus „Aluminiumverbrauch" benutzt. Dieser irreführende Begriff läßt vermuten, daß nach der Nutzungsphase das Metall nicht mehr wieder verwertet wird. Das Gegenteil jedoch ist der Fall. Der Anteil der Produktion und des Einsatzes von Sekundäraluminium steigt sowohl national wie auch international ständig an. Wegen der immer wieder möglichen stofflichen Wiederverwertung sollte deshalb besser von Aluminiumeinsatz oder Aluminiumgebrauch gesprochen werden.

Der Gesamteinsatz an Aluminium in Deutschland lag 1997 bei ca. 2.5 Millionen Tonnen [1]. Der mengenmäßig größte Anwendungsbereich und damit der wichtigste Absatzmarkt für deutsche Aluminiumerzeugnisse ist der Verkehrssektor. Laut Metallstatistik flossen 518.000 Tonnen Aluminium in den Verkehr. Dies bedeutet eine Steigerung von fast 20% gegenüber 1996.

Im Rahmen des (von der DFG geförderten) Sonderforschungsbereichs 525 (Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe) an der Rheinisch Westfälischen Technischen Hochschule Aachen und dem Forschungszentrum Jülich wurde unter anderem vom Teilprojekt Transport der Aluminiumeinsatz im Verkehr einer detaillierten Betrachtung unterzogen. Das Ziel ist eine detaillierte quantitative Darstellung des Aluminiumeinsatzes in den verschiedenen Verkehrssektoren und eine Prognose zur Entwicklung zu geben. Für die in Deutschland hergestellten Verkehrsmittel werden die Gewichtsanteile an Aluminium aufsummiert. Je nach Produkt und Bereich sind die notwendigen verarbeitungstechnischen Zugaben beträchtlich. Hierfür wird ein Mehrbedarf von 15% abgeschätzt und bei der Gesamtmenge berücksichtigt. Für die einzelnen Sektoren wird beispielhaft detailliert beschrieben, wo das Aluminium eingesetzt wird. Dem Pkw-Bereich, der fast 80% der Gesamtaluminiummenge abnimmt, kommt die größte Bedeutung zu.

2 Ermittlung der im Verkehrswesen eingesetzten Aluminiummengen nach Einsatzgebieten

Der Einsatz des Leichtmetalls Aluminium bietet sich aus vielen Gründen auch für den Verkehrsbereich an. Geringeres Gewicht senkt den Kraftstoffverbrauch und reduziert gleichzeitig die Emissionen. Bei Nutzfahrzeugen kann die Eigengewichteinsparung zur Vergrößerung der Nutzlast umgewandelt werden. Neben einem geringen Gewicht bietet Aluminium aber auch noch weitere Vorteile. Es ist korrosionsbeständig, leicht verformbar und bearbeitbar und hat einen sehr hohen Wert als Sekundärmetall, da es sich, sortenreine Sammlung und Aufbereitung vorausgesetzt, wieder zu einem hochwertigen und dem Primärmetall gleichwertigem Werkstoff recyceln läßt. Personenkraftwagen und Nutzfahrzeuge sind die wichtigsten Abnehmer von Aluminium. Allein aufgrund der produzierten Stückzahlen fließt in diese beiden Sektoren der größte Anteil des Gesamteinsatzes. Zum Straßenverkehr gehört der Sektor Zweiräder. Der Schienen- und Luftverkehr sind weitere Abnehmer für Aluminium. Neben dem Schiffsbau und der Produktion von Sonderfahrzeugen vervollständigt der Bereich der Container und Frachtpaletten die Übersicht. Im nachfolgenden werden die Einsatzgebiete von Aluminium im Verkehrswesen quantifiziert.

2.1 **Einsatzgebiete von Aluminium im Pkw**

Das Leichtmetall Aluminium ist im Automobilbau ein relativ junger Werkstoff. Aufgrund zahlreicher Vorteile ist der Trend zu einem ständig wachsenden Anteil von Aluminium in der Autoproduktion ungebrochen. Zylinderköpfe für Pkw-Motoren werden bereits heute zu fast 100% aus Aluminium gefertigt. Bei Motorblöcken wird bis zum Jahr 2003 ein Überschreiten der 50%-Marke erwartet [2]. Der Fahrzeughersteller AUDI ist dem Werkstoff besonders aufgeschlossen. Bereits im Jahre 1923 wurde dort der erste Leichtmetallmotor konstruiert und eine Vollaluminiumkarosserie gebaut. Mit dem Ende der 80er Jahre produzierten ersten Serienfahrzeug mit Ganz-Aluminiumkarosserie (A8) wurden gute Erfahrungen in der Fertigung, dem Betrieb und auch bei der Reparatur gemacht. Mit dem Al 2 kommt nun ein zweiter Fahrzeugtyp auf den Markt. Die Anwendungsgebiete für den Werkstoff Aluminium nehmen weiter zu. Tabelle 1 zeigt die Möglichkeiten der Anwendungen von Aluminium im Fahrzeugbau.

Tabelle 1: Aluminium im Fahrzeugbau

Fahrzeugbereich	**Aluminium-Bauteil**
Motor	Zylinderkopf, Motorblock, Kolben, Zylinderlaufflächen, Luftfiltergehäuse, Wasserpumpe, Kühlungseinrichtung, Ansaugrohre, Ölpumpe, Kraftstoffversorgungseinrichtung
Antriebsstrang	Gehäuse für Kupplung und Getriebe, Gelenkwellen, Differential
Fahrwerk	Räder (Felgen), Bremsanlage und Bremsleitungen, Lenkung, Achsen, Radaufhängung
Karosserie [3]	a) Spaceframe-Konzept: räumlicher Rahmen aus Aluminium-Strangpreßprofilen mit Gußknoten an den Verbindungsstellen. b) Blechschalen-Konzept: Für die tragenden Struktur wird Aluminiumblech verwendet. Die Verbindung der einzelnen Aluminiumblechteile erfolgt durch Punktschweißen oder Kleben. c) Hybrid-Konzept: Das Aluminium Hybrid-Konzept wählt Werkstoff und Werkstofform entsprechend den Anforderungen und versucht, die Vorteile der anderen Konstruktionssystemen und auch anderer Leichtbauwerkstoffe zu nutzen.
Sonstige	Lagerböcke, Hardtop, Sitzschienen, Aggregateträger, Hitzeschilder, Ziergitter, Wärmetauscher, Alu-Zierbänder, Scheinwerferabdeckungen, Dachreling-Stützen, Wagenheber.

Für Fahrzeuge, die Anfang der 70er Jahre produziert wurden, wurde ein durchschnittlicher Aluminiumanteil von 23 kg je Fahrzeug festgestellt. In der Studie: Aluminium, Automobil und Recycling [4] wurden die Fahrzeuge in drei unterschiedliche Klassen eingeteilt. Der Aluminiumgehalt betrug:

- Für Fahrzeuge bis zur Größe eines VW Golf 10 bis 30 kg,
- Für Fahrzeuge der Mittelklasse 30 bis 70 kg,

- Für Fahrzeuge der Oberklasse 50 bis 150 kg.

Von den 26 untersuchten Modellen wiesen nur drei Pkw einen Aluminiumanteil von über 100 kg auf. Ohne Berücksichtigung von Aluminiumfelgen lag der durchschnittliche Aluminiumanteil bei etwa 53 kg je Fahrzeug für das Jahr 1992. Unter Berücksichtigung der eingesetzten Aluminiumfelgen steigt dieser Wert um ca. 5 kg an. Nachfolgend werden diese Zahlen für die deutschen Automobilhersteller (Audi, BMW, Ford, Mercedes-Benz, Opel, Porsche und Volkswagen) für das Jahr 1996 aktualisiert.

2.1.1 Einsatzmengen bei den verschiedenen deutschen Pkw-Herstellern

Die Anzahl der produzierten Fahrzeuge wurde aus „Tatsachen und Zahlen aus der Kraftverkehrswirtschaft“ [5] entnommen. Alle deutschen Automobilproduzenten wurden angeschrieben. Für jedes Modell wurden die durchschnittlich eingebauten Gewichte der Aluminiumteile mit den jeweils hergestellten Stückzahlen multipliziert. Weiterhin lag als Information vor die Anzahl von Fahrzeugen, die serienmäßig ab Werk mit Alu-Felgen ausgestattet sind. Das durchschnittliche Gewicht eines kompletten Satzes lag dann bei ca. 30 kg je Fahrzeug. Der Prozentsatz der mit Alu-Felgen ausgestatteten Fahrzeuge schwankte je nach Hersteller und Modell zwischen 5% (Fiesta) und 100% bei allen Porschefahrzeugen.

Tabelle 2 zeigt die Produktionszahlen und die eingesetzte Menge an Aluminium (Herstellerangaben) der deutschen Pkw-Hersteller für das Jahr 1996.

Tabelle 2: Aluminiumeinsatz in Pkw der deutscher Hersteller

Hersteller	Fahrzeugproduktion 1996	Al-Gewicht je Fahrzeug (ohne Alu-Felgen) [kg]	Gesamt Al-Menge [Tonnen]	Gesamt Al-Menge incl. Al-Felgen (1) [Tonnen]
Audi	483.444	107	51.787	56.638
BMW	562.450	137	76.965	77.836
Ford	539.875	20	10.895	12.633
Mercedes-Benz	509.907	116	59.318	70.555
Opel	1.035.795	38	38.921	42.028
Volkswagen	2.209.059	26	31.857	35.378
Porsche	19.484	197	3.829	3.829
Gesamt	**4.360.914**	**69 (2)**	**273.572**	**298.897**

(1) berücksichtigt wurde die Anzahl von Fahrzeugen, die laut Hersteller mit Alu- Felgen ausgestattet sind

(2) incl. der vom Werk ausgelieferten Alu-Felgen

Sowohl die absolute als auch die relative Menge an im Pkw eingesetzten Aluminiums unterliegen einem großen Schwankungsbereich. Während bei einem Kleinwagen der Aluminiumanteil bei etwa 21 kg liegt (14% der deutschen Produktion), liegt er in der Mittelklasse schon bei 63 kg (83% der deutschen Produktion) und in der Oberklasse gar bei über 231 kg (3% der deutschen Produktion) je Fahrzeug (Spitzenreiter der A8 mit 558 kg Aluminium).

Für die einzelnen deutschen Hersteller ergibt sich folgender Anteil am Aluminiumeinsatz für die Pkw-Produktion.

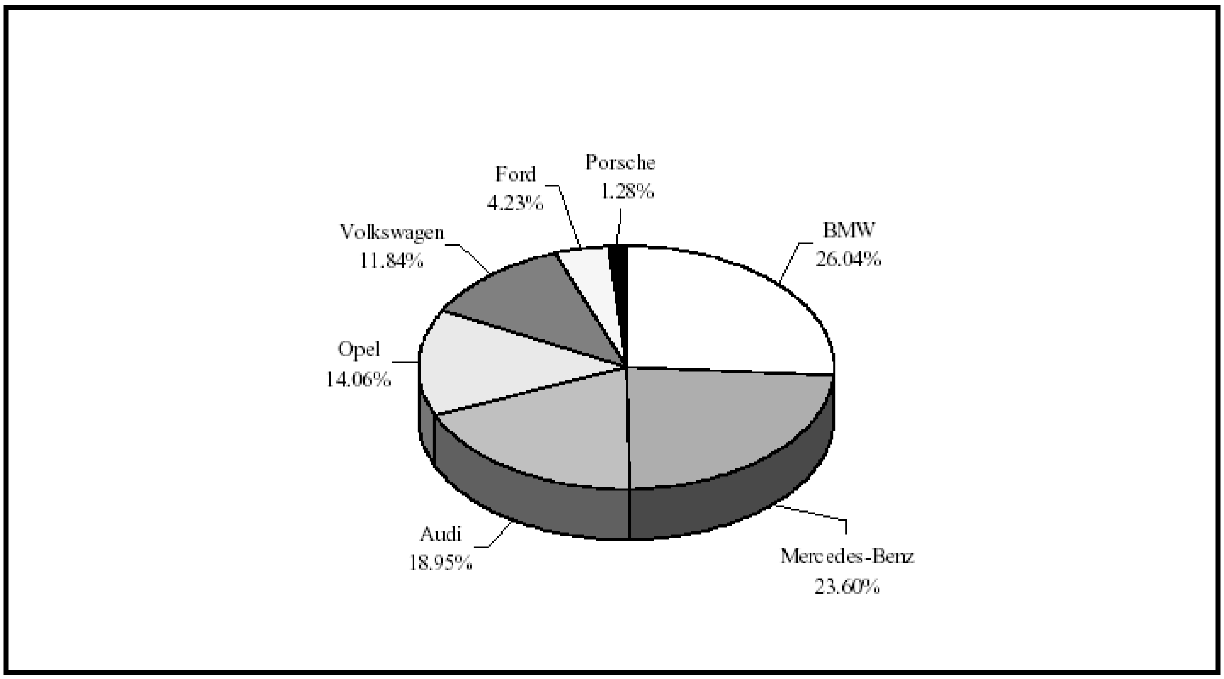

Abbildung 1: Einzelanteile deutscher Pkw-Hersteller an der Einsatzmenge von Aluminium

2.1.2 Entwicklungen des Aluminiumeinsatzes im Pkw

Der Trend zur weiter steigenden Aluminiumanteilen im Automobilbereich ist ungebrochen. Allerdings führt der erhöhte Einsatz des Leichtmetalls nicht zwangsweise zu leichteren Fahrzeugen. Im Gegenteil: Das eingesparte Gewicht wird beispielsweise durch zusätzliche Sicherheitsmaßnahmen (z.B. Airbag) und durch ergänzende Zusatzausrüstung (z.B. Klimaanlage) mehr als kompensiert.

Ein relativ neues Anwendungsgebiet von Aluminium im Fahrzeugbau ist die Anwendung von Aluminiumschäumen. Neben dem Leichtbau und der Energieabsorption wird die Porenstruktur zur akustischen Dämpfung und zur reduzierten Wärmeleitfähigkeit genutzt [6]. In einer Fahrzeugstudie wurden großflächige Leichtbauteile auf Aluminiumschaumbasis entwickelt. Die Steifigkeit der Bauteile konnte bei gleichzeitiger Gewichtsersparnis erhöht werden.

Von 1992 bis 1996 stieg der durchschnittliche Aluminiumanteil je Fahrzeug von 58 kg [4] auf fast 69 kg an [7]. Dies bedeutet eine Steigerung von fast 20% in vier Jahren. Und auch in der Zukunft rechnet die Aluminiumindustrie mit einer weiteren deutlichen Zunahme der Aluminiumeinsatzes. Für einen Pkw mit einem Gewicht von kleiner 1.000 kg wird ein Anteil von 12% Aluminium (120 kg) für das Jahr 2008 prognostiziert (siehe Abb. 2) [8].

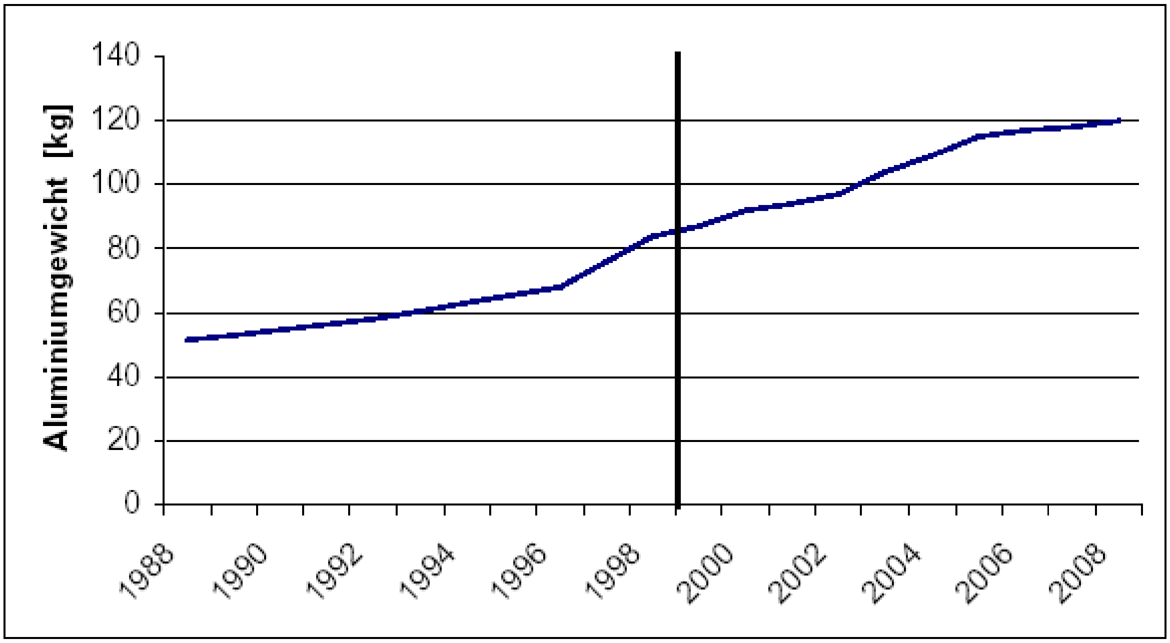

Abbildung 2: Bisherige Entwicklung und Prognose des Aluminiumeinsatzes im Pkw

2.2 Weitere Einsatzgebiete von Aluminium im Verkehr

Aufgrund der hohen Produktionszahlen ist der Pkw-Bereich der größte Abnehmer von Aluminium. Aber auch in allen anderen Bereichen des Verkehrswesens wird das Leichtmetall Aluminium verstärkt eingesetzt.

2.2.1 Nutzfahrzeuge

Steht bei den Pkw der Aspekt der Kraftstoffeinsparung im Vordergrund, so wird die Gewichtseinsparung bei Nutzfahrzeugen dazu genutzt, die Nutzlast zu erhöhen. So kann beispielsweise bei einem 40-Tonnen-Lkw durch Einsatz von Aluminium bei Motorteilen und Leichtbauweise der Aufbauten bis zu 1,5 Tonnen Eigengewicht eingespart werden. Das bedeutet zusätzliche Nutzlast, zusätzliche Einnahmen und Kraftstoffeinsparungen bei eventuellen Leerfahrten.

Die Einsatzmöglichkeiten von Aluminium in Motor und Fahrwerk entsprechen der Herstellung von Pkw. Für Nutzfahrzeuge mit einem zulässigen Gesamtgewicht von >7,5 Tonnen werden nachstehend aufgezählte kleinere Bauteile aus Aluminium gefertigt:

Luftbehälter, Reserveradaufzug, Fahrerhaus, Treibstofftank, Unterfahrschutz, Saugrohre, Ausgleichsbehälter und Federböcke.

Beträchtliche Gewichtseinsparungen sind durch Aufbauten aus Aluminium (Pritschenaufbau, Kofferaufbau, Ladebordwände, Tank- und Silofahrzeuge) zu realisieren. Aluminium hat etwa nur ein Drittel des Gewichts von Stahl, muß aber aus Steifigkeitsgründen stärker dimensioniert werden. Trotzdem beträgt die mögliche Gewichtsreduzierung noch ca. 50%. Maximal wird bei einem Tank- oder Silofahrzeug bis zu 2.500 kg Eigengewicht eingespart.

Die nachfolgende Tabelle 3 gibt eine Übersicht der eingesetzten Aluminiummengen in der deutschen Nutzfahrzeugproduktion. Die Werte resultieren aus Herstellerangaben bzw. wenn nicht möglich, aus eigenen Berechnungen.

Tabelle 3: Zusammenfassung des Aluminiumeinsatzes in der deutschen Nutzfahrzeugproduktion

Hersteller / Fahrzeugart	**Anzahl der Fahrzeuge**	**Aluminiummenge [Tonnen]**
Mercedes-Benz	163.297	12.316
MAN	27.617	4.415
IVECO-Magirus	10.401	1.820
VW (Nutzfahrzeuge)	122.640	5.231
Opel (Lieferwagen)	2.112	73
Omnibusse	10.353	1.833
Aufbauten	4.580	4.628
Gesamtsumme:	**341.000**	**30.316**

2.2.2 Schienenverkehr

Für U-Bahnen und bei der Bundesbahn wurden in den 60er Jahren geschweißte Wagenkästen gebaut. In den 70er Jahren wurde unter anderem durch die fortschreitenden Entwicklungen der automatisierten Schweißtechnik der Einsatz von Aluminium-Knetlegierungen und Strangpreßtechnik vorangetrieben. Mit maßgenauen und optimal gestalteten Profilen gelang es, die Produktionskosten von Aluminiumkästen so zu reduzieren, daß sie nicht teuer als herkömmliche Stahlkonstruktionen war. Heute werden spantenlose Wagenkästen gefertigt, die vollständig aus längsläufigen, doppelwandigen Aluminiumprofilen bestehen [3]. Der Anteil liegt bereits heute bei über 80%.

Der Schienengüterverkehr ist geprägt durch ein starkes Aufkommen an Warenladungsverkehr. Hier ist das Transportvolumen von größerer Wichtigkeit als die Tragkraft des Waggons. Daher beschränkt sich der Aluminiumeinsatz meist auf bewegliche Teile, welche die Bedienbarkeit erleichtern. Diese geringen Mengen wurden in dieser Untersuchung nicht berücksichtigt.

Die insgesamt ermittelte Menge an Aluminium für die Hersteller DUEWAG, Adtranz und Linke Hoffmann Busch (LHB) beträgt ca. 4.440 Tonnen.

2.2.3 Luftverkehr

Gewichtsreduzierung im Luftverkehr hat einen hohen Stellenwert. Zum einen wird Treibstoff gespart, zum anderen können entweder mehr Flugpassagiere befördert oder mehr Nutzlast transportiert werden. Betrachtet wurden nur Flugzeuge mit einem Maximum Take Off Weight

(MTOW) über 5,7 Tonnen. In dieser Größenordnung stellen die Deutsche Airbus (DASA) und die Dornier Luftfahrt GmbH Flugzeuge her. Auffällig in dieser Branche ist das Verhältnis von benötigter Masse der Halbzeuge zu tatsächlich eingebauter Aluminiummasse. Die Deutsche Airbus (DASA) verarbeitet pro Jahr ca. 10.000 Tonnen Aluminiumrohmaterial. Bei der Fertigung fallen bis zu 80% Produktionsschrott (Abfälle bei der Herstellung von Frästeilen) an, die allerdings unmittelbar in den Sekundärkreislauf gelangen und wiederverwertet werden.

Als ein Beispiel der Airbus-Flugzeugfamilie sei der Airbus A 320-200 aufgeführt. Von den 41 Tonnen Betriebsleergewicht beträgt der Bauanteil für die Deutsche Airbus 13 Tonnen. Der Aluminiumanteil hiervon liegt bei 4,6 Tonnen. Bei den betrachteten Flugzeugen von Dornier wurde der Aluminiumanteil mit 55 % des Gewichts angegeben. Aufgrund der geringen Stückzahl wurden nur 250 Tonnen Aluminium verarbeitet. Beide Firmen zusammen kommen auf 10.250 Tonnen verarbeiteten Aluminiums.

2.2.4 Zweiräder

In Deutschland wurden 1996 vom Mofa mit 50 ccm bis hin zum Motorrad mit 1.200 ccm Hubraum rund 65.000 Zweiräder produziert. Zur Abschätzung wurde für die Mofas ein Aluminiumanteil von 2-3 kg, für Motorroller 5-15 kg und für Motorräder bis max. 20 kg angenommen. Über alle produzierten Zweiräder (je 10 kg) ergibt sich eine Gesamtmasse von 650 Tonnen Aluminium.

1996 wurden in Deutschland ca. 2,6 Millionen Fahrräder hergestellt. Der weitaus größte Teil besitzt einen konventionellen Stahlrohrrahmen. Nur ca. 10% der deutschen Produktion sind mit einem Aluminiumrahmen ausgestattet. Bei den Felgen liegt der Aluminiumanteil doch bei ca. 95%. Unter Berücksichtigung eines Felgengewichts von 0,55 kg und einem Aluminiumanteil von 5 kg bei einem Alu-Fahrrad errechnet sich die Gesamtsumme auf etwa 3.730 Tonnen Aluminium für die Fahrradindustrie.

Für den komplette Zweiradmarkt ergibt sich ein Leichtmetalleinsatz von ca. 4.380 Tonnen.

2.2.5 Container und Frachtpaletten

Bis auf wenige Ausnahmen beschränkt sich die Anwendung von Aluminium im Containerbau auf den Luftverkehr. Neben ihrem geringen Gewicht haben sie die Aufgabe, das Frachtgut vor Beschädigung zu schützen. Ein durchschnittlicher Container für die Luftfracht wiegt etwa 85 kg und hat ein Volumen von ca. 4 m^3.
Anstelle von Holz (für den normalen Güterfernverkehr) nutzt man im Flugverkehr eine Palettenkostruktion aus Aluminium. Bei einem Eigengewicht von etwa 100 kg können sie Lasten bis zu 7 Tonnen aufnehmen.

Die Abnahmemenge von Aluminium für Container und Frachtpaletten ergibt für die beiden betrachteten Hersteller 3.000 Tonnen für das Jahr 1996.

2.2.6 Schiffsbau und Sonderfahrzeuge

Auch im Schiffsbau nimmt die Bedeutung von Aluminium als Konstruktionswerkstoff ständig zu. Bei See- und Binnenschiffen werden Lukendeckel, Handläufe, Relings, Fallreeps, Begehplanken, mobile Laderaumunterteilungen sowie Kühlraumauskleidungen, Schwimmfähige Rampen, Leitern und Landstege bevorzugt aus Aluminiumwerkstoffen gefertigt. Aufgrund der aggressiven Seeatmosphäre sind nur geeignete Legierungen zugelassen. Überwiegend werden Bleche und Profile aus AlMg4,5Mn und AlMgSi0,7 verarbeitet. Bei „schnellen Fähren" (Geschwindigkeiten bis zu 45 kn.), die sowohl Passagiere als auch Pkw und Lkw transportieren, können bis zu 1.300 Tonnen Aluminium verarbeitet werden.

Die eingesetzte Aluminiummenge für die Produktion in Deutschland kann nur abgeschätzt werden. Für den Bereich Schiff- und Bootsbau werden ca. 7.000 Tonnen, für Sonderfahrzeuge sonstige Transportmittel etwa 10.000 Tonnen je Jahr angenommen.

Tabelle 4 zeigt zusammenfassend eine Übersicht, wie sich die Aluminiummenge im Verkehrssektor nach Verkehrszweigen aufteilt.

Tabelle 4: Verteilung der Aluminiumeinsatzmengen in den verschiedenen Verkehrszweigen

Verkehrssektor	Aluminiummenge [Tonnen] (1)	Anteil [%]	Durchschnittliche Lebensdauer
Pkw	343.734	82	15
Nutzfahrzeuge	35.770	8,5	20
Schienenverkehr	4.400	1	30-35
Luftverkehr	10.250	2,5	30
Zweiräder	5.038	1,2	7
Container, Frachtpaletten	3.000	0,7	6
Schiffbau (2)	7.000	1,7	k.A. (3)
Sonderfahrzeuge (2)	10.000	2,4	k.A.
Gesamtsumme	**419.192**	**100**	

(1) Werte einschließlich des abgeschätzten produktionstechnischen Mehrbedarfs (ca. 15%)
(2) Werte aus: Aluminium im Verkehr [9]
(3) keine Angaben

3 Ausblick

Die Aluminiumindustrie rechnet für die Zukunft mit einer weiter anhaltenden Zunahme von Aluminiumerzeugnissen sowohl auf dem nationalen als auch internationalen Markt. Hierzu wird neben dem Bausektor der Verkehrssektor und vor allem der Pkw-Bereich maßgeblich beitragen.

Der Anteil an Aluminiumgußteilen im Automobilbereich liegt zur Zeit in der Größenordnung von etwa 80% der Gesamtaluminiummenge [3].

Wenn sich jedoch die Space-Frame-Technologie, mittlerweile auch bei anderen Herstellern eingesetzt, durchsetzen würde, wäre der zusätzliche Bedarf an Aluminium enorm.

Mögliches Szenario für das Jahr 2008:

- 25% der in Deutschland produzierten Pkw werden mit einer Space-Frame-Karosserie gebaut (1 von 4 Millionen gebauten Einheiten)
- Der Aluminiumanteil dieser Fahrzeuge am Gesamtgewicht entspricht dem Verhältnis des Audi A8 (ca. 33%)
- Das Gesamtgewicht eines durchschnittlichen Pkw beträgt 1.000 kg
- Der durchschnittliche Aluminiumgehalt aller Fahrzeuge liegt bei 120 kg/Pkw [8]

Der Aluminiumbedarf für die Produktion von Pkw würde auf fast 700.00 Tonnen erhöhen!

Interessant ist auch eine andere Sichtweise für den Leichtmetalleinsatz. Bei einem Benzinpreis von 1,50 DM/l darf jedes eingesparte Kilogramm am Fahrzeug etwa 3,25 DM kosten. Wenn das Auto deutlich leichter wird, könnte eventuell auf die Servolenkung verzichtet werden. Ein Teil dieser Einsparung kann wieder in den aufwendigen Leichtbau investiert werden.

Sicherheit hat sowohl im Straßen- wie auch im Schienenverkehr eine hohe Priorität. Aluminiumprofilwerkstoffe ermöglichen eine hohe Absorption von kinetischer Energie. Neue Werkstoffe verbinden ausgezeichnete Schweißbarkeit mit guter Duktilität und ausreichender Festigkeit. Dies waren Ergebnisse der Alusuisse mit runden und rechteckigen Rohren [10].

Neben Aluminium finden aber auch neue Fe-Legierungen und andere Leichtmetalle Einzug in die Konstruktionen der Verkehrssparte. Die Firma Thyssen arbeitet an einem „Noppenblech“ welches aus drei Schichten besteht. Kleine Vertiefungen in einem 0.35mm dickem Blech führen zu einer Versteifung der Konstruktion. Dieses Blech ist nicht nur leichter als Aluminium sondern mit einem Preis von 4 DM/kg auch noch preiswerter als Aluminiumblech (7 DM/kg) [11].

Das Metall Magnesium, bereits 1934 erstmals bei Komponenten des luftgekühlten Motors des Käfers eingesetzt, stellt sich auf einigen Gebieten als Konkurrent für Aluminium auf dem Markt. Seit 1990 ist ein starker Anstieg in der Primärerzeugung von Magnesium zu verzeichnen. Die Automobilindustrie hat sich zum Ziel gesetzt, bis zum Jahr 2008 den Einsatz von Magnesium um jährlich 15% zu steigern [12].

4 Zusammenfassung

Mit einem Gesamtgebrauch von mehr als 2,5 Millionen Tonnen im Jahr 1997 ist die Deutschland mit Abstand das Land mit der größten Aluminiumnutzung in Europa. Der größte Abnehmer von Aluminiumprodukten ist der Verkehrssektor.

In dieser Arbeit wird ein quantitativer Überblick über die im gesamten Verkehrssektor verarbeitete Aluminiummenge gegeben, welche über die für die Pkw-Produktion benötigte Menge hinausgeht.

Ca. 420.000 Tonnen je Jahr werden dort eingesetzt. Der Anteil an Aluminiumgußprodukten liegt bei etwa 320.000 Tonnen. Mit einer Produktion von 4,36 Millionen Fahrzeugen im Jahr 1996 fließt erwartungsgemäß der größte Teil in den Pkw- Bereich (82%). Weitere 9% finden Einsatz im Nutzfahrzeugbau. Die restlichen 9% teilen sich der Schienen-, Schiffs- und Luftverkehr, die Produktion von Zweiräder, Containern und Frachtpaletten sowie die Sonderfahrzeuge.

Den Prognosen der Aluminiumindustrie nach wird sich der Trend nach einem erhöhten Bedarf an Aluminium noch verstärken. Ein mögliches Szenario für das Jahr 2008, in dem ein viertel der produzierten Pkw mit einer Aluminiumkarosserie hergestellt wird, läßt den Aluminiumbedarf auf fast die Doppelte Menge gegenüber heute ansteigen.

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ALUMINIUMRÜCKFÜHRUNG AUS DEM AUTOMOBILBEREICH*

(RECYCLING OF ALUMINIUM FROM CARS)

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ABSTRACT
The transport sector is the largest user of aluminium products in Germany. With 90% of its aluminium being recycled, it is also the largest provider of secondary aluminium. Faced with increasing environmental problems incurred by the recycling of used cars, the German legislation has issued the "Altauto-Verordnung" on April 1st, 1998. This has already produced effects on the recovery of secondary aluminium. The legislative powers do therefore redefine the respective roles played by various organisations and bureaus. Consequently, this will produce new structures and routes of transports. By way of example, these changes are being analysed for the aluminium sector.

KEYWORDS
Aluminium, Vehicles, Used Cars, Transport, Recycling

* Source: Erzmetall 52 (1999), Nr. 10, S. 533-540

1. Die Altautoverordnung

Auf bundesdeutschen Straßen sind derzeit mehr als 40 Millionen PKW unterwegs bei steigender Tendenz. Auch die Anzahl der Neuzulassungen und Löschungen von PKW nehmen von Jahr zu Jahr zu. Im Jahr 1997 wurden 3,53 Millionen PKW neu zugelassen und 3,18 Millionen PKW abgemeldet. Angesichts dieser stetig steigenden Zahlen von PKW und den daraus resultierenden Umweltproblemen wird deutlich, daß eine geordnete und umweltgerechte Altautoverwertung zunehmend an Bedeutung gewinnt. Seit dem 01.04.1998 ist die Altauto-Verordnung eingeführt. Diese hatte weitreichende Konsequenzen für die beteiligten Instanzen im Altautorecycling.

1.1 Die Altautoverordnung: Anforderungen und Auswirkungen

Schon frühzeitig hat die Industrie erkannt, daß in Altautos eine Reihe von wertvollen Sekundärrohstoffen enthalten sind, deren Recycling nicht nur aus ökologischer sondern auch aus ökonomischer Sicht sinnvoll ist. Damit war der Grundstein für ein markenübergreifendes Altautorecycling gelegt, das durch folgende drei Instanzen geprägt war:

- Altautoverwerter
- Schrotthändler
- Shredderbetriebe

Im Laufe der Zeit haben sich diese drei Instanzen zu einem, aus wirtschaftlicher Sicht, funktionierenden System zusammengefunden, was die große Anzahl der im Umfeld des Altautorecyclings tätigen Betrieben (rund 5.000) eindrucksvoll dokumentiert [1]. Die in den 60er Jahren entwickelte Technik ist jedoch nur auf die Rückgewinnung metallischer Bestandteile aus dem komplexen Konsumgut Automobil ausgerichtet. Die nichtmetallischen Werkstoffe wie Kunststoffe, Gummi, Glas, Textilien und Lack fallen nach dem Shredderprozeß als Shreddermüll an und werden fast ausnahmslos deponiert. Durch den immer weiter ansteigenden Anteil der nichtmetallischen Werkstoffe, besonders der Kunststoffe, im Automobil erwies sich die gängige Entsorgungspraxis unter ökologischen Gesichtspunkten als problematisch.

Diese zunehmenden Umweltprobleme bei der Altautoverwertung und -entsorgung führten sowohl bei der Automobilindustrie, wie auch auf Seiten der Politik und der beteiligten Wirtschaftszweige und Verbände dazu, daß etablierte System des Altautorecyclings zu überdenken. Im folgenden werden die wichtigsten Gründe für die Einführung einer neugeregelten Altautoverwertung aufgezählt [2].

- Altautos enthalten einen hohen Anteil an wiederverwendbaren Bauteilen und wiederverwertbaren Werkstoffen, die als Wirtschaftsgüter eingestuft werden.
- Der zunehmende Einsatz von Kunststoffen im Automobil bedingt ein Anwachsen der Shredderleichtgutfraktion, die deponiert werden muß.
- Durch die Erhöhung der Recyclingquoten wird weniger Deponieraum in Anspruch genommen.
- Recycling trägt dazu bei, daß der Bedarf an Primärmaterial zurückgeht und damit gleichzeitig Energie für deren Herstellung eingespart wird.
- Durch funktionierende Materialkreisläufe verringert sich die Importabhängigkeit der Verarbeitungsländer (Rohstoffautarkie).

- Der Verbleib von Betriebsflüssigkeiten in der Altkarosserie hat beim Shreddern die Folge, daß die Sekundärmaterialien verunreinigt werden und somit ihre Qualität abnimmt (Downcycling).

Nachdem durch die Wirtschaftsverbände 1996 der erste Schritt zu einer Neuordnung der Altautoverwertung in einer Freiwilligen Selbstverpflichtung (FSV) gemacht wurde, folgte die Bundesregierung Mitte 1997 mit der „Verordnung über die Entsorgung von Altautos und die Anpassung straßenverkehrsrechtlicher Vorschriften". Stichtag für das Inkrafttreten der AltautoV und damit auch zugleich der FSV war der 01.04.1998.

Das Ziel der AltautoV ist es, die FSV durch einen ordnungsrechtlichen Rahmen zu ergänzen, um so die ökologische Neuausrichtung der Altautoverwertung zu regeln. Von besonderer Bedeutung oder gar notwendiger Voraussetzung ist dabei, daß die neuen Rücknahme- und Verwertungsstrukturen auch tatsächlich genutzt werden. Darüber hinaus werden einheitliche Anforderungen an die beteiligten Betriebe aus abfallwirtschaftlicher Sicht normiert, die damit gleichwertige Wettbewerbsbedingungen schaffen.

Der neue Altautostoffstrom wird in Abbildung 1 dargestellt. Zu den beteiligten Instanzen zählen auch in Zukunft die Shredder- und Verwerterbetriebe, nicht mehr am Altautorecycling beteiligt ist aber der klassische Schrotthändler. Ergänzt wird die neue Struktur durch zertifizierte Annahmestellen, die unabhängig von einer einzelnen Marke/Fabrikat die Altautos annehmen und an Verwerterbetriebe weiterleiten.

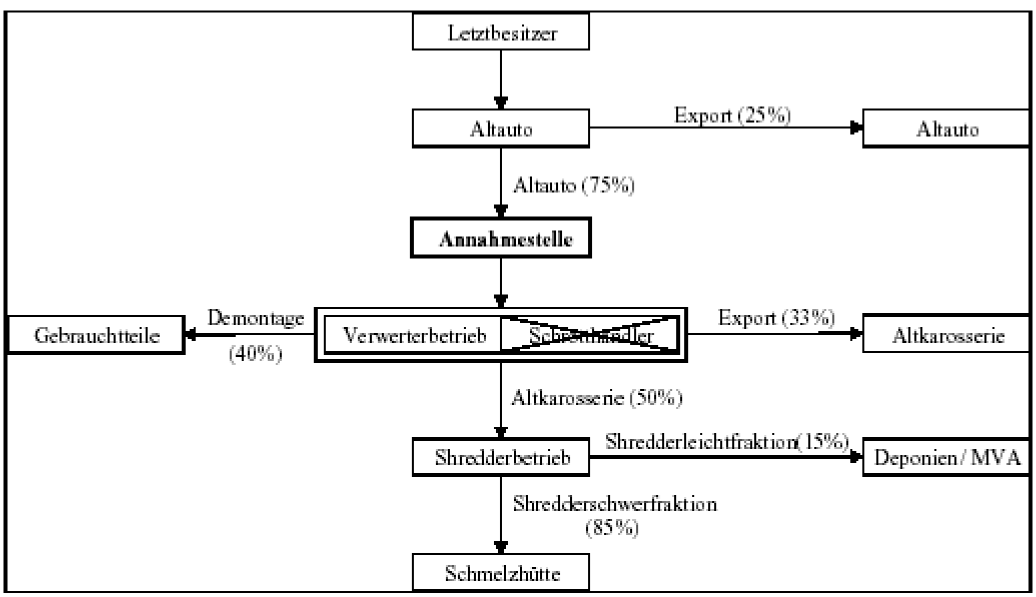


Abbildung 1: Struktur der Aluminiumrückführung aus dem Automobilbereich nach der AltautoV

1.2 Veränderungen und Probleme durch das Inkrafttreten der AltautoV / FSV

Durch die neu geschaffene Struktur der Altautoverwertung wird zum einen dazu beigetragen, daß der gesamte Ablauf der Verwertung infolge der rechtlichen Regelung transparenter wird. Zum anderen werden durch die einheitlichen Anforderungen an Altautoverwertungsbetriebe gleichwertige Wettbewerbsbedingungen und definierte Umweltstandards geschaffen.

Ein Jahr nach Inkrafttreten der AltautoV wird aber deutlich, daß deren Zielsetzung in einigen Punkten nicht erreicht wird. Die bedeutensten Schwachstellen sind:

- Die Zertifizierung der beteiligten Instanzen
- Die Überwachung der Betriebe seitens der Behörden
- Der unkontrollierte Exportstrom

Grundsätzlich sollten durch die **Zertifizierung** der drei beteiligten Instanzen nur solche Betriebe an der Altautoverwertung teilnehmen, die den Gedanken der Kreislaufwirtschaft ernst nehmen, um somit eine technisch und ökologisch ausgewogene Altautoverwertung mit gleichen / allgemeingültigen Standards zu schaffen. Neben der umweltpolitischen Zielsetzung verfolgte der Gesetzgeber auch die Sicherstellung des Wettbewerbs im Bereich der Entsorgungswirtschaft und Monopolisierungstendenzen zu verhindern [3].

Doch in der Praxis sind Defizite bei der Zertifizierung festzustellen. Von den über 800 zertifizierten Altautoverwertern haben ca. 400 Verwerter im Sinne des Gesetzgebers ihr Zertifikat erhalten. Die andere Hälfte der Verwerter ist zwar zertifiziert worden, erfüllt aber nicht die geforderten Auflagen vollständig. Darüber hinaus sind noch rund 500 weitere Verwerter am Markt tätig die nicht zertifiziert sind [4]. Somit ergibt sich eine Gesamtzahl von ca. 1300 Verwertern, von denen nur 1/3 die gesetzlichen Umweltstandards erfüllen. Damit kann weder von einem einheitlichen Umweltstandard noch von gleichwertigen Wettbewerbsbedingungen gesprochen werden.

Expertenmeinungen zufolge liegt das daran, daß es der Gesetzgeber versäumt hat, Vorgaben zu machen, wie die Zertifizierung erfolgen soll. Dadurch entstehen Freiräume/Spielräume für den Gutachter. Zudem kann einem einmal zugelassenen Gutachter die Akkreditierung nicht mehr entzogen werden.

Neben dieser Problematik treten auch **Schwierigkeiten in der Zusammenarbeit** zwischen den Instanzen auf. Vermehrt kommen Hinweise von Verwerterbetrieben, daß die Annahmestellen ihrerseits gut erhaltene Ersatzteile bereits ausgebaut haben. Dies ist zum einen nach der AltautoV nicht zulässig, zum anderen wird dadurch den Verwerterbetrieben ein wichtiger Geschäftszweig beschnitten. Aber auch die Verwerterbetriebe kommen ihrer gesetzlichen Pflicht zur Trockenlegung der Altautos nicht immer nach. So wurde vereinzelt schon von Shredderbetrieben berichtet, die Altkarosserien geshreddert haben, bei denen die Betriebsflüssigkeiten noch nicht abgelassen wurden.

Allgemein wird von der Verwertungsindustrie moniert, daß eine wiederkehrende betriebliche Überwachung seitens der Behörden nicht gegeben ist. Da ein wirkungsvolles Einschreiten der Behörden auch nicht zu erkennen ist, ergeben sich daher Vollzugsdefizite.

Ein prinzipielles Problem der Altautoverwertung in Deutschland hängt mit dem **Export** von Altautos und Altkarosserien zusammen. Die AltautoV / FSV erhebt keinen Anspruch darauf, daß Altautos in der Bundesrepublik Deutschland verbleiben müssen. Der bestehende Exportstrom von Altautos wird also nicht gezielt gebremst. Festzuhalten ist aber, daß durch das Inkrafttreten der AltautoV am 01.04.1998 kein sprunghafter Anstieg des Exportes von Altautos zu erkennen ist. Allerdings ist die steigende Tendenz bei Exporten ungebrochen. Eine prognostizierte Trendwende für Ende 1999 läßt sich nicht auf eine Verbesserung der Situation in Deutschland zurückführen, sondern ist der restriktiven Einfuhrpolitik in den östlichen Nachbarstaaten zuzuschreiben. Durch sogenannte „Scheinverkäufe“ von Altautos ins Ausland werden der heimischen Verwerterindustrie ca. 25% der anfallenden Altautos pro Jahr entzogen. Dabei handelt es sich noch nicht einmal um einen illegalen Vorgang, sondern es hängt vielmehr damit zusammen, daß vielfach Altautos in Deutschland stillgelegt werden müssen, die aber in anderen Ländern noch problemlos einige Jahre betrieben werden können.

Gegenüber der Zulassungsstelle muß der Verkäufer nur eine Verbleibserklärung vorlegen. Wenn sich darin die Adresse eines Käufers in Osteuropa oder in Nahost wiederfindet, so hat die Behörde kaum Möglichkeit den Verkauf des Fahrzeugs auf seine Ordnungsmäßigkeit / Rechtmäßigkeit zu überprüfen. Was mit dem Fahrzeug dann weiter geschieht, ob es tatsächlich noch eingesetzt wird oder ob es als rollendes Ersatzteillager dient, entzieht sich der Kenntnis der deutschen Behörden.

Ein weiterer Exportstrom ist der von Altkarosserien. Nachdem sie bei Verwerterbetrieben demontiert wurden, werden sie nicht nur an Shredderbetriebe im Inland weitergeleitet, sondern auch an solche im benachbarten Ausland. Dabei ist zu beachten, daß mittlerweile 1/3 der zertifizierten Shredder im Ausland zu finden sind. Über den Verbleib der Shredderendprodukte aus ausländischen Shredderbetrieben ist nichts bekannt. Es ist aber zu erwarten, daß zum einen die rückgewonnene Schwerfraktion (Metalle, NE-Metalle) sowie die problematische Leichtfraktion in den einzelnen Ländern verbleibt. Gerade für die Leichtfraktion bietet sich ein Verbleib im Ausland besonders an, weil die Zuordnungswerte für die Ablagerung der Leichtfraktion auf Deponien in keinem anderen Land wie in Deutschland so hohen Anforderungen genügen muß.

Somit gehen auf diesem Wege ebenfalls ca. 25% der anfallenden Altautos bzw. Autowracks der inländischen Shredderindustrie verloren. Von den ca. 3 Millionen Altautos die Jahr für Jahr zur Verwertung anstehen, bleiben also effektiv nur ca. 2,25 Millionen Altautos bzw. 1,5 Millionen Altkarosserien im Inland. Dies bedeutet erhebliche finanzielle Einbußen der beteiligten Instanzen.

2 Das Sekundäraluminiumpotential im Automobilbereich

Angesichts der zuvor beschrieben Exportströme gehen der heimischen Industrie ein Großteil des Potentials an Sekundärrohstoffen verloren. Aus der Sicht des Rohstoffs Aluminium läßt sich für das Jahr 1997 folgende Mengenbilanz für Deutschland aufstellen.

Bei einer durchschnittlichen Lebensdauer von 12 Jahren stehen 1997 Altautos des Jahres 1985 zur Entsorgung an. 1985 betrug der durchschnittliche Aluminiumanteil in einem PKW ca. 47,5 kg [5]. Bei ca. 3,18 Millionen Altautos, die 1997 anfielen, beläuft sich das theoretische Sekundäraluminiumpotential auf 151.000 t.

Aufgrund des Exportes von 25% der Altautos werden dem nationalen Kreislauf ca. 38.000 t Sekundäraluminium entzogen. Es handelt sich dabei um Altautos die in Deutschland nicht verwertet wurden. Damit steht der Sekundärindustrie nur noch ein theoretisches Potential von 113.000 t Aluminium zur Verfügung. Durch die Demontage von Gebrauchtteilen beim Verwerter verringert sich das Sekundäraluminiumpotential nochmals um ca. 31 Gewichtsprozent.

Der zweite Exportstrom von Altkarosserien verringert zusätzlich das Sekundäraluminiumpotential. Auf diesem Wege gehen ca. 0,8 Mio. Einheiten dem Kreislauf in Deutschland verloren. Demnach kann die Sekundäraluminiumindustrie nur noch auf ein theoretisches Potential von ca. 52.000 t zurückgreifen. Abzüglich der Verfahrensverluste beim Shreddern von ca. 15% verbleiben dann nur noch ca. 44.000 t. Insgesamt ist damit das direkte Sekundäraluminiumpotential auf 29% zusammengeschrumpft. In Abbildung 2 ist die Abnahme des Sekundäraluminiumpotential über die einzelnen Stufen zusammenfassend dargestellt. Dabei darf aber nicht außer acht gelassen werden, daß sowohl die Exportströme als auch die demontierten Bauteile dem Sekundärkreislauf nicht verloren gehen. Denn dies bedeutet überwiegend nur eine geographische oder zeitliche Verschiebung des Recyclings. Bezüglich der AltautoV ist aber festzustellen, daß eine nationale Regelung in Anbetracht der Exporte zu kurz greift und bei einer Festlegung von Recyclingquoten sämtliche Abflüsse und deren Verbleib zu berücksichtigen wären.

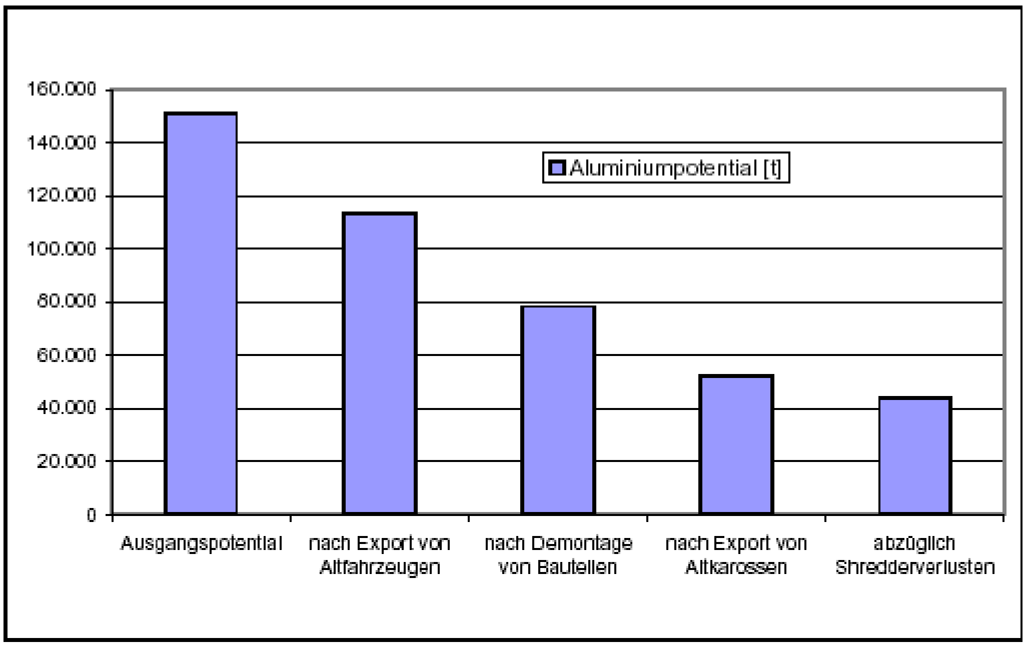


Abbildung 2: Sekundäraluminiumpotential aus dem Automobilbereich innerhalb Deutschlands

3 Die Transportaufwendung für die Aluminiumrückführung

Nachdem die Auswirkungen und Probleme der Altautoverordnung geschildert wurden und der direkte Mengenstrom des Sekundäraluminiums aus dem Automobilbereich aufgestellt worden ist, soll nun eine Abschätzung des Transportaufwandes entlang dieser Kette erfolgen. Der Gesetzgeber hat der Industrie die Vorgabe gemacht ein flächendeckendes Rücknahme nd Verwertungssystem für Altautos und –teile aufzubauen. Am Beispiel der Aluminiumrückführung soll dies geprüft werden. Zusätzlich soll geklärt werden, ob unter ökologischen Gesichtspunkten der Transport von Sekundäraluminium über die zurückzulegenden Entfernungen noch sinnvoll ist.

3.1 Methodik

Betrachtet man Transportaufwendungen für die Aluminiumrückführung im Altauto, so muß nicht nur eine technische, sondern auch eine räumliche Analyse des Sammelsystems erfolgen. Die Transportkette wird hierzu in ihre einzelnen Stufen und Schritte gegliedert und es erfolgt eine Analyse der einzelnen Transportvorgänge. Bei den Transportvorgängen wird nicht nur die eingesetzte Technik (das Transportmittel), sondern auch die Raumänderung und die zu bewegende Transporteinheit betrachtet. Die zu betrachtenden Elemente der Transportorganisation sind damit: Transportmittel / Transporteinheit / Transportweg. Für jeden Transportvorgang müssen die relevanten Daten (**Tabelle:** 1) zu diesen Elementen erhoben werden. Ein Sonderfall ist hierbei die Entfernung, da diese aus den erhobenen Daten erst noch bestimmt werden muß.

Tabelle 1: Elemente der Transportorganisation

Transportmittel		Transporteinheit		Transportweg	
Kriterien	**Ausprägung**	**Kriterien**	**Ausprägung**	**Kriterien**	**Ausprägung**
Technik	Art, Alter, Nutzlast	Aufgabe	Sammlung, Strecken-transport	Verkehrs-situation	Autobahn, Landstraße, Ortsverkehr, ...
Betriebsweise	Auslastung, Verkehrssituation Entfernung	Behälter-technik	Art, Gewicht, Volumen	Entfernung	Anzahl der Standorte, Einzugsgebiet, Relationsbestimmung
Energie Emissionen	Dieselverbrauch, CO2, CO, NOx, SO2, ...	Zusammen-setzung	Aluminium-anteil, Fraktionen		

Eine Entfernungsermittlung beruht grundsätzlich auf einer Distanzbestimmung zwischen zwei Standorten. Da bei Sammelsystemen aber immer eine Vielzahl von Standorten vorliegt, ist eine direkte Entfernungsermittlung nicht immer praktikabel. Hier bietet es sich an Ersatzstandorte zu bilden, indem mehrere Standorte in einer Teilfläche des Bilanzraums zu einem Ersatzstandort zusammgefasst werden, der als Zentrum der Teilfläche definiert wird. In Abhängigkeit von der Festlegung der Standortposition und des Einzugsgebietes kommen dann verschiedene Verfahren zur Ermittlung der durchschnittlichen Entfernung zur Anwendung, diese reichen von der direkten Routenplanung über repräsentative Beispiele bis zur Clusterung und mathematischen Verteilungsberechnung.

3.2 Die Aluminiumrückführung

Für die Auswertungen stehen sowohl die Standorte von zertifizierten Annahmestellen, Verwerten und Shreddern als auch die für Schrottaluminium in Frage kommenden Schmelzhütten zur Verfügung. Wegen der großen Anzahl von Annahmestellen (> 6000) und Verwerter (> 800) beschränkt sich die Analyse der Rückführung auf das Verwerternetz einer ausgewählten Automobilfirma. Diese verfügt über ein ausgewogenes Verhältnis zwischen eigenen zertifizierten Verwerterbetrieben und ihrem Marktanteil. Abbildung 3 zeigt die einzelnen Transportschritte der Aluminiumfraktion vom Letztbesitzer bis zur Sekundärschmelzhütte.

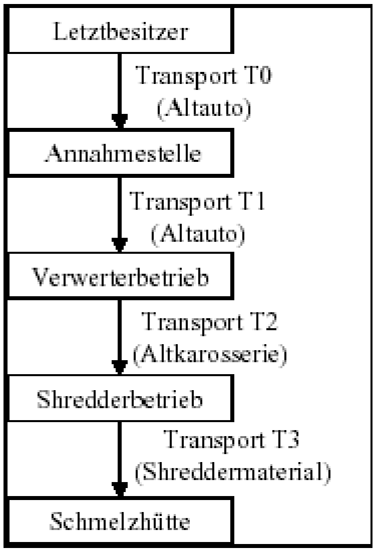


Abbildung 3: Transportkette Altauto

Transportmittel und -einheit

Für die Transporte zwischen den einzelnen Instanzen werden ausschließlich Lkw mit einem zulässigen Gesamtgewicht von 40 t eingesetzt. Allerdings unterscheiden sich die Transportmittel bei ihren Aufbauten und der zu transportierenden Einheit.

Auf dem Transportweg 1 wird ausschließlich ein Autotransporter eingesetzt, der die rollfähigen und nichtdemontierten Altautos transportiert. Wegen der äußeren Abmessungen von Pkw ist die Ladekapazität auf einem Autotransporter auf max. 10 Altautos begrenzt. Bei einem Gewicht von 1000 kg pro Fahrzeug ergibt sich eine Gesamtzuladung von 10 t, was einer gewichtsmäßigen Auslastung des Lkw von 40% entspricht.

Auf dem Transportweg 2 werden teildemontierte und gepreßte Karosserien, mit einen Gewicht von 575 kg pro Stück, befördert. Die äußeren Abmessungen dieser gepreßten Altkarosserien lassen es zu, daß die max. Zuladungen von 25 t für Lkw voll ausgenutzt wird. Somit lassen sich in der Praxis bis zu 43 Altkarosserien auf einem Lkw transportieren [6]. Für das Shreddermaterial, vergleichbar mit Schüttgütern, das auf dem Transportweg 3 transportiert wird, kann ebenfalls die max. Zuladung von 25 t für einen Lkw angesetzt werden. Eine Übersicht über die einzelnen Transporte gibt die nachstehende Tabelle 3. Die notwendigen Kraftstoffverbräuche für die Lkw mit einem zulässigen Gesamtgewicht von 40 t (25 t Nutzlast) sind Tabelle 3 zu entnehmen.

Transportwege

Die zurückzulegenden Entfernungen zwischen den vier beteiligten Instanzen werden durch die jeweiligen Transportwege 0 – 3 berücksichtigt. Der Transportweg 0 (T0) wird nicht weiter betrachtet, weil der Letztbesitzer in der Regel sein Altauto bei einer Annahmestelle oder einem Verwerter selbst abgibt. Die Summe der Transportentfernungen aus den drei verbleibenden Transportschritten werden in der nachfolgenden Abbildung nach Bundesländern geordnet dargestellt

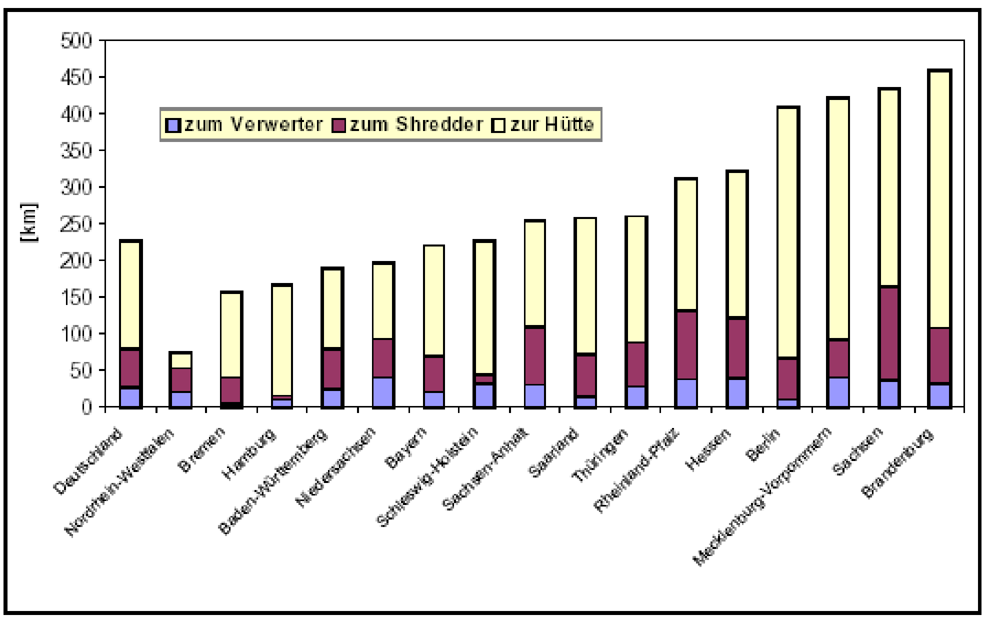
Tabelle 2: Definition der Transportwege T1, T2 und T3

Transport-Weg	Güterart	Transport-gewicht	Transportmittel	Anzahl der Transporteinheiten	Transportgewicht
T1	rollfähige / nichtdemontierte Altautos	1000 kg	Autotransporter	Max. 10	Max. 10 t
T2	teildemontierte / gepreßte Altkarosserien	575 kg	Lkw	Max. 43	Max. 25 t
T3	Shreddermaterial (Schüttgüter)	-	Lkw	-	Max. 25 t

Tabelle 3: Kraftstoffverbrauch der Lkw in Abhängigkeit der Auslastung [7]

Transport	Auslastung	Kraftstoffverbrauch
T1	40%	29 l / 100km
T2 / T3	100%	35 l / 100km

Abbildung 4: Transportentfernungen für T1, T2 und T3 in [km]



Anhand der Abbildung wird deutlich, daß sehr große Unterschiede bei den Transportentfernungen (Faktor 6) bestehen. Die mit Abstand geringsten Entfernungen finden sich in Nordrhein-Westfalen. Dort müssen insgesamt nur 75 km zurückgelegt werden bis das Schrottaluminium zur Schmelzhütte gelangt. Dagegen liegen die Transportentfernungen in Berlin, Mecklenburg-Vorpommern, Sachsen und Brandenburg fast doppelt so hoch wie im bundesdeutschen Durchschnitt, der bei 227 km liegt. Für die Transportschritte T1 und T2 ist aufgrund der durchschnittlichen Entfernung von unter 100 km ein flächendeckendes Rücknahme- und Verwertungssystem gegeben.

3.3 Transportaufwendungen für den Transport von Schrottaluminium aus Altautos

Anhand der zuvor ermittelten Transportentfernungen sowie der Anzahl der Transporteinheiten läßt sich der Kraftstoffverbrauch, als Beispiel für die Energieaufwendungen, für den Transport von 1t Schrottaluminium, von der Annahmestelle bis zur Schmelzhütte, ermitteln. Die Bilanzierung des Kraftstoffverbrauchs bezieht sich dabei auf die bei der Schmelzhütte eingetroffene Menge an Schrottaluminium, wobei über die Transportkette selbstverständlich nur die verfahrensbedingten Verluste eingerechnet sind.

Bei der Ermittlung des Kraftstoffverbrauchs stehen zwei verschiedene Ansätze zur Verfügung. Das bei der Schmelzhütte eingetroffene Aluminium kann auf den Gesamtkraftstoffverbrauch bezogen werden, d.h. der Gesamtverbrauch wird ausschließlich der Aluminiumfraktion zugerechnet (Fall 1). Dies entspricht einer Sichtweise, als würde die Altautoentsorgung nur wegen des Aluminiums existieren. Da dies aber in der Realität nicht der Fall ist wird im zweiten Ansatz (Fall 2) der Verbrauch gewichtsmäßig dem Aluminium zugewiesen. So wird z.B. in der ersten Relation, von der Annahme zum Verwerter, der Fraktion Stahl der größte Anteil des Verbrauchs zugewiesen.

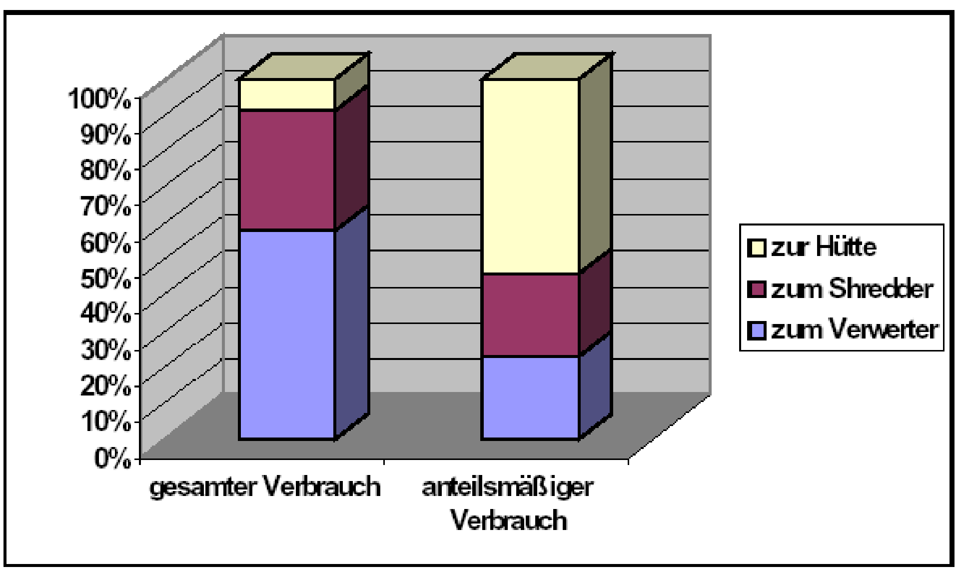


Abbildung 5: Anteil der Relationen am Verbrauch bei unterschiedlichen Zuteilungen

Betrachtet man sich die Aufwandsverteilung in den beiden Fällen (Abbildung 5), so stellt man fest, daß im Fall 1, wo der gesamte Verbrauch dem Aluminium angelastet wurde, der Transportschritt zum Verwerter die höchsten Aufwendungen besitzt, während bei einer anteilsmäßigen

Zuteilung des Energieverbrauchs der letzte Transportschritt zur Hütte den größten Anteil besitzt. Dies unterstreicht den Einfluß der Fraktionszusammensetzung und die Zuteilung der Aufwendungen auf diese.

Insgesamt beträgt der Primärenergieverbrauch für den Transport auch unter der ungünstigen Annahme im Fall 1 durchschnittlich nicht mehr als 1 GJ/t Al. Im Vergleich zum Primärenergieverbrauch zur Sekundärerzeugung einer Tonne Aluminium von 20 GJ/t Al fällt der Transport kaum ins Gewicht. Auch wenn die ungünstigste Transportrelation (Brandenburg) herangezogen wird, beträgt der Energieverbrauch für den Transport nicht mehr als 6% bezüglich der Sekundärerzeugung. Obwohl also Aluminium aus dem Automobilbereich im ungünstigsten Fall durch halb Deutschland transportiert werden muß, ist der Primärenergieverbrauch für den Transport im Vergleich zur Sekundärerzeugung relativ gering. Diese Relation kann sich für anderer Metalle, mit anderen Verfahrensschritten und Energieverbräuchen, anders darstellen.

4 Zusammenfassung

Gut ein Jahr nach Inkrafttreten der Altautoverordnung werden die Schwachstellen der Verordnung deutlich. Durch Defizite bei der Zertifizierung liegt bei den beteiligten Instanzen weder ein einheitlicher Umweltstandard vor, noch kann von gleichwertigen Wettbewerbsbedingungen gesprochen werden. Allgemein wird von der Verwertungsindustrie moniert, daß eine wiederkehrende Überwachung seitens der Behörden nicht gegeben ist. Da ein Einschreiten der Behörden auch nicht zu erkennen ist, ergeben sich daher Vollzugsdefizite. Ein prinzipielles Problem ergibt sich durch die Exporte von Altautos und -karosserien, die sich auf ca. 50% summieren. Dies bedeutet erhebliche finanzielle Einbußen der beteiligten Instanzen.

Verfolgt man den in der Altautoverordnung geregelten Entsorgungsweg für das im Automobil eingesetzte Aluminium, ergibt sich folgende Mengenbilanz. Bei ca. 3,18 Millionen Altautos, die 1997 angefallen sind, beläuft sich das theoretische Sekundäraluminiumpotential auf 151.000 t. Zieht man von dem jährlichen Gesamtaluminiumpotential Exporte, Demontage von Aluminiumteilen beim Verwerter und verfahrensbedingte Verluste beim Shreddern ab, so verbleibt nur noch ein direktes Sekundäraluminiumpotential für den deutschen Kreislauf von 29%. Damit ist festzustellen, daß eine nationale Regelung in Anbetracht der Exporte zu kurz greift und bei einer Festlegung von Recyclingquoten sämtliche Abflüsse und deren Verbleib zu berücksichtigen wären.

Die Analyse der Aluminiumrückführung ergab, daß hierfür eine durchschnittliche Strecke von unter 100 km zurückzulegen sind und damit ein flächendeckendes Rücknahme- und Verwertungssystem gegeben ist. Für den gesamten Verwertungsweg ergeben sich zwischen den einzelnen Bundesländern sehr große Unterschiede (Faktor 6). Aber auch im ungünstigsten Fall, wenn Aluminium aus dem Automobilbereich durch halb Deutschland transportiert werden muß, ist der Primärenergieverbrauch für den Transport im Vergleich zur Sekundärerzeugung relativ gering. Unter ökologischen Gesichtspunkten ist der Transport von Sekundäraluminium auch über große Entfernungen noch sinnvoll.

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THE SECONDARY ALUMINIUM MATERIAL FLOW IN GERMANY WITH SPECIAL VIEW ON THE TRANSPORT AND LOGISTIC ASPECTS

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ABSTRACT[1]

Germany is the biggest aluminium user in Europe. Because of the high energy effort, which is necessary for the production of the primary aluminium, the recycling of aluminium products is very important. In 1997 the production of secondary aluminium was for the first time higher than the production of primary aluminium.

This PhD thesis deals with the secondary material flow including a special view on the transport aspect. The consideration starts at the end of the use of the product and ends with the substantial recycling of the aluminium products. The aim of the thesis is to point potential weak out and to show optimisation potential from the view of the transport.

After an analysis of the aluminium application in Germany a detailed examination of the aluminium re-feed is made. This re-feed is divided into three sections: collecting, processing / recycling and re-melting.

The most important collecting systems (transportation, DSD, aluminium windows and storefronts) are examined along the process chain. The examination considers the used means of transport, the transport way, the transport unit and the transported commodity. Operation figures are determined to describe the re-feed of the aluminium. Based on the operation figures a system is developed, which makes the analyse and judgement of the various collecting systems possible.

[1] Summary of Ph.D. thesis

POTENTIAL FUTURE LOCATIONS OF PRIMARY ALUMINUM SMELTERS: SELECTION FOCUSSING ON ASPECTS RELATED TO THE TRANSPORT ECONOMY*

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ABSTRACT

This article occupies with the optimum transport links between deposits of bauxite and hard coal. For the calculation and transport demonstration the over seas and the inland destination are considered as well as the handling costs.
In a first step all worldwide distances between the existing essential production and export regions of bauxite and hard coal are identified. In a second step the distances of inland transport between the producing mines and the assigned export harbours, each for bauxite and hard coal, the means of transportation as well as the referring transport and handling costs are reviewed. In a further step all costs of seaborne transports between all harbour locations from the group of hard coal and bauxite export ports are identified, by multiplying all initially gathered distance data with the specific transport costs for seaborne transport. The next step considers with the overall transport costs of the relations including a hard coal and a bauxite export harbour are calculated. The last step listed all transport relations between the reviewed hard coal and bauxite export harbours.
The analysis of the transportation demonstrate, that the costs for a transport of hard coal and bauxite show a broad range depending on the various specific costs of the applied transport means and significant differences in respect to the distances which need to be bridged.

KEY WORDS
Bauxite deposits, hard coal deposits, transport, means of transportation, transport costs

* Source: Aluminium 77 (2001), Nr.12, S. 978-982

1. Introduction

Within the scope of this analysis, optimum transport links between deposits of bauxite and hard coal are to be identified, which can ensure a raw materials supply for future aluminum smelters inducing cost positions which are as low as possible in respect to the occuring expenses for transportation of the mentioned materials. Bauxite is needed for alumina production whereas hard coal serves as a primary input energy for the respective electric power production.

To achieve such an in-depth result focussing on aspects of the transport economy, land-based as well as seaborne transports are reviewed. Exclusive emphasis is laid on questions concerning transport costs as well as the size of global economically recoverable raw material deposits in order to guarantee a long-term stable resource supply for the aluminum production process.

In the following „relations“ are referred to as transport links between two harbours as either the location of shipment or the destination port for raw materials.

As afore-mentioned, the two raw materials, bauxite and hard coal, which are necessary input materials for aluminium production will be examined considering their local land-based transport and port handling costs as well as the corresponding seaborne transport costs.

The aim of this macro-analysis is the identification of potential future sites for primary aluminum production. This shall be achieved by a combined model which is based on general assumptions as well as including actual economic data sets.

The limitation of the model to hard coal as the exclusive potential energy carrier for the future electric power supply of aluminium smelters results from the fact, that hard coal does not require any especially complex infrastructures, neither in the transport chain, nor anywhere else and is therefore characterized by an exceptionally high mobility on a global scale. In contrast, other important primary or secondary energy carriers such as natural gas or hydropower (electric power), which also contribute a very significant share to the global energy portfolio for aluminium production, have a considerably lower transport eleasticity and are therefore relatively confined to the region of their occurrence. This spatial restriction results from the fact, that on the one hand they require a much more complex transport infrastructure (pipelines for natural gas, electric power grid for hydropower) which often is simply not available or hard to establish, on the other hand they are characterized by comparatively high specific transport costs, already inducing high overall transport costs when bridging rather short distances. These high specific and overall costs are caused by the expenses for the construction, operation and maintenance of the pipelines and grids as well as the energy losses occuring during transport.

Hydropower is already being used to a great extent for the power supply of aluminum smelters currently in operation. Economically or technically exploitable hydropower potentials have already been developed for the purposes of the energy economy in large regions of the world, thus increasingly limiting a further expansion of this energy source. This suggests an increasing future importance of a primary energy carrier like hard coal, which exists or is available almost everywhere across the globe.

2. General framework

Within the scope of the analysis, as mentioned in the introductory part, some general assumptions are made beside the actual dataset to create a solid and coherent base for the combined model.

1. As far as the analysis centers on a model of transport economy, the production costs for hard coal, which depending on the respective geological conditions and the overall economic environment of the deposit, show a very large bandwidth across the globe, are not included in the model calculations. Trying to determine the overall costs along the entire coal chain these factors can be additionally included in a further step and be added to the cost positions induced by transport activities. This would result in an even more extensive result concerning all questions of the operating efficiency.

2. Beside the inclusion of the transport costs as the essential selection criterion, also the production or handling amounts of the materials reviewed at the respective deposits or the assigned harbours are considered, in order to eliminate transport links with insufficient material quantities of at least one commodity from the overall number of potential transport relations already at an early stage of the identification process.
3. On a global scale, uniform specific transport costs of inland transports for various means of transportation (train, inland barge, truck, conveyor belt) are assumed, which are based on published reference cost data (see table 1).
4. Based on the assumption, that the world seas comprise a somehow homogenic transport area, globally uniform specific transport costs are postulated for seaborne transport (see table 1).
5. Due to the high specific costs for land-based transport of bulk materials as well as general reasons of spatial accessability for the input materials of the aluminum production process and the succeeding export of the finished output product (aluminum) for the global market, it is assumed, that all future aluminum smelter sites will be on the world`s coastlines. Furthermore it is postulated, that the alumina production plants are located at the site of the aluminum smelter.
6. In the context of the considerations focussing on the transport economy it is not necessary to distinguish between bauxite and hard coal as far as the transport conditions or the direction of the respective transport relations are concerned, because the handling of both materials as well as the means of transportation used are rather similar as are the amounts of the both commodities as required inputs for the aluminum production process (reference production unit is 1 ton of primary aluminum).

Means of transport	Specific transport costs [US-$ / tkm]
Bulk cargo vessel [Seaborne transport]	0,00046
Train [Land-based transport]	0,0300
Truck [Land-based transport]	0,0450
Inland barge carrier [Land-based transport]	0,0100
Conveyor belt [Land-based transport]	0,0100

Table 1: Specific costs of various transport means

[For alumina production and the succeeding production process in the aluminum smelter, approximately 4.2 t of bauxit (Al_2O_3-content of about 56%) are necessary for each ton of aluminum. A current reference process with a specific electric power demand of about $e_{AL} = \frac{14,000 kWh_{el}}{t_{AL}}$, coal demand amounts to roughly $m_C = \frac{e_{AL}}{H_u \cdot \eta_{el}} \approx 4.5 \frac{t_C}{t_{AL}}$ (with H_U = 29,64 MJ/t_C and η_{el} = 38%. In the case of the most modern hard coal-fired power plants with efficiency ratios of about 46% coal demand is reduced to approximately 3.8 t_C/t_{AL}, with the respective importance of bauxite being increased and the importance of hard coal being reduced in the overall input portfolio. This however only applies to the bare quantities without considering the market price developments and the resulting economic weight of the commodities in question.]

3. Proceedings

In a first step all worldwide distances between the existing essential production and export regions of bauxite and hard coal are identified while picking the distance between the respective export harbours assigned to the producing mines as a first approximation. The corresponding distances between all potential transport relations are collected within the framework of a matrix, with transport distances varying in a range between a minimum 1,867 km (1,008 nautic miles)[1] with the relation Port Rhoades (Jamaica, Bauxite) and Mobile (USA, Hard coal) and a maximum 24,320 km (13,132 nautic miles) with the relation Weipa (Australia, Bauxite) and Gdansk (Poland, Hard coal).

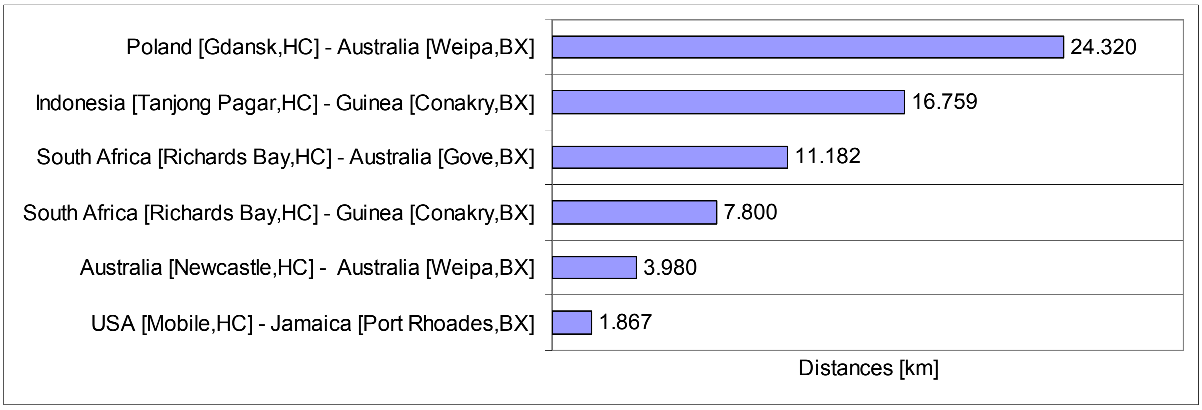

Fig. 1: Distances of selected transport relations between export harbours of hard coal and bauxite

In a second step the distances of inland transport between the producing mines and the assigned export harbours, each for bauxite and hard coal, the means of transportation as well as the referring transport and handling costs are reviewed.
The very different mining regions of hard coal such as Australia, USA, South Africa, Indonesia or Canada as well as the broad range of inland distances to be bridged, which vary between a minimum of 70 km (Indonesia, Tanjong Pagar / truck) and a maximum of 2,000 km (USA, Mobile, inland barge carrier), result in similarly significant diffrences concerning the overall transport costs from the mines to the export harbours.
Those costs vary in a range from US$ 46.50/t (USA, Newport News, train, 1,550 km) and US$ 3.15/t (Indonesia, Tanjong Pagar, truck, 70 km). Those extreme cost differences are on the one hand caused by the different distances and on the other hand even more by the various specific costs of the transport means used. Furthermore country-specific cost differences can also contribute significantly to the overall costs induced (operating costs, maintenance costs, wages) and can therefore lead to a lacking economic export attractiveness of some transport relations right from the outset.
In general it can be claimed, that the costs of inland transports have a disproportionately high absolute share of the overall costs in comparison with the later on reviewed seaborne transportation costs and related to the overall transport distances also have an even more disproportionately high relative share of the overall costs along the coal transportation chain as a whole. Furthermore costs induced by inland transports also represent a very significant share of the overall costs for coal supply to the market (including mining costs) and therefore even amount to a great percentage of the final revenues delivered by selling the commodity at market prices. A long-distance transport or a transport which is carried out with an especially cost-intensive means of transportation therefore can be considered as a „knock-out“-criterion when discussing the competitiveness of hard coal on the world markets. This segment of the coal chain can quickly induce prohibitively high absolute and relative cost shares, explaining the need for short distances and cost-efficient transportation systems.

[1] 1 nautic mile = 1.852 km

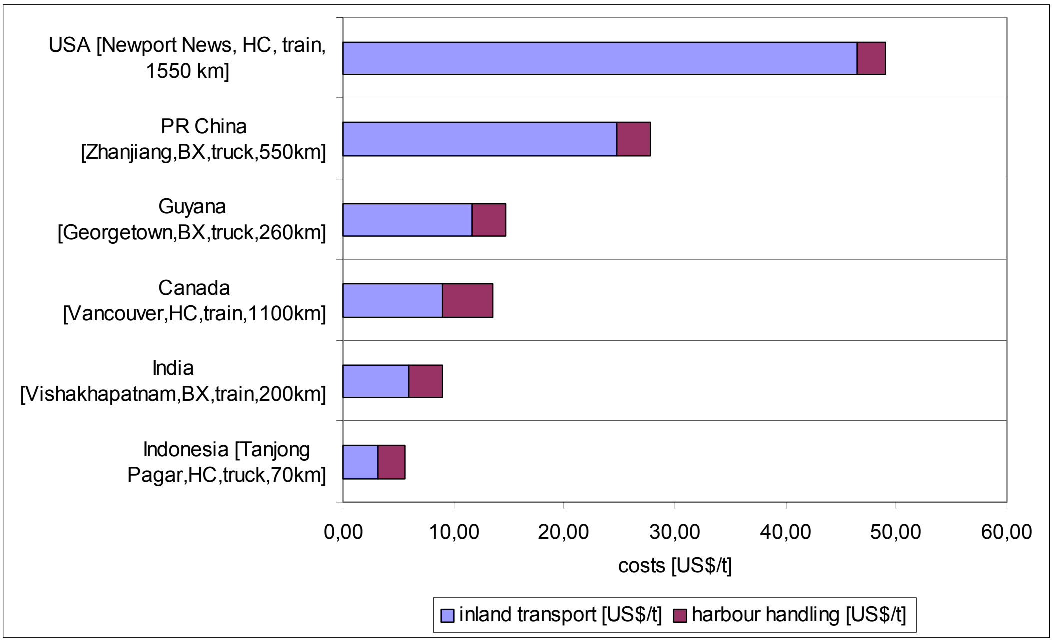

Fig. 2: Costs of inland transport and harbour handling of hard coal and bauxite at selected locations

Beside the various inland transport costs also the handling costs in the harbours vary significantly. Although they show a smaller range than the transport costs, in certain cases these costs can exceed the global average value of US$ 3.15-3.30/t by up to US$ 2.5/t. A similar picture is true for the transport- and handling structures of the bulk commodity bauxite, the details of which will not be further elaborated on due to this reason.
In a further step all costs of seaborne transports between all harbour locations from the group of hard coal and bauxite export ports are identified, by multiplying all initially gathered distance data with the specific transport costs for seaborne transport. The location with the smallest amount of transport costs is Tanjong Pagar (Indonesia). Here no transport costs are induced, because there exists concurrent deposits of hard coal and bauxite in the same region theoretically making superfluous any seaborne transports.
For other transport relations there is again a broad range of costs. From a low case of US$ 0.86/t for the relation between Port Esquivel (Jamaica, BX) and Mobile (USA, hard coal) with a distance of 1,867 km the overall sea-transport costs can rise to a high case of US$ 11.19/t on the transport relation between Gove (Australia, BX) and Gdansk (Poland, hard coal) with a distance of some 23,617 km.

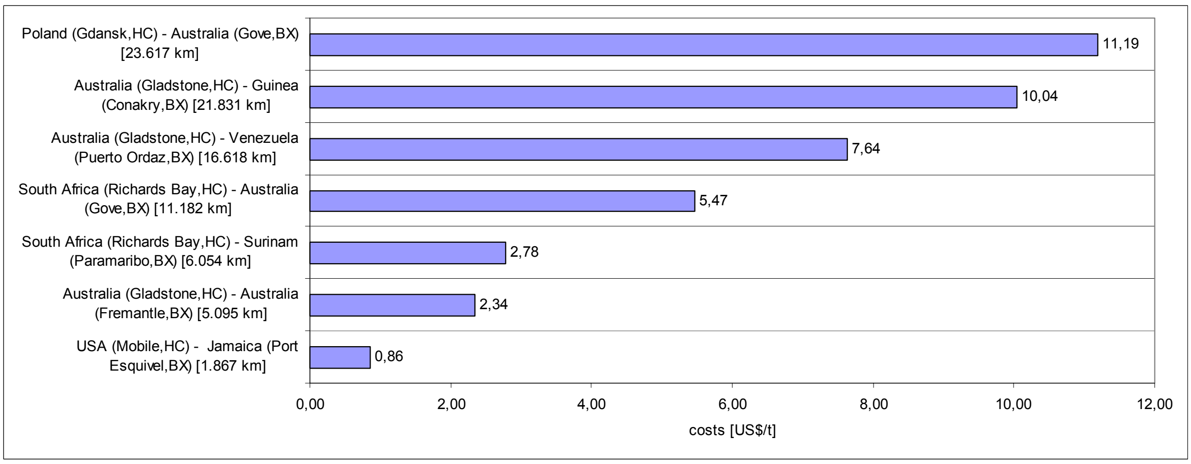

Fig. 3: Costs of seaborne transports for bauxite and hard coal on various relations

In a further step the overall transport costs of the relations including a hard coal and a bauxite export harbour are calculated. These overall transport costs are therefore comprised of two inland transports, caused by the transport of bauxite and hard coal from their respective mine locations to their assigned harbours, as well as the seaborne transport between both ports of the relation. The corresponding term for the overall costs is the following:

$$OC_T = C_{I,1} + C_{I,2} + C_S$$

[with OC_T = overall costs of transport, $C_{I,1}$ = Cost of inland transport 1, $C_{I,2}$ = Cost of inland transport 2, C_S = Cost of sea transport]

Corresponding to the broad range of costs in the already mentioned single segments of the coal transport chain, also an aggregated review of the overall costs for various relations show significant differences. Those range from a low of US$ 11.46/t for the relation Gove (Australia, BX) and Tanjong Pagar (Indonesia, Hard coal) to a high figure of US$ 85.64/t for the relation Zhanjiang (PR China, BX) and Newport News (USA, Hard coal), which has to be categorized as completely improvident.
An exceptional case is again the relation Panjong Tagar (Indonesia, BX) and Tanjong Pagar (Indonesia, Hard coal), which in fact equals to a location with a coincidence of both commodities, with very low overall transport costs (only inland transport) of US$ 8.63/t.
In a next step all transport relations between the reviewed hard coal and bauxite export harbours are listed. In addition to the figures concerning the overall transport costs of each relation, the data of the respective production or handling amounts of both commodities are included. From the proportion (ratio) between the commodity amount and the required transport costs a figure is derived, which mirrors a specific mass-to-cost ratio. This indicates a tendency, how to categorize the attractiveness of a relation considering the available commodity amounts as well as the induced transport costs. As a term to calculate the mass-cost-ratio it can be defined:

$$MC = \left(\frac{kt}{a}\right) \div \left(\frac{US\$}{t}\right)$$

[with MC = mass-/cost ratio, kt/a = commodity handling in 1.000 t per year, US$/t = overall transport costs per ton on the entire distance]

A low ratio can be interpreted as an indicator which hints at a relatively low available commodity amount while the costs are also rather high. A high ratio hints at either a large available commodity amount or very low transport costs or even the simultaneous existence of both beneficial factors.
Such a relation would have to be assessed as an especially attractive option for potential future locations of primary aluminum smelters. In an optimum case, a very low transport cost level would exist with the available commodity amounts being so high at the same time, that an adequately large-sized smelter could more than sufficiently cover its raw material demand and also ensure a long-term secure supply.
With the commodity quantities in the actual model being the production or handling amounts of the mines or the assigned harbours, a well-founded statement concerning the long-term sustainability of a potential future production site would furthermore require an analysis of the long-term reserve base of the producing deposits. The result matrix is then modified such, that a ranking of the relations with the most favourable mass-/cost-ratio, therefore a high ratio figure, is created, in order to further approach the final aim of identifying the most favourable transport relations and the respective attractive potential smelter sites. The entire process of taking single analysis steps concerning the various relations and their related cost structures can therefore be labelled as a method of iteration.
Obviously uneconomic relations are eliminated from the portfolio of potential combinations and only attractive (semi-optimum) and optimum locations remain at the end of the selection process.

This final choice of relations and locations can then be further examined by applying some in-depth research instruments and criteria like tax situation, labour costs, Business Environment Ratings or any other economic analysis data. Within the scope of this publication which focusses on pure aspects of the transport economy, these proceedings would exceed the aim of the topic.
In a concluding step the result matrix is then transformed into a ranking, which enumerates all relations in the order of their overall transport costs, putting the most cost-attractive relations at the top of the list. Moreover the relations are ranked by their most favourable (highest) mass-/cost ratio.

4. Results

The first variant, the classification by the criterion of the cumulated overall transport costs (2 inland transports, 2 harbour handlings, 1 seaborne transport) leads to the identification of the already mentioned relation Tanjong Pagar (Indonesia, Hard coal) combined with Gove (Australia, BX) as the most favourable relation. In table 2 and 3 an overview of the 10 most attractive transport relations as well as five economically unattractive relations for reasons of comparison are displayed.

rank	transport relations		costs [US$/t]	mass-/ cost-ratio	rank
	hard coal	bauxite			
1	Indonesia [Tanjong Pagar]	Australia [Gove]	11,46	610,62	9
2	Indonesia [Tanjong Pagar]	India [Cuttack]	11,95	200,86	14
3	Australia [Newcastle]	Australia [Gove]	12,21	573,44	10
4	Indonesia [Tanjong Pagar]	Australia [Weipa]	12,26	897,41	4
5	Indonesia [Tanjong Pagar]	Australia [Fremantle]	12,86	1.151,05	2
6	Australia [Newcastle]	Indonesia [Tanjong Pagar]	12,87	101,03	21
7	Australia [Newcastle]	Australia [Weipa]	13,00	846,10	5
8	South Africa [Richards Bay]	Surinam [Paramaribo]	14,28	140,01	18
9	Australia [Newcastle]	Australia [Fremantle]	14,52	1.239,35	1
10	South Africa [Richards Bay]	Indonesia [Tanjong Pagar]	14,91	87,17	24

Table 2: Overview of the most cost-attractive transport relations

transport relations		costs [US$/t]	mass-/ cost-ratio
hard coal	bauxite		
PR China [Qinhuangdao]	Brazil [Obidos]	36,84	230,72
Canada [Prince Rupert]	Australia [Gove]	44,45	155,25
Canada [Prince Rupert]	Surinam [Paramaribo]	53,41	37,45
USA [Newport News]	Australia [Fremantle]	64,88	277,42
USA [Newport News]	PR China [Zhanjiang]	85,64	9,34

Table 3: Overview of some selected economically unattractive transport relations

It becomes obvious, that the most unfavourable transport relation, USA (Newport News) and PR China (Zhanjiang) with overall costs of US$ 85.64/t almost amounts to the eight-fold costs of the cheapest transport relation.
The following figure (Fig. 4) presents the prior results in the form of an overview of the most favourable transport-relations. The most expensive relation of the displayed 10 top-pick relations is the one between Richards Bay (South Africa, hard coal) and Tanjong Pagar (Indonesia, BX) with US$ 14.92/t. The cheapest relation is Tanjong Pagar (Indonesia, hard coal) and Gove (Australia, BX) with overall costs of US$ 11.46/t. The display of the overall costs is divided by the cost shares of the first inland transport (hard coal) plus the respective harbour handling costs. Costs for the second inland transport (bauxite) and the handling costs of the assigned harbour as well as the costs for seaborne transport between both locations rounds of the cost aggregation.
The cost share of inland transports related to the overall costs along the entire transport chain are increasingly more significant with an increasingly low ratio of the seaborne distance towards the inland transport distance. Analogously this is also valid the higher the ratio of inland transport distance is towards the seaborne transport distance.
The respective term to calculate the ratio in relation to the distance is the following:

$$Q = \frac{S_{[km]}}{I_{1[km]} + I_{2[km]}}$$

[with $S_{[km]}$ = Seaborne transport distance (km), $I_{1[km]}$ = Inland transport 1 distance (km), $I_{2[km]}$= Inland transport 2 distance (km)]

Including the specific costs in the term results in the following formula:

$$Q = \frac{S_{[km]} \cdot C_{SP,Ship}}{I_{1[km]} \cdot C_{SP,TM,1[\$/tkm]} + I_{2[km]} \cdot C_{SP,TM,2[\$/tkm]}}$$

[with $S_{[km]}$ = Seaborne transport distance (km), $C_{SP,Ship}$ = specific transport costs of transport means (ship), $I_{1[km]}$ = transport distance of first inland transport, $C_{SP,TM,1\ [\$/km]}$ = specific transport costs of first inland transport depending on specific transport means ($/tkm), $I_{2[km]}$ = transport distance of second inland transport, $C_{SP,TM,\ 2\ [\$/km]}$ = specific transport costs of second inland transport depending on specific transport means ($/tkm).]

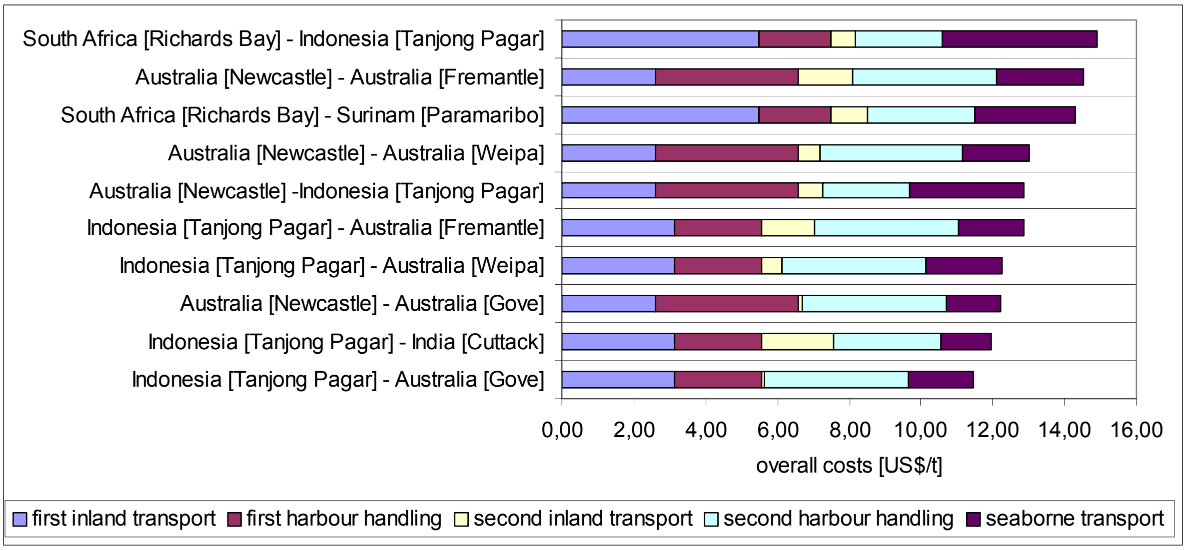

Fig. 4: The 10 most cost-attractive transport relations for comparison

Figure 5 clarifies the proportion between the percentual shares of inland transport 1 and 2 as well as the seaborne transport and the assigned respective shares of the transport costs along the entire transportation chain for some exemplary relations.

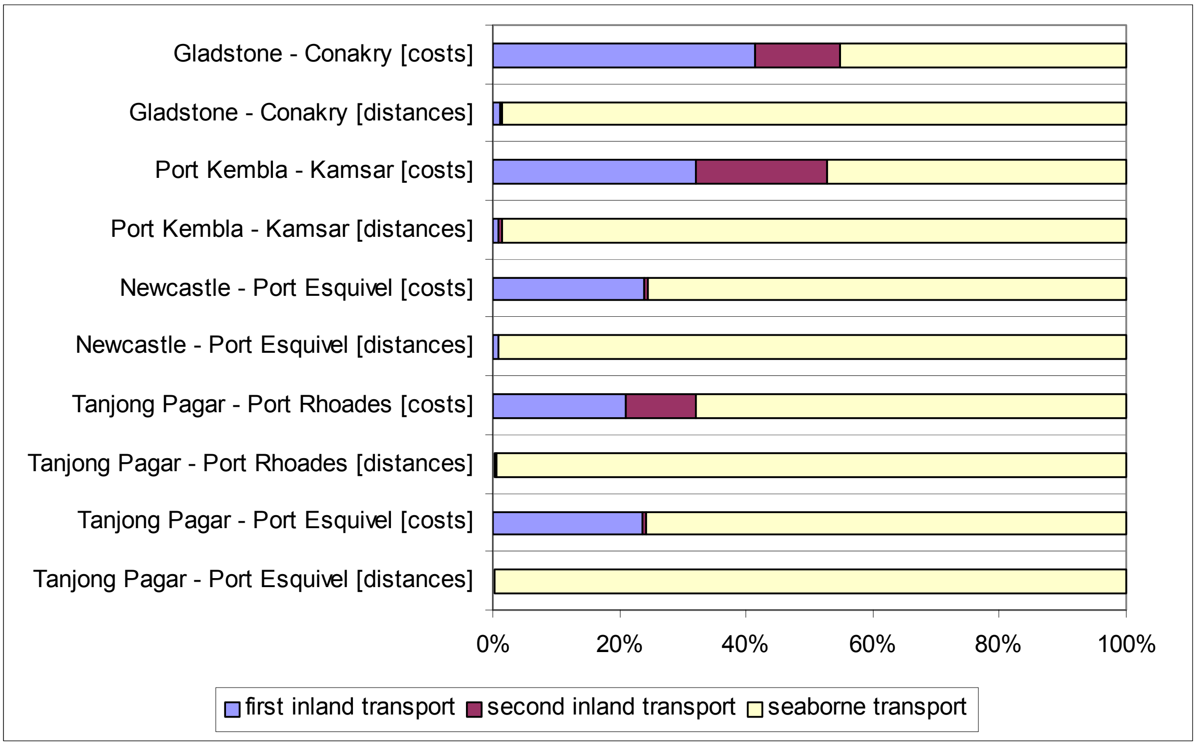

Fig. 5: Proportion between the shares of the partial distances of selected transport relations related to the overall distance and respective shares of costs along the entire transport chain

The second variant, which categorizes according to the height of the mass-/cost-ratio, leads to the result, that the relation Newcastle (Australia, hard coal) and Fremantle (Australia, BX) with the highest figure of 1,239.25 has the most favourable mass-/cost-ratio. The most unfavourable figure with a value of 87,17 is assigned to the relation Richards Bay (South Africa, hard coal) and Tanjong Pagar (Indonesia, BX).

In order to link both review categories „transport costs“ and „mass-/ cost-ratio“ and attain a consistent statement aiming at identifying the most favourable transport relations, the most cost-attractive transport relations are listed in a ranking table and are compared with the respective mass-/cost-ratios (see table 4).

This leads to the result, that the following relations simultaneously are cost-attractive in respect to their transport economy and furthermore have a favourable amount of available commodity.

rank	transport relations hard coal	bauxite
1	Australia (Gove)	Indonesia (Tanjong Pagar)
2	Australia (Gove)	Australia (Newcastle)
3	Australia (Weipa)	Indonesia (Tanjong Pagar)
4	Australia (Fremantle)	Indonesia (Tanjong Pagar)
5	Australia (Weipa)	Australia (Newcastle)
6	Australia (Fremantle)	Australia (Newcastle)
7	Australia (Fremantle)	South Africa (Richards Bay)
8	Australia (Weipa)	South Africa (Richards Bay)
9	Australia (Weipa)	Australia (Port Kembla)
10	Australia (Gove)	Australia (Port Kembla)
11	Australia (Gove)	South Africa (Richards Bay)

Table 4: Favourable transport relations

It becomes clear that almost all the relations are spatially concentrated in the greater indo-pacific region between Australia and Indonesia or directly between locations on the australian continent. In some cases this spatial system is expanded by the south-african port of Richards Bay. All of the above mentioned harbours, namely Weipa, Fremantle, Gove, Port Kembla, Newcastle (all Australia), Tanjong Pagar (Indonesia) and Richards Bay (South Africa) are therefore to be assessed as the most favourable future locations for primary aluminum smelters.

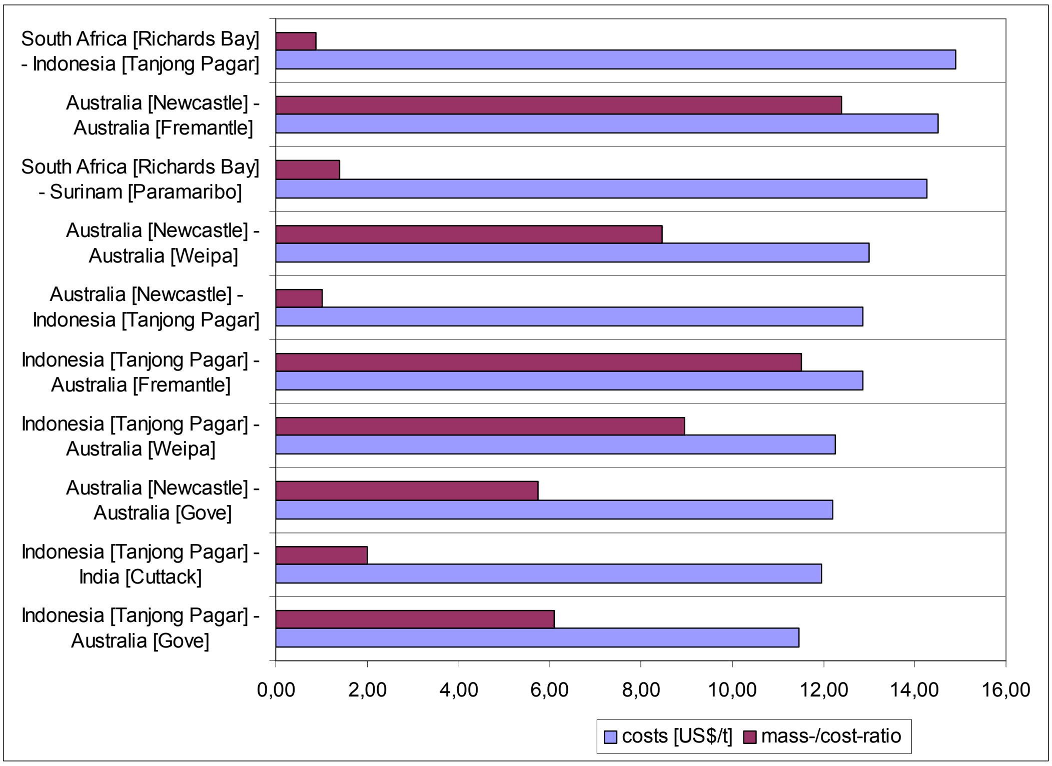

Fig. 6: The 10 most favourable transport relations in relation to the mass-/cost-ratio

5. Summary

The previous analysis show, that the costs for a transport of hard coal and bauxite show a broad range depending on the various specific costs of the applied transport means and significant differences in respect to the distances which need to be bridged. Within the scope of the transport economy, by choosing various raw meterial sources, very different transport relations with largely varying cost constellations can be identified. Inland transports are generally linked with high specific costs in comparison with seaborne transports, therefore quickly inducing prohibitively high overall costs along the entire transport chain. Optimum transport relations for the supply of future potential aluminum smelter locations are therefore such combinations, which only involve inland transports to a very low extent.

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CONCEPTION AND DEVELOPMENT OF AN INFORMATION SYSTEM AS PART OF AN INTERDISCIPLINARY RESEARCH PROGRAM

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ABSTRACT[1]

Information systems are used in places where a big amount of data has to be executed. A research program is divided into several subprograms, each of them needs a different kind of data.

The CRC 525 is such a kind of research program with nine sub programs and many researcher from different kind of fields are included. The aim of the research program is to develop a method, which helps to identify options of the resource sensitive supply and the use of metallic raw materials considering technical development and economic and ecological aims. The information system assists the link of the data and the integration of the different kind of aspects.

This PhD thesis deals with the conception and realisation of a data model from one of the nine sub programs. The request in the data model is worked out and the expert method is introduced. It will be shown, that the data model is flexible enough to consider the expert demand and coexistent to serve the complexity of the whole object of research.

[1] Summary of Ph.D. thesis

MODELLING THE MATERIAL FLOW OF RECYCLING PROCESSES FOR ALUMINIUM ALLOYS BY MEANS OF TECHNICAL RECYCLING QUOTAS*

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ABSTRACT

The amount of aluminium alloys used for different applications such as cars, packaging or buildings has risen considerably during the past 20 years. This will effect a growing amount of scrap being available for recycling in the future.

The special properties of the metal aluminium require sophisticated processing of different types of aluminium containing material prior to re-melting and refining. Aluminium and other materials in composites have to be liberated and afterwards separated from each other. Moreover, residues deriving from the re-melting and refining process such as salt slag or dross have to be treated.

Within a collaborative research centre sponsored by the DFG (Deutsche Forschungsgemeinschaft) a model is set up which includes the different types of processes in use for recycling of aluminium containing material. The efficiency of the recycling process is determined by the properties of the material to be recycled and the technology used. A technical recycling quota based on metal yield was defined as a tool for measuring the efficiency of the recycling process.

The model helps to identify losses of metallic aluminium during the recycling process and thus gives hints on ideas for processes or process steps which may be improved or altered. Based on data collected in Germany the structure of the model can well be transferred to other countries.

KEYWORDS

Material flow, aluminium recycling, aluminium alloys, recycling quotas

* Source: Proceedings of REWAS, San Sebastian, 1999

I. Introduction

No other metallic material is discussed at the moment more critically in public than aluminium. The discussion about the position of this metal within an economy which aims at sustainable development is conducted strongly controversial. The adversaries of aluminium name the production of the metal "one of the environmentally most harmful activities of mankind" **/1/**, whereas the proponents denote aluminium the "green metal" **/2/**.

These controversial points of view are based mainly on different parts of the life-cycle of aluminium. The primary production of the metal uses large amounts of primary raw materials, mainly bauxite (up to 4 t are necessary to produce 1 t of aluminium), is energy-intensive (13-15 kWh/kg_{Al} are consumed during electrolyses only) and causes large amounts of solid waste materials (mainly 1.600-3.200 kg/t_{Al} red mud from the Bayer-process). On the other hand, the secondary production of aluminium from scrap material consumes only about 5-15 % of the energy necessary for primary production and the recycling quotas for aluminium are reported to be high **/3/**.

Where the primary production of aluminium is well examined and data on the different processes is readily available, the secondary production is not investigated in detail and data on the recycling processes is available to a limited extent only. Especially the processing of different aluminium containing waste materials is often neglected if the recycling process chain for aluminium is looked at.

In order to make information on the recycling process for different aluminium containing waste materials available and to compile the basis for a well founded evaluation of the different recycling processes, a model of the processes for the provision of raw materials for the secondary aluminium production has been developed. This model describes the process chains established for the recovery of aluminium and its alloys from different applications such as cars, packaging, refrigerators or electronic devices. As a tool to measure the efficiency of the recycling processes, a "technical recycling quota" has been defined which is based on metal yield.

The model can be used to identify weak points within the recycling process chain and thus can be the base for possible improvements.

II. Recycling quotas

As has been mentioned before, the model of the processes for the provision of raw materials for the secondary aluminium production uses a "technical recycling quota" to measure the efficiency of the different recycling technologies. As the recycling quota is a very important issue when it comes to the evaluation of a recycling business, this issue will be discussed in more detail in the following.

In literature the terms "recycling quota" or "recycling rate" are used in very different contexts and with different meanings. First, two typical definitions of the recycling rate are given:

a) *Share of secondary aluminium in overall production of aluminium* **/4/**

This definition describes how much of the overall production of aluminium in a country is contributed for by the secondary production. The recycling rate R_r can be calculated on the basis of production statistics using equation (1).

$$R_r = \frac{secondary\ production\ [t]}{secondary\ production\ [t] + primary\ production\ [t]} \quad (1)$$

The recycling rate defined by equation (1) is useless for countries such as e.g. Japan where primary production does not take place (recycling rate 100 %) or for countries such as e.g.

South Africa where primary production takes place in much higher orders of magnitude than secondary production (recycling rate well below 10 %).

b) *Share of secondary aluminium in total amount of aluminium* **/4/**

This definition describes how much of the aluminium contained in a certain product is made from secondary raw materials. The recycling rate R_r can be calculated on the basis of production statistics and estimations using equation (2).

$$R_r = \frac{amount\ of\ secondary\ aluminium\ [t]}{total\ amount\ of\ aluminium\ [t]} \qquad (2)$$

The recycling rate defined by equation (2) does not take into consideration the long life span of some aluminium containing products during their use. Also, a growing use of aluminium reduces the recycling rate and a declining use of aluminium leads to a rise of the recycling rate.

Besides the "recycling rate" which measures relative amounts of aluminium, the term "recycling quota" describes how much aluminium is recovered at the end of the use phase. In order to use a recycling quota for the evaluation of the efficiency of an aluminium recycling process it is necessary to base the calculation on metal yield. This leads to the definition of a "technical recycling quota" $R_{q,t}$ **/5/** which can be calculated using equation (3).

$$R_{q,r} = \frac{amount\ of\ secondary\ aluminium\ produced\ [t]}{amount\ of\ aluminium\ made\ available\ for\ utilisation [t]} \qquad (3)$$

The amount of secondary aluminium produced is a function of the processing and melting technology applied. Therefore, the technical recycling quota is a function of metal yield of the processing and the melting steps. Also, the recovery of metal losses from the by-products of melting (dross and salt slag) have to be included into the calculation.

Finally, if the collection of the aluminium containing waste material is also included in the calculation using a "collection quota" it is possible to determine a "resource-oriented recycling quota" **/6/** which describes the efficiency the resource "aluminium containing waste material" is used with in order to produce new aluminium.

III. Provision of raw materials for the secondary aluminium production

The main factor of the secondary aluminium production is the raw material which can be divided into the two categories "new scrap" and "old scrap". "New scrap" originates from the first processing stage (e.g. pressing or rolling) and from the second processing stage as well as from production (e.g. of window frames or car parts). This material can be easily re-melted in most cases, sometimes a simple preparation such as a size reduction or compacting is necessary. The main portion of "new scrap" is directly re-melted in-house in the foundries of rolling-slabs and pressing-bolts.

More important for the evaluation of the efficiency of the recycling-loop for aluminium is the "old scrap". This material originates from the different products which contain aluminium and its alloys after the products have reached the end of their service life. Before the aluminium can be re-melted, the products have to be collected and the metal has to be recovered by means of different, sometimes very sophisticated processing techniques.

III.1 Structure of the model

The structure of the model used to describe the recycling processes for aluminium and its alloys is outlined in figure 1.

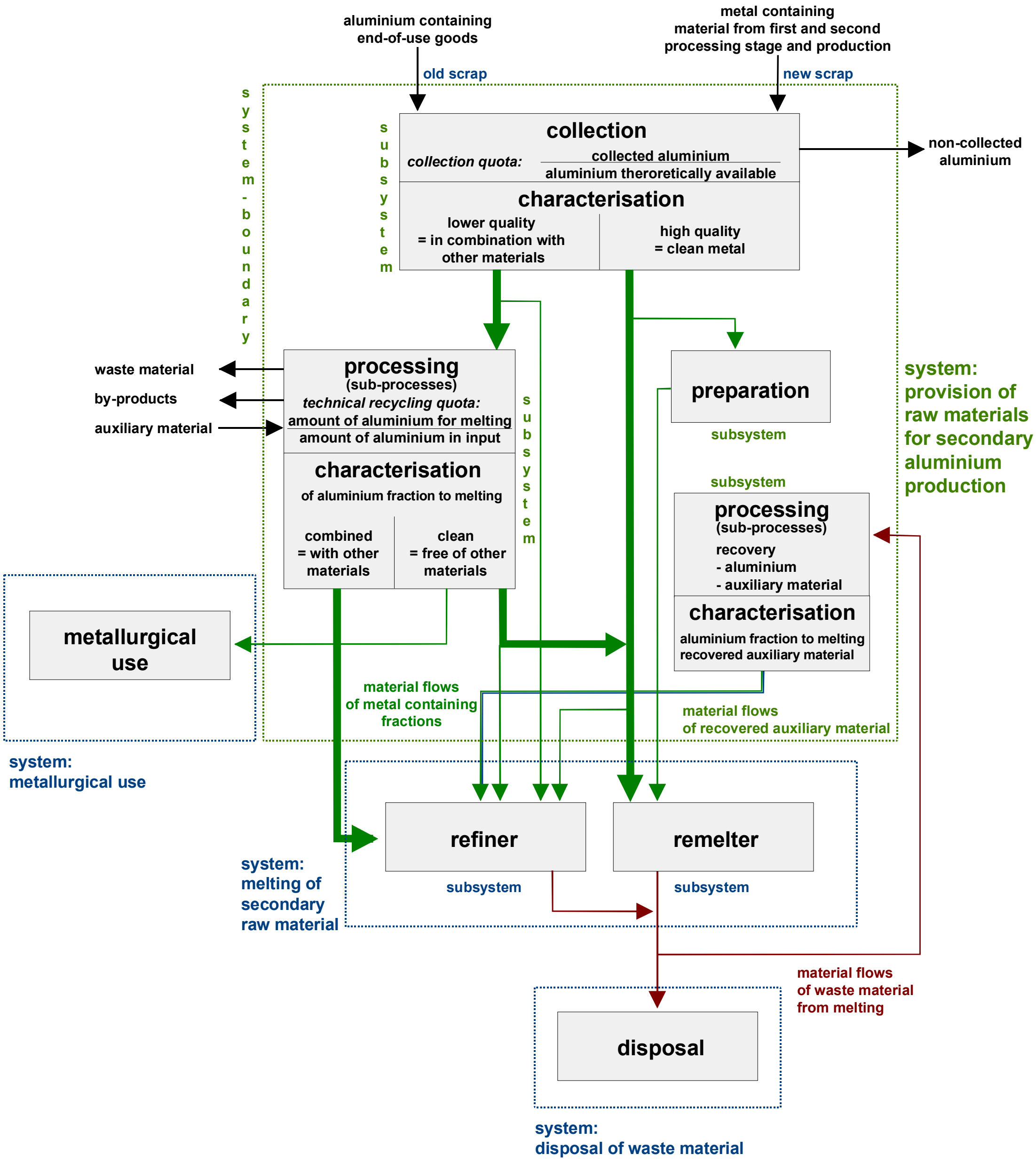

Figure 1: Structure of the model of the recycling processes for aluminium

First, the collection of the different aluminium containing waste materials is looked at. The most important point is how much of the theoretically available aluminium is actually collected (collection quota). The collected material is characterised based on a newly developed characterisation system where one of the main issues is the quality of the aluminium. If it is clean (which is often the case for new scrap) it is typically directly re-melted. If the aluminium occurs in combination with other materials such as e.g. iron or plastics (which is typical for old scrap) different processing steps are necessary in order to produce an aluminium fraction which can be re-melted.

The processing sub-processes are described with their technical, economic and resource-oriented data (namely the technical recycling quota). The characterisation of the processed aluminium fraction allows the identification of all melting processes applicable. If the metal fraction is clean it can either be used for metallurgical applications or it can be re-melted. If the aluminium is still combined with certain amounts of foreign materials it is typically remelted by the so-called refiners. Finally, waste materials from melting arise at the refiners as well as the remelters. These waste materials, mainly dross and salt slag, can be processed in order to recover the aluminium and/or the salt flux or they are disposed of.

An important point of the model is the characterisation of the different material flows with regard to their processing- and their metallurgical properties, because the highest potential for improvements within the whole process chain of the recycling of aluminium can be found at the interface between processing and re-melting.

III.2 Modelling the sub-processes of the processing of aluminium containing waste materials

The central point of the model described is the processing of aluminium containing waste materials. In order to achieve a model structure which is flexible and can be easily changed with regard to e.g. technological improvements a modular design was chosen. The process chain is divided into different sub-processes. The degree of detail has to be as low as possible and as high as necessary in order to achieve a clear structure and to have all important information contained. The sub-processes are represented by modules whose structure is shown in figure 2.

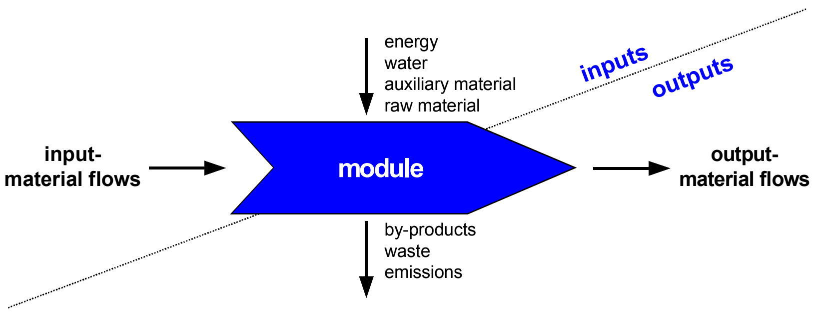

Figure 2: Structure of the modules representing sub-processes /7/

The input- and output-material flows of the modules are the aluminium containing fractions, the output of the module representing the final processing stage is the aluminium fraction to be melted.

The data which is necessary to describe a module with orientation towards resources is the following:

- energy consumed for processing (electrical and thermal)
- amount of water consumed for processing
- type and amount of auxiliary and raw materials consumed for processing
- type and amount of by-products arising
- type and amount of waste materials arising
- type and amount of emissions arising
- amount of aluminium contained in the different inputs and outputs

IV. Application of the model: Recycling of aluminium from obsolete cars

In the following, the model described above will be applied to the recycling of aluminium alloys from obsolete cars. Starting from a rough characterisation of the "raw material" the different sub-processes for the recovery of aluminium alloys from obsolete cars are described in the form of modules and the data for these modules is given. Finally, using the tool of calculating the technical recycling quota, an example for the evaluation of the whole process chain is given.

The collection system for obsolete cars is not included in the model structure described below as only the technical parameters of the processing stages are discussed in this paper.

IV.1 Model structure for the processing stages of the recycling of aluminium alloys from obsolete cars

Based on the structure shown in picture 2, the model of the processing stages for the recycling of aluminium alloys from obsolete cars was set up according to figure 3.

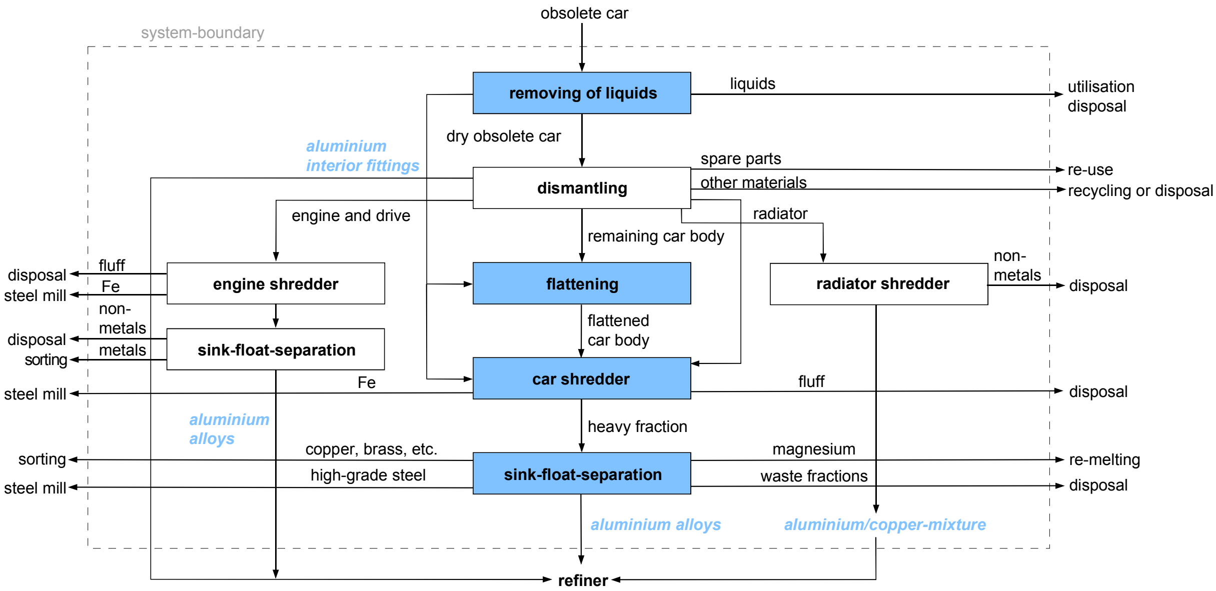

Figure 3: Model of the processing stages for the recycling of aluminium alloys from obsolete cars

In the following only one of the possible processing chains is discussed in detail. The sub-processes included in this processing chain are marked grey in figure 3 and include the removing of liquids, the flattening of the car body, shredding of the car body and sink-float-separation of the heavy fraction from shredding.

IV.2 Characterisation of aluminium alloys contained in obsolete cars

The main application of aluminium alloys is their use in different car parts. The most important types of alloys used in cars are the cast alloys AlSi6Cu4 and AlSi9Cu3 for engine parts and chassis. Wheels are mainly made from the alloy AlSi11. At the moment, the amount of cast alloys contained in obsolete cars is by far larger than the amount of wrought alloys. This will change in the future as the use of aluminium for body parts (where wrought Al-alloys prevail) is increasing.

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The amount of aluminium alloys contained in obsolete cars is difficult to determine. Based on an extensive literature review it can be established that the weight of an obsolete car is on average 957 kg (920-1120 kg), the aluminium share is about 3,8 % (3,0-8,0 %) and the resulting aluminium content is 36,4 kg (28-90 kg). These figures take into account the fact that mainly cars of low and middle class are recycled at the moment as cars belonging to upper classes are in use for a longer period of time.

Table 1 shows the typical distribution of aluminium alloys in cars to be recycled in Germany.

Table 1: Distribution of aluminium alloys in obsolete cars in Germany /**8**/

component	share of total aluminium in the car	share of cast Al-alloys	share of wrought Al-alloys
engine parts	50 %	90 %	10 %
chassis	30 %	90 %	10 %
body	15 %	20 %	80 %
interior fittings	5 %	40 %	60 %
total car	100 %	85 %	15 %

IV.3 Modules of the sub-processes

a) Removing of liquids

Before the car is shredded, the liquids such as fuel, oil, cooling water etc. are removed in order to avoid contamination during shredding. Figure 4 shows the module "Removing of liquids" with the respective data /**9**/.

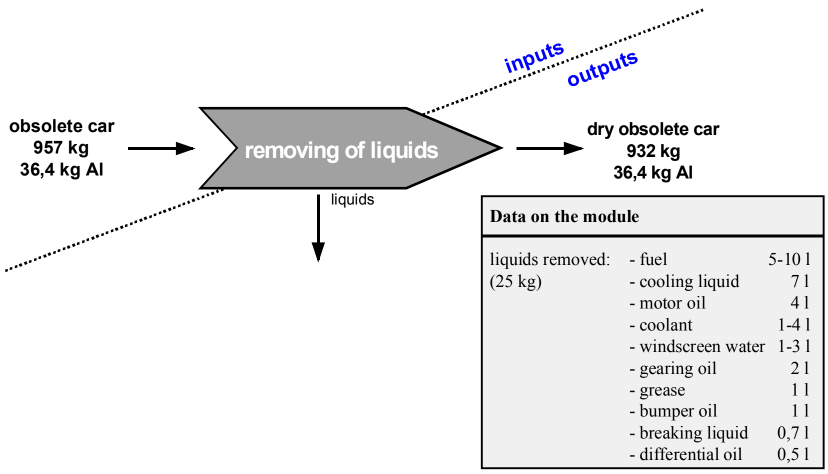

Figure 4: Module "Removing of liquids"

b) Flattening

In order to reduce the volume to be transported to the shredding plant the dry obsolete car can be flattened using a car-press. Also, the flattening reduces the energy demand of the shredding process.

Figure 5 shows the module "Flattening" with the respective data.

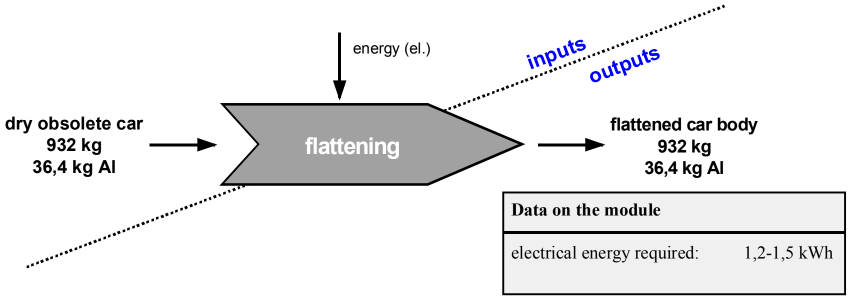

Figure 5: Module “Flattening”

c) Car shredder

The central module of the recycling process for obsolete cars is shredding. A shredder liberates the different materials of which a car is assembled by crushing the whole car body in a housing where hammers rotate with a speed of more than 200 km/h. By tearing and shearing action the car is crushed to pieces of 100-5 mm while a blower steadily sucks off the air from the housing thus removing fine non-metallic particles. After crushing an air separation stage is used in order to separate light materials from the heavy materials (which are mainly metals). Finally, a magnetic separation takes place where the main output of the shredder plant is separated, the iron and steel fraction. The remaining heavy, non-magnetic fraction contains the non-ferrous metals, high-grade steel, rubber, wood, textiles etc. and is further processed for recovery of the metals. As the aluminium alloys report mainly to the heavy fraction this material flow forms the output of the module “Car shredder” which is shown in figure 6 with the respective data.

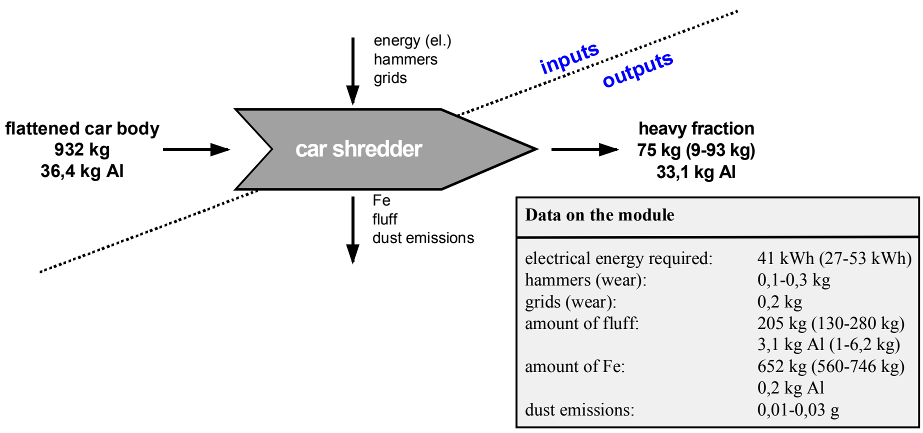

Figure 6: Module “Car shredder”

d) Sink-float-separation

As the aluminium alloys contained in the heavy fraction from the shredder are mixed with other non-ferrous metals such as copper, brass, magnesium and zinc as well as non-metals such as rubber, wood, textiles and plastics, a further processing is necessary in order to produce an aluminium fraction which can be re-melted. This processing is achieved by sink-float-separation. Here, the heavy fraction from the shredder is sorted into the fractions heavy metals (copper, brass, zinc, etc.), high-grade steel, magnesium, waste (rubber, wood, textiles, etc.) and aluminium alloys by a combination of screening, hand-sorting, eddy-current separation, jigging and two-stage heavy-media separation. The module "Sink-float-separation" is shown in figure 7 together with the respective data.

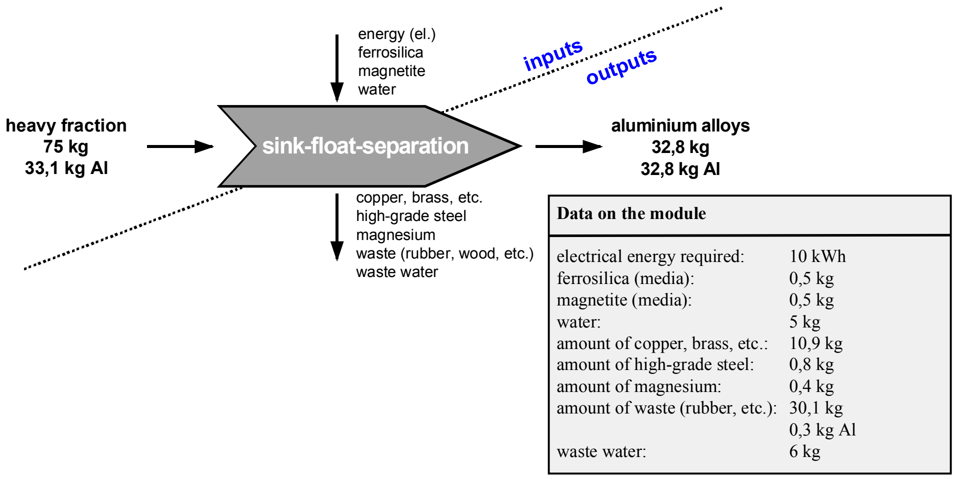

Figure 7: Module "Sink-float-separation"

IV.4 Characterisation of the aluminium alloy fraction, re-melting

The aluminium fraction from sink-float separation is typically re-melted under a salt layer in a rotating drum-type furnace. The chemical composition of the re-melted aluminium alloy can be seen from table 2.

Table 2: Chemical composition of re-melted aluminium alloy from sink-float material **/10/**

element	Cu	Zn	Si	Fe	Mn	Mg	Cr
min.	1,70	0,40	5,60	0,70	0,16	0,03	0,01
max.	2,80	0,90	8,90	0,90	0,25	0,50	0,05

The metal yield of the re-melting process for the aluminium alloy fraction from sink-float-separation is in the order of about 92 %. Furthermore, 1,5 % of the aluminium is recovered after the melting process when the salt slag is recycled. This amount equals 90 % of the metallic aluminium becoming entrapped in the salt slag during melting in the rotating drum-type furnace.

The surface of the aluminium alloys can be found to be dull due to oxidation caused by the wet processing in the sink-float-separation process.

V. Determination of the technical recycling quota as a tool for the evaluation of the efficiency of the recycling process

The technical recycling quota of the process chain (as described in chapter IV) for the recovery of aluminium alloys from obsolete cars can be calculated for the single modules as follows ("Removing of liquids" and "Flattening" do have no influence on the Al-content):

- "Car shredder": 33,1 kg Al of 36,4 kg Al recovered in heavy fraction (90,9 %)
- "Sink-float-separation": 32,8 kg Al of 33,1 kg Al recovered in aluminium fraction (99,0 %)
- Melting: 30,2 kg Al of 32,8 kg Al re-melted (metal yield 92 %)
- Salt slag processing: 0,5 kg Al recovered (1,5 % of melted Al)

Total:

$$R_{q,r} = \frac{30{,}7\ kg\ secondary\ aluminium}{36{,}4\ kg\ aluminium\ available\ in\ obsolete\ car} = 84{,}3\,\%$$

Figure 8 shows the material flow of the aluminium through the recycling process thus indicating where the main metal losses occur.

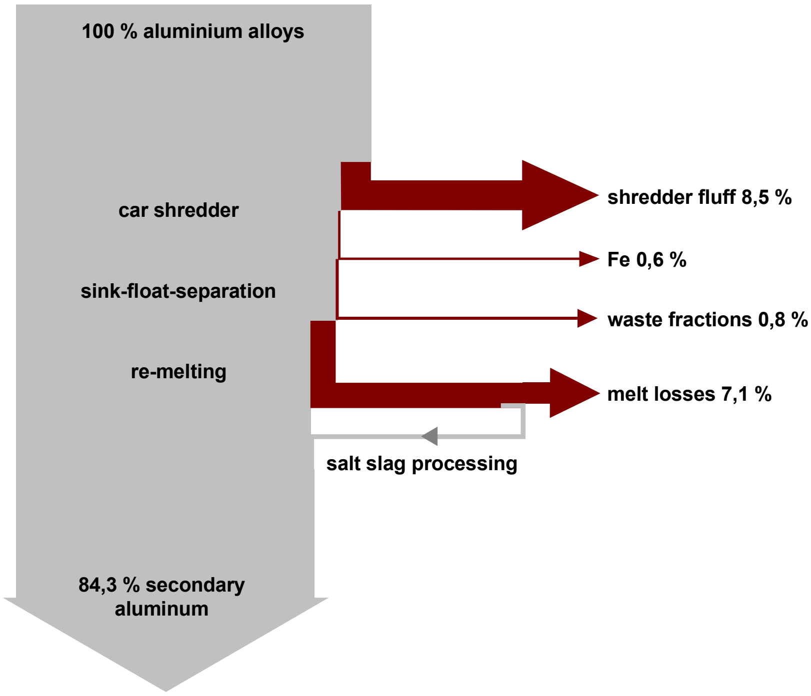

Figure 8: Aluminium flow including metal losses during recycling

V. Conclusions

As can be seen from figure 8 the main metal losses occur at two points of the process chain:

- during shredding of the car when fine aluminium particles become entrapped within the shredder fluff thus being not recovered in the heavy fraction
- during melting

With regard to the processing steps for the recovery of aluminium alloys from obsolete cars it can be ascertained that two possibilities for improvements exist: either a processing of the shredder fluff for recovery of the metals or a technical improvement of the air separation process at the shredder plant. On the other hand, an improvement of the sink-float-separation is not possible at all as the process is already working with an efficiency of 99 %.

By characterisation of the aluminium alloy fraction produced by sink-float-separation, though, it was found that the wet processing causes a relatively strong oxidation of the aluminium surfaces. Therefore, a dry separation process could help to increase metal yield during re-melting.

The technical recycling quota calculated to be 84,3 % will also increase if the dismantling of aluminium bearing parts of the car takes place before shredding. Although this process is labour- and thus cost intensive it is nevertheless the most effective way to raise the recycling quota for aluminium alloys from obsolete cars. In this context the possibility to keep wrought and cast aluminium alloys separate from each other by dismantling will become important in the future.

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STUDY OF THE PREPARATION OF RAW MATERIALS FOR THE PRODUCTION OF SECONDARY ALUMINIUM IN GERMANY

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ABSTRACT[1]

The recycling of aluminium in Germany is able to provide secondary aluminium and alloys of high value. For the time being there exists no structured mass stream management system. Furthermore, no methods are developed to collect information concerning these mass streams. Also tools are missing which help to analyse recycling processes and process chains.

Therefore, this study focuses on the development of methods to analyse the recent recycling system.

In a further step, these methods are applied to the situation of aluminium recycling in Germany on the basis of the year 1997. The resulting information system contains all data to enable a management system for the mass streams.

The knowledge of the mass streams is the necessary background to detect weak points of processes and of the whole process chain. For this, tools have to be developed, which mainly focus on the metal content of secondary products after the recycling processes.

Based on the analyses of these weak points improvements can be deducted to optimise the quality and quantity of regained aluminium.

One further interesting aspect which results out of this thesis is the expansion of the analyses to an international scope. And a second aspect can be the application of the information system for other metallic mass streams. Thus the possibility of a further development and enlargement of methods is supported.

[1] Summary of Ph.D. thesis

A CONTRIBUTION TO THE ESTIMATION OF ALUMINIUM OLD SCRAP *

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ABSTRACT

In this article a model for estimating the availability of aluminium old scrap is developed. First, we aggregate products containing aluminium into end use categories and then employ statistical distributions to describe the lifetime of products in each category. This statistical approach is applied to the German aluminium market. The results obtained show that the proposed model yields better estimates than commonly used approaches which assume a fixed service life for products.

KEYWORDS

Scrap availability, statistical methods, lifetime of products, lifetime intervals

* Source: ALUMINIUM 75, 1999

Introduction

Over the past decades there has been a growing awareness that industrialised societies are living beyond their means of available resources. The concept "sustainable development" has become very popular, and suggestions of how to achieve sustainability have been proposed ranging from clean production to the extreme approach of reduced production by the reuse of products.

Due to its excellent recycling properties, aluminium can contribute to a more efficient use of energy resources, to the increased productivity of natural resources and to a reduction of the demand for landfill sites. An important contribution to resource conservation is already made by those manufacturers who process new scrap arising during the fabrication processes. As a result of the combination of properties such as low density, high strength and excellent resistance to corrosion, aluminium has become a widely used metal for products, many of which have a very long service life. Hence, aluminium contained in consumer products builds up a huge stock that will eventually be returned to industry to be recycled. Industry has responded to the increasing availability of aluminium scrap through investments in refiners and remelters. In countries like the USA, old scrap is the source of 48% of the total scrap recovered, while 52% arises from new scrap [1]. Reliable models for estimating the availability of old scrap are still lacking, though they could support decision makers in secondary as well as in primary industry. The lack of appropriate models is caused by many factors, the absence of data being the most important one. The few attempts to conduct a quantitative analysis of the estimation of aluminium old scrap rely on considerable simplifications of reality. These simple approaches can be improved by realising that the ageing process of aluminium products is not fixed, and that suitable models for describing the lifetime need to be developed. This aspect will be addressed in this article and an illustration of our analysis will be carried out for the German aluminium market.

General considerations

The main factors affecting the recovery of aluminium old scrap include the consumption of products containing this metal as well as the lifetime of the products.

As indicated by Glimm [2], several problems arise regarding the quantification of the actual amount of aluminium that is consumed in Germany. According to [3], annual consumption is derived by the identity: production + imports – exports ± changes in stocks. All the terms refer to primary and secondary aluminium and do not take into account the foreign trade in semi-fabricated and finished products. Therefore, the formula does not give the exact aluminium consumption in Germany. Although our calculations are simply based on the consumption figures in [3], they can easily be extended to a world model, thus reducing the data problems just mentioned.

To estimate the old scrap potential, the diversity of aluminium applications, and in particular their lifetime, must be taken into account. Lifetime can vary from a few weeks as for beverage cans, to several decades as for window frames. Obviously, it is impossible to consider each product individually. We will aggregate products by end use categories and discuss different models for describing the lifetime in each category.

Finally, it is well known that not all aluminium consumed is recycled. As a result, recovery fractions will be established by end uses in order to determine the expected net old scrap.

Lifetime modelling

The ageing process of aluminium products is commonly assumed to correspond to a fixed number of years. For example, Glimm [2] and Kirchner [4] consider that passenger cars have a mean life expectancy of 11 years. Clearly, this is a simplification of reality. To cope with the uncertainty in the ageing process we will represent the latter by a statistical model. Such a model describes the lifetime of products in a given interval $[a,b]$, where a and b denote the minimum and maximum age of the products upon disposal. Since there is a large variety of aluminium

Table 1: The lifetime interval in the German transportation sector

Sub-class	Aluminium consumption share (%) [1]	Age upon disposal (years) [2]		Contribution to total age	
		min	max	min	max
	A	B	C	$\frac{A \times B}{100}$	$\frac{A \times C}{100}$
passenger cars, caravans	76.5	8	15	6.12	11.48
trucks	15.9	10	15	1.59	2.39
trains	4.1	30	30	1.23	1.23
aircraft, spacecraft	1.6	20	20	0.32	0.32
ships, ferries	1.3	60	60	0.78	0.78
(motor)bikes	0.6	8	12	0.05	0.07
Sum	100.0			**10**	**16**

[1] Source: Aluminium-Zentrale e.V., *Aluminium-Märkte*, Germany, 1996
[2] Source: Fachinformationszentrum Karlsruhe, *Instrumente für Klimagas-Reduktionsstrategien*, Germany, April 1998, Version 2.0

products, values for a and b are specified by end uses. Each end use category consists of several product sub-classes. Sub-classes are characterised by their average lifetime and their share of the total aluminium consumed in the category. For the German transportation sector, Table 1 illustrates the characterisation of the sub-classes and how to obtain a lifetime interval.

After the identification of the lifetime interval, the next step is to place a probability function on $[a,b]$ that is thought to be representative of the lifetime distribution. It is unlikely that the probability of discarding a product will remain the same in $[a,b]$. A more realistic assumption is to consider that the probability increases until a certain age after which it slowly declines. Figure 1 shows examples of density functions of two statistical models in the lifetime interval [10,16] which was determined for the transportation sector. Turowski [5] and Rink [6] suggest the normal (or Gaussian) distribution as a life model for aluminium products. The normal distribution provides a good representation of many physical phenomena and is the most widely used statistical model. The probability p_t that products are scrapped t years after their consumption corresponds to the area under the curve of the density function enclosed between t and t+1. In the case of the normal distribution, p_t is given by

$$p_t = \Phi\left(\frac{t+1-\mu}{\sigma}\right) - \Phi\left(\frac{t-\mu}{\sigma}\right)$$

with μ and σ the parameters of the distribution. Tabulated values for the standard normal distribution function Φ can be found in most statistics books. Due to the symmetric shape of the normal model, the mean coincides with the midpoint of the lifetime interval, that is, $\mu = (a+b)/2$. Thus, the transportation sec-tor has a mean life expectancy of 13 years ($\mu = 13$). Since the range of variation of a normal distribution is minus to plus infinity, the value selected for σ ensures that 99.7% of the distribution is enclosed in the lifetime interval, i.e. $\sigma = (b-a)/6$.

As illustrated in Figure 1, the probabilities p_t are the same for $t \leq 13$ and $t \geq 13$. This characteristic of the normal model does not always yield an appropriate representation of the lifetime. Actually, the most frequently used statistical distribution for modelling lifetime is the Weibull [7]. One of the advantages of this model concerns the large variety of shapes it can assume and that are likely to arise in practice. The Weibull distribution is characterised by two parameters: α and β. Figure 2 shows the effect of changing the scale parameter α. For the transportation sector we se-

Figure 1: Density functions of the normal and Weibull distributions in the interval [10,16]

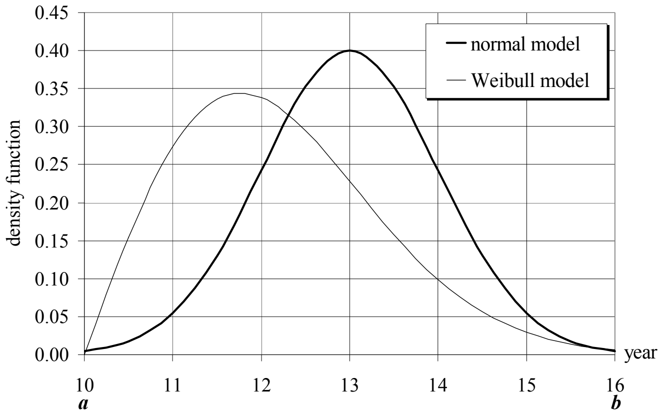
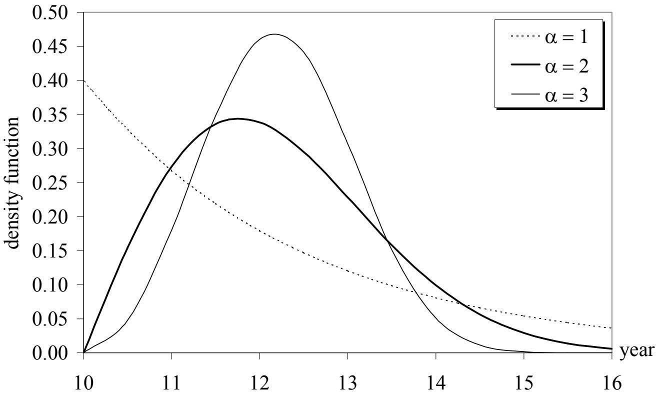


Figure 2: Density functions of the Weibull distribution in the interval [10,16] for β = 2.5 and various values of α.



lected α = 2 so that the mean life expectancy is closer to 12 years, and there is a high probability of scrapping a product between 11 and 13 years . The probability p_t is given in this case by

$$p_t = e^{-\left(\frac{t-a}{\beta}\right)^2} - e^{-\left(\frac{t+1-a}{\beta}\right)^2}$$

Since a Weibull distribution can take values from a up to infinity, the shape parameter β is obtained by stipulating that 99.7% of the distribution is located within the ranges of the lifetime interval. This corresponds to $\beta = (b\text{-}a)/2.41$. In the case of the transportation sector, we get β = 2.5 and the mean $\mu = a+\beta\sqrt{\pi}/2 = 12.2$ which is lower than that of the normal model (13 years).

Observe from Figure 1 that unlike the normal, the Weibull model has a right tail indicating that there is a higher probability that products last less than 13 years. For example, there is a 32.5% chance that a product in the transportation sector will be scrapped 11 years after consumption. In the normal model the chance is about two times lower, namely 13.6%.

Due to the absence of sufficient data, it is difficult to single out a model as being particularly suitable for representing the lifetime of aluminium products. The choice can be made on the basis of qualitative information gathered from experts.

Potential scrap availability

For a given end use category, the amount of old scrap that can theoretically be recovered depends on the consumption and lifetime of aluminium products. This means that the expected old scrap in year j is given by

$$\sum_{t=a}^{b-1} c_{j-t}\, p_t$$

with c_{j-t} denoting the amount of aluminium consumed in year j-t.

By identifying lifetime intervals for different end use categories and defining the corresponding parameters of the lifetime models described above, we estimated the total old scrap that could be recovered in Germany annually. The characteristics of the models chosen for the German aluminium market are displayed in Table 2.

Packaging products have a short lifetime that varies from a few weeks to some months. Since consumption data for this sector are only available on an annual basis, we assume a fixed lifetime of one year. For comparison purposes, this simple approach is extended to the other end use categories by setting the lifetime equal to the midpoint of the interval [a,b]. Figure 3 displays the theoretical availability of aluminium old scrap in Germany.

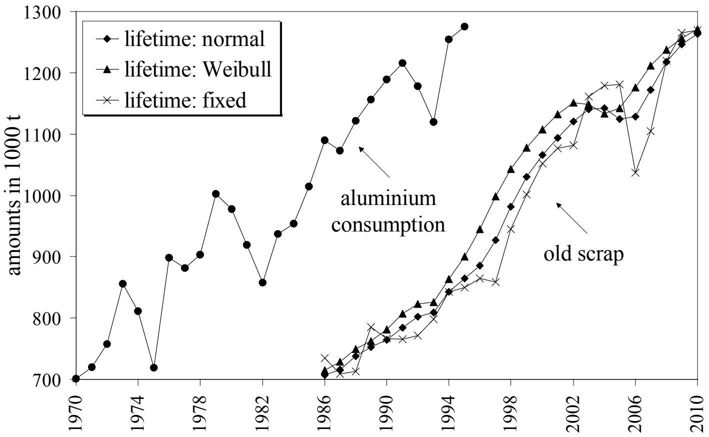
A common characteristic of the two statistical models is the smooth progress of the old scrap estimates over time. In contrast, the fixed lifetime approach is very sensitive to

Table 2: Lifetime intervals (in years) and mean life expectancy by aluminium end uses in Germany

End use	Lifetime interval [a,b] [1]	Mean life expectancy (years)	
		Normal model	Weibull model
Transportation	[10,16]	13.0	12.2
Mechanical Engineering	[10,20]	15.0	13.6
Electrical Engineering	[10,25]	17.5	15.5
Building & Construction	[23,40]	31.5	29.3
Packaging	1		
Household & Office Equipment	[5,15]	10.0	8.6
Other	[5,15]	10.0	8.6

[1] Rink [5] and in-house calculations

Figure 3: Aluminium consumption and potential old scrap availability in Germany according to different lifetime models (Source of consumption figures: [3] until 1995, afterwards an annual consumption growth of 1.5% is assumed)



fluctuations in consumption. This feature is clearly illustrated in Figure 3 for the year 2006. Since the transportation industry is the largest consumer of aluminium, variations in consumption in this sector have a strong impact on the total old scrap availability. The recession that occurred in 1993 in the German transportation market is reflected 13 years later in the scrap estimates when a fixed lifetime approach is used. The statistical approaches translate the effect of the recession in a more realistic way by considering that the scrap availability will gradually decrease during a certain future time period, namely 2004-2005 in the Weibull model, and 2005-2006 in the normal model. The fixed lifetime approach overestimates the scrap availability in the time period 2003-2005, and yields a pessimistic estimate of 1 037 000 t for 2006 which corresponds to a drastic decrease of 14% compared to the previous year. Furthermore, the estimation for 2006 is 8% lower than that of the normal model (1 128 000 t), and 12% lower than that of the Weibull model (1 176 000 t). These differences are even higher in 1998. Overestimation or underestimation of the scrap availability may naturally have a negative impact on the planning of future activities in the aluminium industry.

The differences between the normal and the Weibull lifetime models are explained by the effect of the shape of the distributions, as shown in Figure 1 for the transportation market, combined with the growth trend in consumption.

It is interesting to notice that the old scrap estimates for 2010 reach the consumption level of 1995. As long as aluminium consumption keeps on growing rapidly, the recovery of old scrap will not cover supply demands in the near future since large amounts of aluminium are stored in long-life products (especially in building and construction).

Expected net scrap

The results presented in Figure 3 are obtained on the assumption that 100% of aluminium consumed in Germany is recovered. In practice, only a fraction of the theoretically available amount is recovered. Many factors have a direct impact on the recovery of old scrap as described by Rink [6]. Since it is very difficult to quantify them, Rink suggests using recycling rates by end uses. For instance, it is claimed that nowadays 90% of the aluminium used in transportation is recycled. Hence, at least 90% of the potential old scrap arising in this sector should be available to the secondary aluminium industry. Table 3 indicates the recovery potential by end uses.

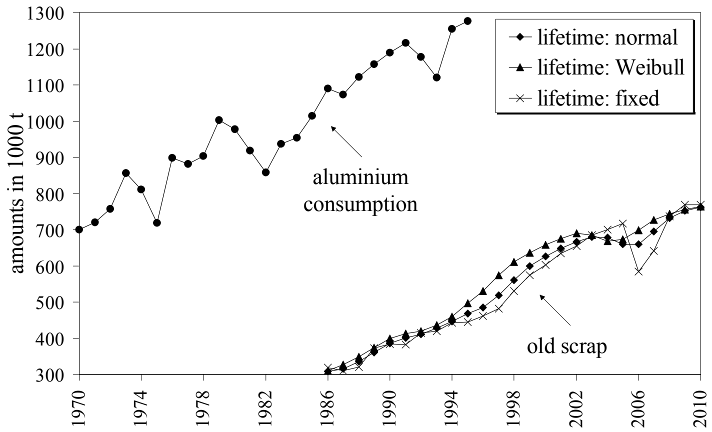
Using the rates in Table 3 the total old scrap availability is recalculated. The results obtained are displayed in Figure 4. Compared to the gross amounts, the total net scrap gradually increases from 43% to 60% in the time period 1986-2010. In other words, of all the aluminium sold to end

Table 3: Recovery potential of old scrap in Germany by end uses

End use	Recovery potential (%) [1]
Transportation	90
Mechanical Engineering	80
Electrical Engineering	80
Building & Construction	85
Packaging	3-6 until 1992, currently 40
Household & Office Equipment	20
Other	not known

[1] Rink [5] and Aluminium-Zentrale e.V., Aluminium-Märkte, 1994.

Figure 4: Aluminium consumption and net old scrap availability in Germany according to different lifetime models (Source of consumption figures: [3] until 1995, afterwards an annual consumption growth of 1.5% is assumed)



consumers, 43-60% is eventually returned for recycling.

Summary

In this article a model for estimating the availability of old scrap was presented and illustrated for the German aluminium market by considering several end use categories. The latter may differ from country to country, and the lifetime of their products may also diverge. However, the calculations can easily be extended to countries other than Germany. In summary, our analysis consisted of

- building end use categories based on available consumption data;
- deriving lifetime intervals for end use categories either directly or through the partition of each category into sub-classes of products. The latter involves the specification of lifetime intervals for the subclasses and their share of the total aluminium consumption in the category;
- choosing a lifetime model and calculating the potential old scrap availability;
- adjusting the results obtained by incorporating recovery potentials by end uses.

In particular, statistical methods for modelling the lifetime distribution of aluminium products were introduced to provide estimations of old scrap availability closer to reality than the commonly used fixed lifetime models.

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Statistical analysis of metal scrap generation: the case of aluminium in Germany

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Abstract

The recovery of metal scrap for recycling contributes to the supply of many of the key metals used in our society. Recycling provides environmental benefits in terms of energy and landfill savings, reduced volumes of waste, and reduced emissions. In this paper several models for estimating the potential arising of scrap from discarded metal-containing products are developed. The proposed models assume a categorisation of products by end uses, and are based on a probabilistic representation of the service life of products in each end use category. This statistical approach is applied to the German aluminium market. The performance of the statistical models is compared to commonly used approaches that assume a fixed lifetime for aluminium-containing products. The results obtained suggest that the new models yield better estimates than the fixed lifetime procedures, and therefore can be of assistance to decision makers in secondary and primary industries. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Aluminium; Lifetime estimation; Post-consumer scrap estimation; Statistical models

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1. Introduction

Increasing public concern for environmental protection and resource conservation has generated interest in the recyclability of materials. The recyclability of a material is determined not only by the intrinsic characteristics of the material itself, but also by the technological, economical, social and environmental context in which the material is used. To be recyclable, the discarded material must be supported by an infrastructure engaged in collecting, separating and sorting the material out of the waste stream, and in processing it into a form suitable for reuse. Furthermore, the recovered material must be marketed efficiently.

It has long been recognised that recycling of metals uses less energy than primary production. In addition, most metals can be recycled again and again with little or no decline in material performance and quality. Secondary production relies on the availability of metal scrap. Generally, scrap is categorised as new or old. The sources of new scrap are the various fabrication stages that precede an end product. New scrap is either fed back into the original application without leaving the production site (home scrap), or is directly transported to the secondary industry (prompt industrial scrap). Home scrap has a recycling rate of virtually 100% [1]. Old or obsolete scrap concerns material recovered from metal-containing products that are discarded at the end of their service life. Most old scrap is conveyed to the secondary industry via a network of scrap dealers.

In order to operate a scrap management system successfully, reliable methods for predicting metal scrap generation are required. This entails the knowledge of the factors affecting the generation of obsolete scrap. Two of the major factors concern the metal content in manufactured goods sold to end consumers, and the duration of the products' service life at the end of which disposal occurs and the obsolete metal is recovered for recycling. Reliable estimates of old scrap generation are of interest not only to the secondary industry, but also to decision makers in the primary industry. For instance, as more metal is recycled, the need for additional smelting capacity in primary production will be lessened. Ayres [2] predicts a decline in the mining and smelting industries in the long term as a result of increasing recycling activities. The emergence of new technologies for reducing scrap into reusable metal, the application of economies of scale to the recycling industries, and the accumulation of large inventories of recyclable metals over time account, among others, for the expected growth in recycling.

In spite of the importance of recovering obsolete metal, little quantitative analysis is usually carried out to estimate its reclamation. The lack of appropriate methods is caused by many factors, the absence of data being often the most important one. Moreover, some attempts rely on considerable simplifications of reality as in the case of aluminium where the lifetime of products containing this metal is assumed to be fixed [1]. This simple approach can be improved by realising that the time between consumption and disposal of a material has a stochastic nature, rather than a deterministic one. This aspect will be addressed in this paper and appropriate models for describing the service life of metals will be proposed. Our analysis is based on a probabilistic representation of the lifetime and will be illustrated for the estimation of aluminium old scrap generated in Germany.

The present study is organised as follows. In the next section the main characteristics of the German aluminium market are briefly described. Section 3 addresses the problem of selecting a representative distribution for the lifetime of products containing aluminium. The normal, Weibull and beta probability distributions are introduced and their adequacy as life models is discussed. Section 4 illustrates the application of the statistical approaches to the estimation of aluminium old scrap in Germany. Finally, in Section 5 some conclusions are presented.

2. General considerations on aluminium

As a result of the combination of properties such as low density, high strength, formability, good thermal conduction, and excellent resistance to corrosion, aluminium has become a widely used metal in areas such as transportation, housing, packaging, electrical engineering and construction. Aluminium consumption has grown in recent decades primarily because of the mentioned appealing properties. Fig. 1 indicates the amounts consumed in Germany between 1985 and 1995 by end uses. Annual consumption figures stem from Metal Statistics [3] which are derived using the identity: production + imports + decrease of stocks − exports − increase of stocks. All the terms refer to primary and secondary aluminium.

In Germany, as well as worldwide, the transportation industry is the largest market for aluminium. In 1995 it had a share of about 34% (429.3 kt) over domestic consumption. Automotive uses in passenger cars and light trucks dominate this end use sector. The second dominant market is the building and construction sector, accounting for 20% (254.1 kt) of total consumption, where aluminium is used for roofing, cladding, partitioning walls, ceilings, window and door frames. The

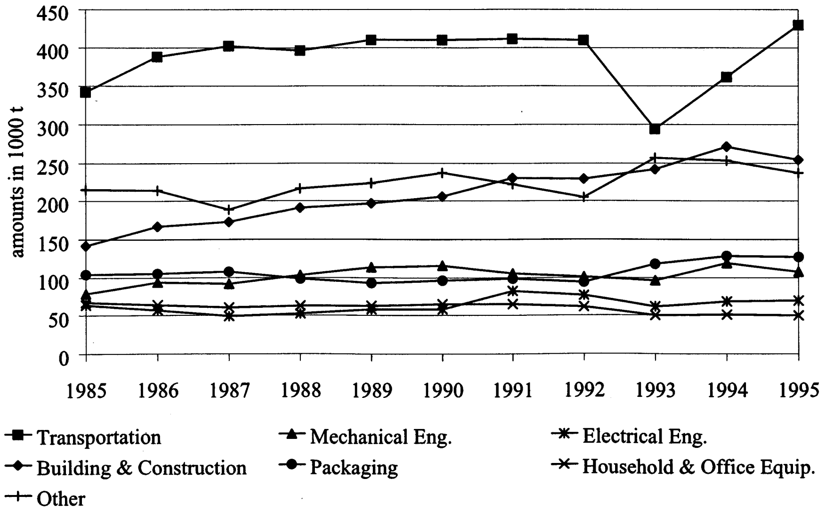

Fig. 1. Consumption of aluminium by end uses in Germany from 1985 to 1995 [3].

category *Other* in Fig. 1 comprises applications in chemical and agricultural industries, in powder consuming industries, in iron and steel industries, and miscellaneous applications.

In the last decades aluminium demand has faced an important growth not only in Germany (see Fig. 6 in Section 4.1) but also worldwide [1]. The increase in content and number of products using aluminium leads to the generation of large volumes of obsolete metal which will eventually be returned to the secondary industry for recycling. Aluminium has excellent recycling properties and therefore can contribute not only to a more efficient use of energy resources by only using 5–10% of the energy required to produce metal from raw materials, but also to a reduction in the need of raw materials and consequently to a decrease of the environmental damage associated with extraction and processing of raw materials, including their by-products. Ayres [2] lists the savings on energy, raw materials and by-products that can be obtained by recycling aluminium and other metals.

The recovery of aluminium from scrap has become an important component of metal supply in countries like the US, where recycled scrap provides about 31% of the total aluminium supply. Old scrap is the source of 48% of the total scrap recovered, while 52% arises from new scrap [4].

To be able to assess the degree to which reclamation of scrap from discarded aluminium-containing products occurs in Germany, the variety of aluminium applications, and in particular their lifetime, must be taken into account. Recycling can only take place at the end of a product's service life which varies from a few weeks, as for beverage cans, to several decades as for window frames. Obviously, it is not possible to consider each product individually. Therefore, we will aggregate products into end use categories and propose different models for describing the lifetime in each category. In the next section the selection of a representative statistical distribution for modelling lifetime will be discussed.

3. Lifetime modelling

In the case of aluminium it seems common practice to assume that the ageing process of products containing this metal is fixed. In other words, the service life of a product corresponds to a given number of years. For example, according to the International Iron and Steel Institute [1] automobiles and consumer goods have a mean life expectancy of 9 years. Hence, the potential arisings of aluminium from automobiles and consumer goods are calculated from the amount of aluminium used in these products 9 years previously. It is clear that this approach relies on considerable simplifications of reality since it neglects the uncertainty inherent to any ageing process. In our analysis we will represent the latter by a statistical model. Rink [5] and Turowski [6] recognised the importance of statistical models for describing the lifetime of products containing aluminium. Their analyses are based on the supposition that the disposal of post-consumer articles occurs when their service life reaches t years with $t \in [a, b]$, and a and b denoting the minimum and maximum average age of products upon disposal, respectively. Clearly, $0 \leq a < b$. We will follow this assumption and will dedicate the next section to the derivation of intervals in which it is felt that the average lifetime of products lies with probability close to 1. After the identification of a lifetime interval for each end use category indicated in Fig. 1, a probability function that is thought to be representative of the lifetime distribution is placed on $[a, b]$. In Section 3.2 three probabilistic models will be introduced and their adequacy for modelling life distributions will be discussed.

3.1. Identification of lifetime intervals

Realistic intervals for the lifetime of aluminium applications are very difficult to obtain as a result of the large diversity of products and the lack of information on their age upon disposal. In order to keep the analysis tractable, we will aggregate products into end use categories and derive a lifetime interval for each category. In addition to technical reasons, other factors also influence the actual lifetime of a product. For instance, in some sectors such as housing, products may be stored for several years before being scrapped. This so-called storage effect varies with different applications and in practice is very difficult to quantify. Consequently, the identification of an interval $[a, b]$ is made by specifying subjective estimates of a and b. This can be achieved by asking experts for their most optimistic and pessimistic estimates. Such an approach seems to have been followed by Neubauer [7], Rink [5] and Turowski [6].

An alternative approach to the subjective estimation of a and b is based on the identification of product sub-classes within each category. Let us assume that a given category contains n sub-classes. Each sub-class s is identified by its average lifetime interval $[a_s, b_s]$ and the fraction w_s of the total amount of aluminium consumed in a given year in the category. Clearly, $0 < w_s < 1$ and $\Sigma_{s=1}^{n} w_s = 1$. The lifetime interval of the category under study is determined by the weighted sum of the intervals over the sub-classes:

$$a = \sum_{s=1}^{n} w_s a_s,$$

$$b = \sum_{s=1}^{n} w_s b_s,$$

For the German transportation, and building and construction industries, Table 1 illustrates the characterisation of their sub-classes and the derivation of the corresponding lifetime intervals. These sectors were selected due to their importance with respect to domestic consumption. In the last two decades they have accounted for about 50% of the total annual consumption. Moreover, data on their main product sub-classes are available.

Table 1
Determination of lifetime intervals for the transportation and building and construction industries in Germany

End use	Sub-class	Aluminium consumption (%)[a]	Age upon disposal (years)[b]		Contribution to total age (years)	
			Min	Max	Min	Max
		$100 \times w_s$	a_s	b_s	$w_s a_s$	$w_s b_s$
Transportation	Passenger cars, caravans	76.5	8	15	6.12	11.48
	Trucks	15.9	10	15	1.59	2.39
	Trains	4.1	30	30	1.23	1.23
	Aircraft, spacecraft	1.6	20	20	0.32	0.32
	Ships, ferries	1.3	60	60	0.78	0.78
	(Motor) bikes	0.6	8	12	0.05	0.07
	Sum	100.0			10	16
Build. & Const.	Window and door frames	64.5	20	40	12.90	25.80
	Handles, fittings, locks	9.7	20	40	1.94	3.88
	roofs, walls	11.3	50	50	5.65	5.65
	Facades	9.7	20	35	1.94	3.40
	Wire, screws, rivets	4.8	20	30	0.96	1.44
	Sum	100.0			23	40

[a] Source: [26] for transportation, [27] for building and construction.
[b] Source: [28] for transportation, [29] for building and construction.

3.2. Selection of a lifetime distribution

Once an interval $[a, b]$ has been identified for each end use category, the next step is to place a probability density function on $[a, b]$ that is thought to be representative of the lifetime distribution of the products in the category. It is unlikely that the probability of discarding a product will remain constant in the interval $[a, b]$. A more realistic assumption is to consider that some kind of gradual ageing takes place yielding an increasing probability until a certain age after which the probability of scrapping a product gradually declines. In the next sections the normal, Weibull and beta distributions will be introduced and their adequacy for modelling the time to disposal of products containing aluminium will be discussed. Before describing these models in detail we introduce the main notation used in the following sections. Let T denote a continuous random variable representing the lifetime of products belonging to a given end use category. In addition, let p_t be the probability that products have a service life of t years, that is,

$$p_t = IP(t \leq T \leq t+1)$$
$$= \int_t^{t+1} f(x)\, \mathrm{d}x$$

with $f(x)$ the probability density function (p.d.f.) of T. The probability p_t corresponds to the area under the graph of the density function enclosed between t and $t+1$. The choice of an appropriate density function may be evoked from experts through judgmental assessments or obtained from historical data. For the special case of the German aluminium market, very little knowledge is available about the actual life distribution of products. Hence, expert judgment will be used.

The selection of a model is greatly influenced by the form of the associated distribution. The p.d.f. of a continuous distribution is characterised by three types of parameters: location, scale and shape parameters [8]. A *location parameter* (also known as shift parameter) specifies a location point in the t axis of the distribution's range of values. As this parameter changes, the associated distribution merely shifts to the left or right without otherwise changing its shape. A *scale parameter* determines the scale (or unit) of measurement of the values in the range of the distribution. A change in this parameter compresses or expands the associated distribution without altering its basic form. Finally, a *shape parameter* determines the basic form or shape of a distribution within a given family of distributions. The properties of a distribution are more influenced by changes in this parameter than a change in location and scale.

3.2.1. The normal model

The few authors who favour a statistical approach for modelling the ageing process of aluminium applications, among those Rink [5] and Turowski [6], choose the normal distribution as a life model. The normal (or Gaussian) distribution is the most widely used of all statistical models and empirical evidence has indicated that it provides a good representation for many physical phenomena. Examples include

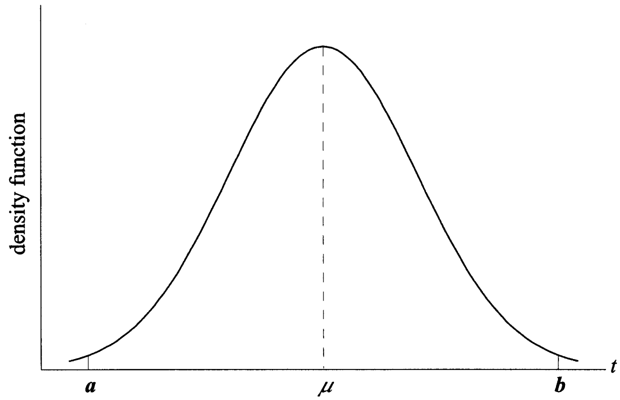

Fig. 2. The density function of the normal distribution. The area enclosed in the range $a \leq t \leq b$ represents 99.7% of the total area. The area under the curve between any two points x and $y (a \leq x < y \leq b)$ gives $IP(x \leq T \leq y)$.

errors of various types (e.g. instrumentation errors), average temperature in a given area and scores on an intelligence test [8]. The theoretical justification for the role of the normal distribution is a central limit theorem [9], which states that the distribution of the mean of n independent observations from any distribution, or even from up to n different distributions, with finite mean and variance approaches a normal distribution as the number of observations in the sample becomes large, that is, as n approaches infinity. The result holds regardless of the original distribution of each of the n observations. When a random variable represents the effect of a large number of independent small causes, the central limit theorem thus leads us to expect the distribution of that variable to be normal. This argument could be applied in our case due to the large number and variety of products that contain aluminium. Therefore, the ageing process of the metal depends upon the time until disposal of all different products.

A normally distributed variable is characterised by a location parameter μ and a scale parameter σ. The distribution has no shape parameter. It can easily be proven that the parameters μ and σ are the mean and the standard deviation of the distribution, respectively [8]. The variance of the distribution is given by σ^2.

The graph of a normal variate is a bell-shaped curve which is symmetric about the mean μ. Since the distribution is to be placed in the lifetime interval $[a, b]$, it follows that the mean must coincide with the midpoint of the interval, that is, $\mu = (a + b)/2$ as shown in Fig. 2. Regarding the standard deviation σ, a value should be selected such that the area under the distribution is located within the ranges of the interval $[a, b]$. Since the range of variation of a normal distribution is minus to plus infinity, it is not possible to have the distribution completely enclosed in $[a, b]$. However, one can set a percentage sufficiently close to 100% in order to obtain σ. It can be shown that 99.7% of the area under a normal distribution is located within the range $\mu \pm 3\sigma$ [8]. This corresponds to setting $\mu - 3\sigma = a$ and $\mu + 3\sigma = b$. Since $\mu = (a + b)/2$, it follows that $\sigma = (b - a)/6$.

With the knowledge of μ and σ we can determine the probability p_t that products are scrapped t years after having been sold to end consumers:

$$p_t = \int_t^{t+1} \frac{1}{\sigma\sqrt{2\pi}} \exp\{-(x-\mu)^2/2\sigma^2\}\,\mathrm{d}x, \quad a \leq t < b$$

with

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\{-(x-\mu)^2/2\sigma^2\}$$

the p.d.f. of the distribution.

Instead of evaluating the above integral by approximate methods [10], we can transform the variable T into the so-called standard normal for which tabulated values can be found in most statistics books. This leads to

$$p_t = \Phi\left(\frac{t+1-\mu}{\sigma}\right) - \Phi\left(\frac{t-\mu}{\sigma}\right), \qquad a \leq t < b,$$

with $\Phi(x) = IP(X \leq x)$ the tabulated standard normal variate X with mean 0 and standard deviation 1. This function is embedded in a number of software packages that are commercially available for desktops.

As illustrated in Fig. 2, the normal model ensures an equal probability of selecting values that are the same amount above and below μ. This characteristic does not always provide an appropriate representation of the lifetime. In many practical applications a skewed distribution is preferred since it can portray gradual ageing through an increasing probability until a certain age after which the probability of scrapping a product gradually declines. The Weibull model allows such a description of the lifetime. Its main characteristics will be described in the next section.

3.2.2. The Weibull model

The main justification for considering the Weibull distribution is that it has been shown experimentally to provide a good fit to many different types of lifetime data. For example, satisfactory representations have been obtained for time to failure phenomena concerning electron tubes, relays and ball bearings. In economic applications, the years to failure for some businesses have also been found to follow a Weibull distribution [11].

A Weibull random variable T is characterised by a location parameter a, a scale parameter α and a shape parameter β. The p.d.f. of the distribution is given by

$$f(t; a, \alpha, \beta) = \begin{cases} \alpha\beta^{-\alpha}(t-a)^{\alpha-1}\exp\{-((t-a)/\beta)^{\alpha}\} & \text{if } t > a, \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

for $a \geq 0$, $\alpha > 0$ and $\beta > 0$. Fig. 3 presents plots of the density function of various Weibull variates.

The probability p_t that a product has a service life of t years is given by

$$p_t = \exp\{-((t-a)/\beta)^{\alpha}\} - \exp\{-((t+1-a)/\beta)^{\alpha}\}, \qquad a \leq t < b. \tag{2}$$

From the definition of p.d.f. in Eq. (1) it follows that the Weibull can take values from a up to infinity. Since we want to fit the model into a given interval $[a, b]$, we may stipulate that a percentage $\gamma \times 100\%$ of the total area under the curve of the density function must be located within the ranges a and b, that is,

$$IP(a \leq T \leq b) = 1 - \exp\{-((b-a)/\beta)^{\alpha}\} = \gamma. \tag{3}$$

Recall that in the normal model we set $\gamma = 0.997$. In addition to the above equation we need a second condition to be able to determine the values of the parameters α and β. A measure of interest that characterises the distribution is the *mode* (m). The mode or modal value corresponds to the point in which the maximum value of the p.d.f. is attained. The mode can be interpreted as the most likely value to be observed. The mode of a normally distributed variate coincides with its mean μ. In the case of the Weibull, if $\alpha = 1$ then $m = a$, otherwise

$$m = a + \beta\left(\frac{\alpha - 1}{\alpha}\right)^{1/\alpha}, \qquad \alpha \geq 1. \tag{4}$$

The distribution in Fig. 3 with $a = 10$, $\alpha = 2$ and $\beta = 2$ has its maximum at 11.4. In case $a = 10$, $\alpha = \beta = 8$, the mode becomes 17.9.

Given a subjective estimate of m, the parameters α and β are calculated by solving Eqs. (3) and (4) under the assumption that $\alpha \geq 1$. The solution of this system of equations is presented in the appendix.

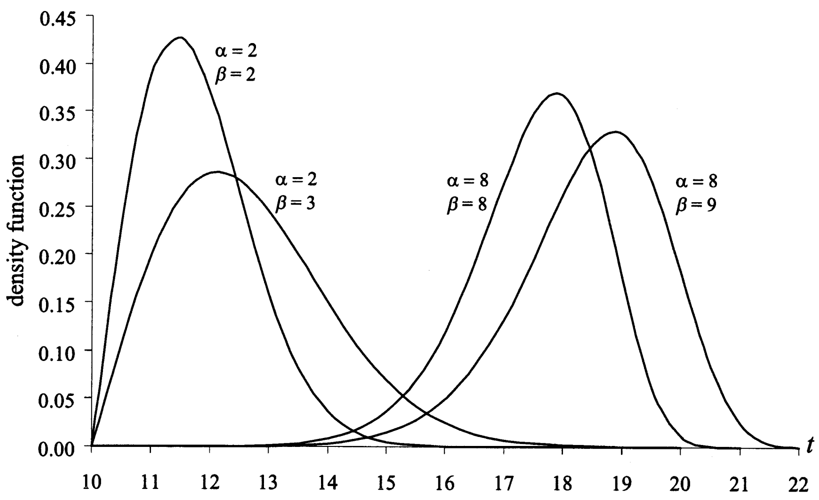

Fig. 3. Density functions of the Weibull distribution for $a = 10$ and various values of α and β.

In selecting a subjective estimate of the mode one should bear in mind that $m \in]a, b[$. Choosing a value smaller than the midpoint of the interval (i.e. $m < (a+b)/2$) yields a positively skewed distribution, that is, a distribution with a right tail similar to those displayed in Fig. 3 for $\alpha = 2$. Many real-world data often have this shape. In our case, it indicates that there is a higher probability that products last less than $(a+b)/2$ years. Conversely, the selection of a value larger than $(a+b)/2$ leads to a distribution that is skewed to the left as shown in Fig. 3 for $\alpha = 8$.

With the knowledge of α and β, the probabilities p_t of scrapping products with a service life of t years are easily obtained from Eq. (2). Also, we can determine the mean (μ) and variance (σ^2) of the distribution:

$$\mu = a + \frac{\beta}{\alpha}\Gamma\left(\frac{1}{\alpha}\right),$$

$$\sigma^2 = \frac{\beta^2}{\alpha}\left\{2\Gamma\left(\frac{2}{\alpha}\right) - \frac{1}{\alpha}\left[\Gamma\left(\frac{1}{\alpha}\right)\right]^2\right\},$$

with $\Gamma(x)$ the well known Gamma function, i.e.

$$\Gamma(x) = \int_0^\infty t^{x-1}\,\mathrm{e}^{-t}\,\mathrm{d}t.$$

Tabulated values for this function can be found for example in [12]. Also, many software packages available for desktops include an implementation of $\Gamma(x)$.

The popularity of the Weibull model comes not only from the fact that it provides a good description of many types of lifetime data, but also from the simple expression of the density function in Eq. (1) which makes the calculation of the probabilities p_t in Eq. (2) straightforward.

3.2.3. The beta model

The beta model is frequently used based on the premise that very little knowledge is available about the actual distribution and its associated parameters, e.g. only subjective estimates of high, low and most likely values are available. Moreover, the beta distribution is a useful model for variates whose values are restricted to an identifiable interval. This occurs in our case for the ageing process of products containing aluminium which makes the beta model a natural candidate to approximate the lifetime distribution.

Another important characteristic of the distribution refers to its modelling flexibility due to the large variety of shapes it can assume and that are likely to arise in practice. As a result, it can approximate a wide range of random variables, including positively skewed, negatively skewed and symmetrical variates. Fig. 4 presents plots of beta distributions in the interval [0, 1] for different combinations of the shape parameters α_1 and α_2 that characterise the distribution. Note that the beta has no scale parameter.

Typical applications of the beta distribution include the estimated time to complete a task in so-called PERT networks, the proportion of defective items in a production line and the proportion of a population located between the lowest and highest values in a sample [8]. Applications also arise frequently in quality control and reliability.

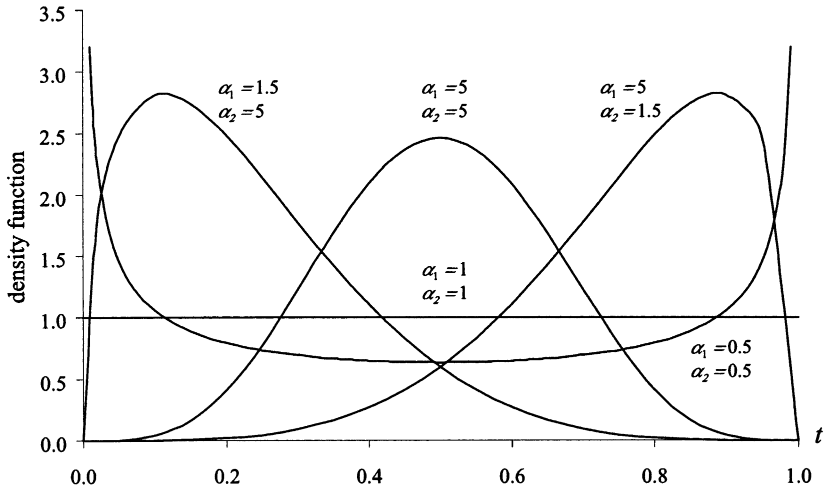

Fig. 4. Density functions of the beta(α_1, α_2) in [0, 1].

The beta p.d.f. defined over the interval $[a, b]$ is

$$f(t; a, b, \alpha_1, \alpha_2) = \frac{1}{b-a} \frac{\Gamma(\alpha_1+\alpha_2)}{\Gamma(\alpha_1)\Gamma(\alpha_2)} \left(\frac{t-a}{b-a}\right)^{\alpha_1 - 1} \left(1 - \frac{t-a}{b-a}\right)^{\alpha_2 - 1} \tag{5}$$

with $a < t < b$, $\alpha_1 > 0$, $\alpha_2 > 0$ and $\Gamma(x)$ the Gamma function.

Given an interval $[a, b]$, we need to determine the parameters α_1 and α_2 in order to specify the distribution of the beta random variable T completely. If we assume that the p.d.f. of T is skewed to the right then $\alpha_2 > \alpha_1 > 1$ [13]. Many real-world data often have this shape. In this case, apart from the range $[a, b]$, we also need subjective estimates of the mean μ and the mode m such that $\mu > m$. By [13] it follows that the parameters α_1 and α_2 are estimated by

$$\tilde{\alpha}_1 = \frac{(\mu - a)(2m - a - b)}{(m - \mu)(b - a)}, \tag{6}$$

$$\tilde{\alpha}_2 = \frac{b - \mu}{\mu - a} \tilde{\alpha}_1. \tag{7}$$

As a result, the variance (σ^2) of the beta model is determined by [13]:

$$\sigma^2 = (b-a)^2 \frac{\alpha_1 \alpha_2}{(\alpha_1 + \alpha_2)^2 (\alpha_1 + \alpha_2 + 1)}.$$

To conclude the discussion on the adequacy of the beta as a lifetime model, we note that to obtain the probability p_t that products are scrapped t years after having been sold to end consumers, we need to determine $\int_t^{t+1} f(x)\,dx$ with $f(x)$ the density function in Eq. (5). Although in general this integral has no closed form, there exist tables containing the desired values [12] and numerical procedures for computing them [10]. In addition, a number of commercially available software packages for desktops include implementations of the beta density function.

To conclude this section, we remark that obviously there are many potential life models. Although the Weibull distribution is the most frequently used parametric lifetime model, many other models are available, and are sometimes used in applications [11]. In the absence of data, as it happens in our case, it is very difficult to single out a model as being particularly appropriate. The choice is then made on the basis of considerations such as the degree of complication of the calculations involved using the model and qualitative information gathered from experts.

3.3. An illustrative example

To illustrate the impact the life models presented in the previous section have on the probabilities of scrapping aluminium products, we consider the transportation industry and the corresponding lifetime interval derived in Section 3.1. Recall that $[a, b] = [10, 16]$. If we opt for the normal model, the knowledge of a and b suffices to determine the parameters μ and σ that characterise the distribution. From Section 3.2.1 it follows that this sector has a mean life expectancy of 13 years ($\mu = (10 + 16)/2$) and a variance of 1 year ($\sigma^2 = (16 - 10)^2/36$). The form of the distribution is displayed in Fig. 5. It can be seen, for example, that the probabilities that a vehicle is registered for 11 or 14 years are the same. If we feel that it is more realistic to assume that most vehicles have a lifetime shorter than 13 years, we should select the Weibull or the beta model. In the first case, in addition to a and b we also need a subjective estimate of the most likely lifetime, that is, of the mode of the distribution. Assuming that the most likely value is $m = 11.8$ years, it follows

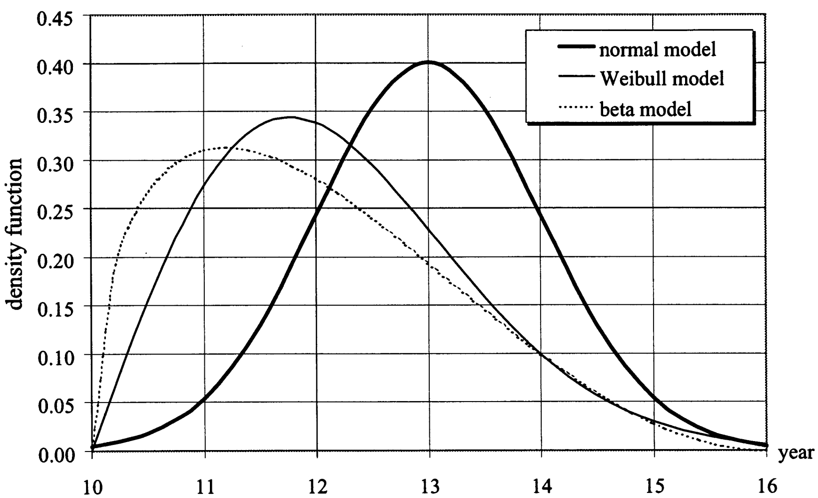

Fig. 5. The density functions of the normal, Weibull and beta models for the lifetime distribution in the transportation industry.

Table 2
The probabilities p_t of scrapping a product with a service life of t years according to the normal, Weibull and beta models selected in the interval $[a, b] = [10, 16]$

Year	Lifetime model		
	Normal	Weibull	Beta
t	p_t	p_t	p_t
10	0.021	0.148	0.242
11	0.136	0.325	0.304
12	0.341	0.290	0.239
13	0.341	0.160	0.145
14	0.136	0.059	0.061
15	0.021	0.015	0.009
Sum	0.996	0.997	1.000

from the algorithm in the appendix that $\alpha = 2$ and $\beta = 2.5$. Fig. 5 indicates the form of the Weibull model with these parameters. In this case, vehicles have a mean life expectancy of 12.2 years ($\mu = 10 + 2.5\sqrt{\pi/2}$) and a variance of 1.3 years ($\sigma^2 = 10 + 2.5/\sqrt{2}$). Finally, if we favour the beta model, subjective estimates of the mean and the mode are required in order to determine the shape parameters α_1 and α_2. Supposing that the mean life expectancy is 12 years ($\mu = 12$) and the most likely lifetime is 11.2 years as in [14] (i.e. $m = 11.2$), it follows by Eq. (6) and Eq. (7) that $\alpha_1 = 1.5$ and $\alpha_2 = 3$. Furthermore, the variance equals 1.5 years. The shape of the beta model is shown in Fig. 5. If we had chosen the mode $m = 11.8$ years, a similar shape to that of the Weibull model would have been obtained.

As a result of the different shapes considered for the lifetime of vehicles, the areas below the graphs of the density functions in each interval $[t, t + 1]$ for $t = 10,\ldots, 15$, vary substantially. In other words, the probabilities p_t of discarding vehicles t years after having been sold to end consumers, differ considerably as indicated in Table 2. Both the Weibull and beta models have a right tail indicating that there is a higher probability that products last less than 13 years. For example, if the Weibull model is used, there is a 32.5% chance that the service life is 11 years while in the normal model the chance is about two times lower, namely 13.6%.

4. Old scrap generation in Germany

For a given end use category, the potential arising of old scrap depends on the metal content in manufactured goods that are sold to end consumers, and on the duration of their service life. It is shown in [15] that regardless of the statistical model selected to describe the lifetime, the expected volume of old scrap that is theoretically generated in year j in a given end use category is calculated by

$$S_j = \sum_{t=a}^{b-1} c_{j-t} p_t \qquad (8)$$

with c_{j-t} denoting the amount of aluminium consumed in year $j-t$ in the category. Consumption figures by end use categories can be found in [3].

By identifying lifetime intervals for the different end use categories and defining the corresponding parameters of the lifetime models described in the previous section, we estimated the total annual potential arising of old scrap in Germany. The characteristics of the models chosen for the German aluminium market are indicated in Table 3. Recall that the modal value of a normally distributed variate coincides with the mean (i.e. $\mu = m$), and therefore it is not included in the table. In the beta model, the mean was selected by truncating the value of μ in the Weibull model. To the value thus obtained one unit was subtracted in order to set the mode. In the transportation sector, however, the mode ($m = 11.2$) was chosen according to [14].

All lifetime intervals in Table 3 are taken from Rink [5] with the exception of those in the transportation and building and construction industries, which result from the calculations presented in Section 3.1. Packaging products such as beverage cans and foil articles have a short lifetime that varies from a few weeks to some months. Since consumption data for this sector are only available on an annual basis, we assume a fixed lifetime of one year. For comparison purposes, this simple approach is extended to the other end use categories by setting the lifetime equal to the midpoint of the interval $[a, b]$. If $(a+b)/2$ is not integer, we round it off. Clearly, the potential arising of scrap in a given year j corresponds to the amount of aluminium used in the category $j-(a+b)/2$ years previously. In addition to this simple procedure, we consider a further approach suggested by Glimm [16], which consists in deriving a weighted lifetime for the whole aluminium sector. This is accomplished by assigning weights to the fixed lifetime in each end use category. The weights correspond to the share of each category in the total volume of aluminium consumed in a given year. Due to the variability of the latter, the weighted average lifetime in the aluminium market may also change with time. The total volume of old scrap generated in year j is approximated by the consumption in year $j-\hat{w}_j$, with $\hat{w}_j$ denoting the weighted lifetime in year j, that is,

$$\hat{w}_j = \frac{1}{TC_j} \sum_s \tau_s c_{sj}, \tag{9}$$

where, τ_s is the fixed lifetime in end use category s, i.e. the midpoint $((a+b)/2)$ of the lifetime interval $[a, b]$ derived for the category; c_{sj} is the aluminium consumed in end use category s during year j; and TC_j is the total volume of aluminium consumed during year j, i.e. $TC_j = \Sigma_s c_{sj}$.In case $\hat{w}_j$ is not integer, we round it off. For $j = 1986$ and $j = 1987$ the weighted average lifetime equals 14 years. Afterwards, we obtain $\hat{w}_j = 15$. This means that after 1987 we simply need to shift the total aluminium consumption by 15 years. The potential arising of old scrap given by this procedure is termed *weighted lifetime*.

4.1. Potential scrap generation

Fig. 6 displays the theoretical volume of aluminium old scrap that could be generated in Germany in the time period 1986–2012. A common characteristic of

Table 3
Lifetime intervals, mean life expectancy and most likely service life (in years) by end uses in Germany

End use	Lifetime interval (years)	Mean life expectancy (μ) (years)			Most likely service life (m) (years)	
	$[a, b]$	Normal	Weibull	Beta	Weibull	Beta
Transportation	[10, 16]	13.0	12.2	12.0	11.8	11.2
Mechanical engineering	[10, 20]	15.0	13.6	13.0	12.9	12.0
Electrical engineering	[10, 25]	17.5	15.5	15.0	14.4	14.0
Building and construction	[23, 40]	31.5	29.3	30.0	28.0	30.0
Packaging	1					
Household and office equipment	[5, 15]	10.0	8.6	8.0	7.9	7.0
Other	[5, 15]	10.0	8.6	8.0	7.9	7.0

the three statistical models is the smooth progress of the old scrap estimates over time. In contrast, the deterministic lifetime approaches are very sensitive to fluctuations in consumption. This feature is clearly illustrated for the years 2006 and 2008. Since the transportation industry is the largest consumer of aluminium, variations in consumption in this sector have a strong impact on the total generation of old scrap. The recession that occurred in 1993 in the sector (Fig. 1) is reflected 13 years later in the scrap estimates when the fixed lifetime approach is used. The statistical models translate the effect of the recession in a more realistic way by considering that the generation of scrap will gradually decrease during a certain future time period, namely 2003–2004 in the Weibull and beta models, and 2005–2006 in the normal model. The fixed lifetime approach overestimates the scrap availability in the time period 2003–2005, and yields a pessimistic estimate of 1037 kt for the year 2006 which corresponds to an abrupt decrease of 14% compared to the previous year. Furthermore, the estimation for 2006 is 8% lower than that of the normal model (1128 kt), and 12% lower than that of the Weibull and beta models (1180 kt). Similar differences occur in 1997. Regarding the weighted lifetime approach, the recession of 1993 in the transportation industry is reflected 15 years later, namely in 2008, although it is not so pronounced as in the fixed lifetime procedure due to the assignment of weights to the lifetime in each category based on the total volume of aluminium consumed. Nevertheless, this approach has the disadvantage of not taking explicit account of the large differences in the ageing processes of the end use categories. With the exception of 1990, for the time period 1986–1995 this procedure yields considerably higher estimates than all the other approaches. Overestimation or underestimation of the scrap availability may naturally have a negative impact on the planning of future activities in the aluminium industry.

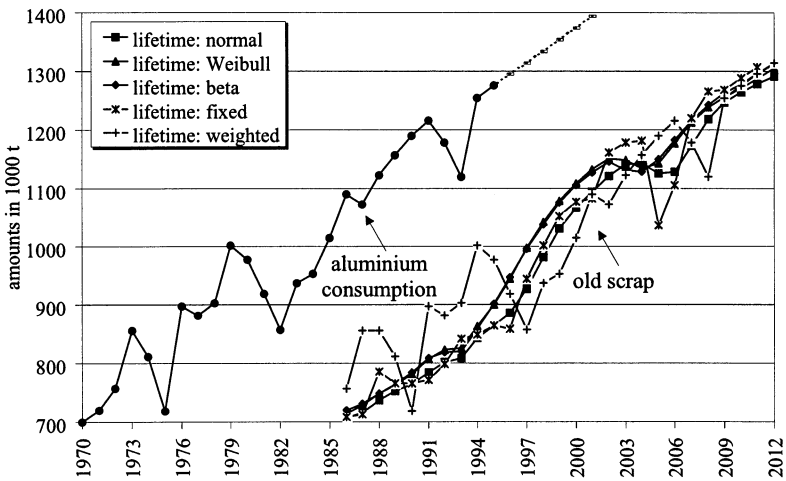

Fig. 6. Estimation of total old scrap potential in the German aluminium sector assuming an annual consumption growth of 1.5% after 1995.

From Fig. 6 we observe that there are no significant differences in choosing the Weibull or the beta distributions as life models. This is not unexpected since the parameters selected for these distributions yield similar density functions (Fig. 5). The differences in old scrap estimates between the normal and the other two statistical life models result from the distinct shapes of the distributions, as shown in Fig. 5 for the transportation industry, combined with the growth trend in consumption. It is interesting to notice that the old scrap estimates for 2010 reach the consumption level of 1995. As long as aluminium consumption keeps on growing rapidly, the recovery of old scrap will not cover supply demands in the near future since large amounts of aluminium are stored in long-life products (especially in building and construction, see Table 1).

4.2. Expected net scrap

The results displayed in Fig. 6 are obtained under the assumption that 100% of the aluminium sold to end consumers is returned to the secondary industry for recycling. In practice, only a fraction of the theoretically generated amount is recovered. Many factors have an impact on the recovery of old scrap as described by Rink [5], such as the foreign trade in semi-fabricated and finished products. Both the statistics in Refs. [17] and [3] do not take into account the metal content in semi-fabricated and manufactured goods that are imported and exported. Also, only aggregated figures on international scrap trade including both new and old scrap are available in [17] and [3].

An important factor affecting the recovery of metal is the cleanliness of scrap. Contaminants often pose an obstacle for separation after disposal, and thus reduce the economic feasibility of recovering metal scrap [18]. Conversely, state regulatory measures have a positive impact on the volume of scrap that is actually recovered for recycling. This could be observed after the release in 1991 of mandatory measures on recycling and reuse of packaging products from municipal solid waste in Germany. Finally, old scrap recovery is sensitive to changes in energy costs as observed by Carlsen [19] and Wernick [20]. Increased energy prices promote secondary consumption and therefore, encourage the reclamation of scrap.

Since it is very difficult to quantify the impact of the above described elements, Rink [5] suggests using recycling rates by end uses to determine the actual volume of old scrap that is annually generated. For instance, it is claimed that nowadays 90% of post-consumer aluminium scrap from the transportation industry is recycled. Hence, at least 90% of the potential old scrap arising in this sector should be available to the secondary industry (that is, $0.9 \times S_j$ with S_j given by Eq. (8)). Table 4 indicates the recovery potential by end uses. Until 1992 a relatively small fraction of scrap arising in the packaging industry used to be recovered. The introduction of federal legislation in 1991 changed this situation and currently it is estimated that about 40% of aluminium contained in packaging products is recycled [21]. In our calculations we took into account the transition that started at the end of 1992, and assumed until then a recovery rate of 6% of packaging scrap. In 1993 and 1994 we fixed the rate at 20 and 30%, respectively. For the subsequent years we took 40%.

Table 4
Recovery potential of old scrap in Germany by end uses [26,5]

End use	Recovery potential (%)
Transportation	90
Mechanical engineering	80
Electrical engineering	80
Building and construction	85
Packaging	3–6 until 1992, currently 40
Household and office equipment	20
Other	Not available

The category *Other* in Table 4 includes diversified aluminium applications in chemical, agricultural, powder consuming, iron and steel industries, and miscellaneous uses. About one third of the aluminium consumed in this category is used as an ancillary metal in the iron and steel industries, and is not recovered. Since no information is available concerning the recovery potential of the remaining applications, we did not include this category in the further analysis.

Using the above rates we recalculated the potential volume of old scrap generated between 1986 and 2012. The results obtained are depicted in Fig. 7. Recall that in the weighted lifetime approach, old scrap generated in a given year j corresponds to the volume of aluminium consumed in year $j - \hat{w}_j$, with $\hat{w}_j$ defined by Eq. (9). Hence, to determine the amount of old scrap that is likely to be annually recovered, we first need to obtain the average recovery potential for the whole aluminium industry. For the values indicated in Table 4 the total average recovery potential

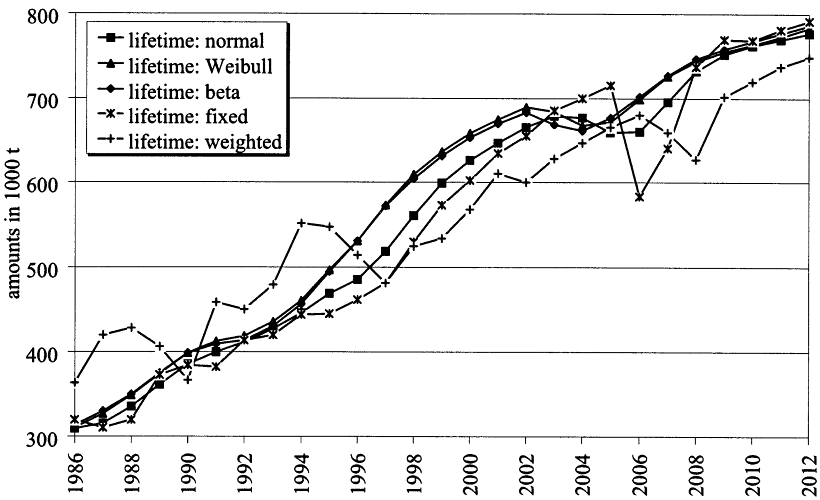

Fig. 7. Estimation of total net old scrap potential in the German aluminium sector assuming an annual consumption growth of 1.5% after 1995.

varies between 50 and 56%, depending on the rates chosen for the packaging industry. We applied these rates to the gross values displayed in Fig. 6.

Compared to the theoretical amounts, the recovery potential gradually increases from 43 to 60% in the time period 1986–2012. In other words, of all aluminium sold to end consumers, 43–60% is eventually returned for recycling. Our estimates are below the forecasts of Gielen and van Drill [22] for aluminium scrap recovery in Western Europe. These authors already expect a recovery of 60% by 2000 and claim that it will gradually grow to 75% by 2015. It would be interesting to compare the results displayed in Fig. 7 with the actual amounts of old scrap collected. Unfortunately, detailed statistics on scrap recovery do not exist for the German aluminium market. Rink [5] predicted that about 430 kt of old scrap were collected in 1991. The statistical models only deviate 5% yielding 408 kt, while the fixed lifetime procedure lies 11.2% below. The weighted lifetime approach estimates that 6.5% more scrap should have been collected.

5. Conclusions

In this study several models for estimating the potential arising of metal scrap were developed. The modelling approach consisted in first aggregating metal-containing products into end use categories and then employing statistical distributions to describe the service life of products in each category. This statistical approach was applied to the German aluminium market. Due to the absence of historical data regarding the age of products upon disposal, it is very difficult to single out a model as being particularly appropriate for representing lifetime. The choice is made on the basis of considerations such as the degree of complication of the calculations involved using the model and qualitative information gathered from experts. Naturally, modelling uncertainty on the basis of subjective judgments by experts is not exempt of criticism. We considered the normal, Weibull and beta distributions as life models. In contrast to the normal, the other two models have the advantage of assuming a wide variety of shapes that are likely to arise in practice. In terms of analytical tractability, the Weibull distribution is easier to manipulate. The results obtained show that the proposed models yield better estimates of old scrap than commonly used approaches that assume a fixed service life for products. The fixed lifetime procedures are highly influenced by fluctuations in the consumption of metal, and can significantly underestimate or overestimate the scrap potential. Hence, the information provided by such approaches may naturally have a negative impact on the planning of future activities in the secondary and primary industries. Although our models were applied to the German aluminium market, they can easily be extended to other countries and metals. As a final note, we remark that more attention should be focused on the development of reliable techniques to estimate metal scrap generation, since they provide a valuable assistance in decision making both in secondary and primary industries. The models presented in this study give a contribution in this direction. Alternative techniques dealing with the subjective assessment of uncertainty include e.g. those described by Clemen [23] and those provided by Bayesian analysis [24].

Appendix A. Estimating the parameters in the Weibull model

To determine the scale parameter α and the shape parameter β that characterise the Weibull model we need to solve the system of non-linear equations derived in Section 3.2.2:

$$1 - \exp\{-((b-a)/\beta)^{\alpha}\} = \gamma \tag{10}$$

$$a + \beta\left(\frac{\alpha-1}{\alpha}\right)^{1/\alpha} = m \tag{11}$$

with γ the fraction of the distribution that is enclosed in $[a, b]$, and m the modal value. Recall that γ and m are pre-specified. We have chosen $\gamma = 0.997$ (similar to the normal model) and selected m according to the values indicated in Table 3.

Using the relations $x^y = \exp(y \ln x)$ and $\ln(x/y) = \ln x - \ln y$, it follows by Eq. (10) that

$$\left(\frac{b-a}{\beta}\right)^{\alpha} = \ln\left(\frac{1}{1-\gamma}\right)$$

$$\Leftrightarrow \alpha[\ln(b-a) - \ln\beta] = \theta$$

with $\theta = \ln\ln(1/(1-\gamma))$.

Knowing that $\ln x^y = y \ln x$, we obtain from Eq. (11) that

$$\ln\beta = \ln(m-a) - \frac{1}{\alpha}\ln\left(\frac{\alpha-1}{a}\right).$$

Replacing $\ln\beta$ in Eq. (5) by the above expression yields

$$\alpha\ln\left(\frac{b-a}{m-a}\right) + \ln\left(\frac{\alpha-1}{\alpha}\right) - \theta = 0. \tag{12}$$

Since the above non-linear equation cannot be solved analytically for α, we must use a numerical procedure such as Newton's method or some other iterative scheme. The solution of Eq. (12) by employing Newton's method [25] involves calculating

$$\alpha_{k+1} = \alpha_k - \frac{f(\alpha_k)}{f'(\alpha_k)} \tag{13}$$

with

$$f(\alpha_k) = \alpha_k \ln\left(\frac{b-a}{m-a}\right) + \ln\left(\frac{\alpha_k-1}{\alpha_k}\right) - \theta,$$

and $f'(\alpha_k)$ the first derivative of f, that is,

$$f'(\alpha_k) = \ln\left(\frac{b-a}{m-a}\right) + \frac{1}{\alpha_k(\alpha_k-1)}.$$

Given an initial value α_0, we use Eq. (13) to determine α_1. This process is repeated until the difference between two successive iterative points α_{k-1} and α_k is within a

Table 5
Illustration of Newton's method for the transportation sector

k	α_k	$f(\alpha_k)$	$f'(\alpha_k)$	$\|\alpha_{k-1}-\alpha_k\|$
1	1.10000	−2.83296	10.29488	
2	1.37518	−1.40268	3.14217	0.27518
3	1.82159	−0.36252	1.87216	0.44641
4	2.01522	−0.01878	1.69275	0.19364
5	2.02632	−0.00004	1.68482	0.01109
6	2.02634	−0.00000	1.68481	0.00003
7	2.02634	−0.00000	1.68481	0.00000

given tolerance ε, that is, $|\alpha_{k-1} - \alpha_k| < \varepsilon$. For the six end use categories indicated in Table 3 the algorithm is started with $\alpha_0 = 1.1$. Taking a precision $\varepsilon = 1 \times 10^{-5}$, convergence is attained within a few iterations. Upon determining α, the shape parameter β is easily obtained from Eq. (11).

An illustration of the iterative procedure is given in Table 5 for the transportation sector. Recall that $[a, b] = [10, 16]$ and $m = 11.8$. The method yields $\alpha = 2.02634$ and by Eq. (11) it follows that $\beta = 2.51807$.

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A NEW SYSTEM FOR THE CLASSIFICATION OF ALUMINIUM SCRAP MATERIAL*

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ABSTRACT

Different fields of application result in a combination of aluminium or the Al-alloy with many different materials. According to the manifestations of the product aluminium, there are a large number of different aluminium scrap materials available on the market for secondary raw material. For the support of an optimal system for the management of material flow in the processing, re-melter and refiner industry a classification system should be created.

This paper shows the advantages of an aluminium-classification-system and explains the parameters which were used to analyse and describe aluminium-particles.

KEYWORDS

Classification, scrap, class-criteria, alloys, material differentiation

* Source: Proceedings REWAS, San Sebastian, 1999

1 Introduction

Metallic raw materials, particularly aluminium, are used in many different areas. Aluminium be applied in almost all sectors or industries. Each application places special demands on the material aluminium. This fact requires numerous variations of the product aluminium. These differences are especially characterised by the used aluminium alloy and the physical form. Furthermore, the different fields of application result in a combination of aluminium or the Al-alloy with many different materials.

After the use of aluminium, this material arises within the different areas as aluminium scrap material. According to the manifestations of the product aluminium, there are a large number of different aluminium scrap materials available on the market for secondary raw material. These materials respectively these flows of material can be distinguished by the aspect of the subsequent treatment or the way of recycling concerning the material and metallurgical composition as well as the physical characteristics. For the recycling of these materials different processes or processing combinations are necessary. Materials with particular characteristics can be processed in an economic way only with certain technologies.

2 Objectives

For the support of an optimal system for the management of material flow in the processing, remelter and refiner industry a classification system should be created. This system enables the arrangement of the different aluminium scrap material in classes, which have defined characteristics within a certain bandwidth. The objective of the classification is to simplify the material flow variety and to summarise or to unite the extensive whole of the aluminium scrap material in classes. Nevertheless, one has to take care that no important data is lost. The definition of the classes is done according to the principle:

"as rough as possible but as fine as necessary "

With the classification-system it is possible to unite those material flows in relative homogeneous classes, which are similar concerning selected processing and metallurgical criteria. The groups themselves should be as different as possible, so that either an existing and natural classification is found or the unstructured totality is ordered as useful as possible.

The following advantages can be expected by the participants of the secondary aluminium industry when applying the instrument "classification system":

- ⇨ development of new sources of aluminium scrap material
- ⇨ bundling of the material flow before processing
- ⇨ better specification of the aluminium scrap material (contribution to quality assurance)
- ⇨ increase of the " transparency of the market "
- ⇨ selection (purchase decision) of aluminium scrap material or classes of such material with which the best overall economic results can be obtained, thus fulfilling the following requirements:
    1. aluminium scrap material is available on the market.
    2. aluminium scrap material can be processed in an economic way with the available processing technology.
    3. aluminium scrap material can in an economical way fulfil the demands of the customer

With the help of the classification system decisions can be supported concerning the purchase of secondary raw material. This can be seen in more detail in Figure 1.

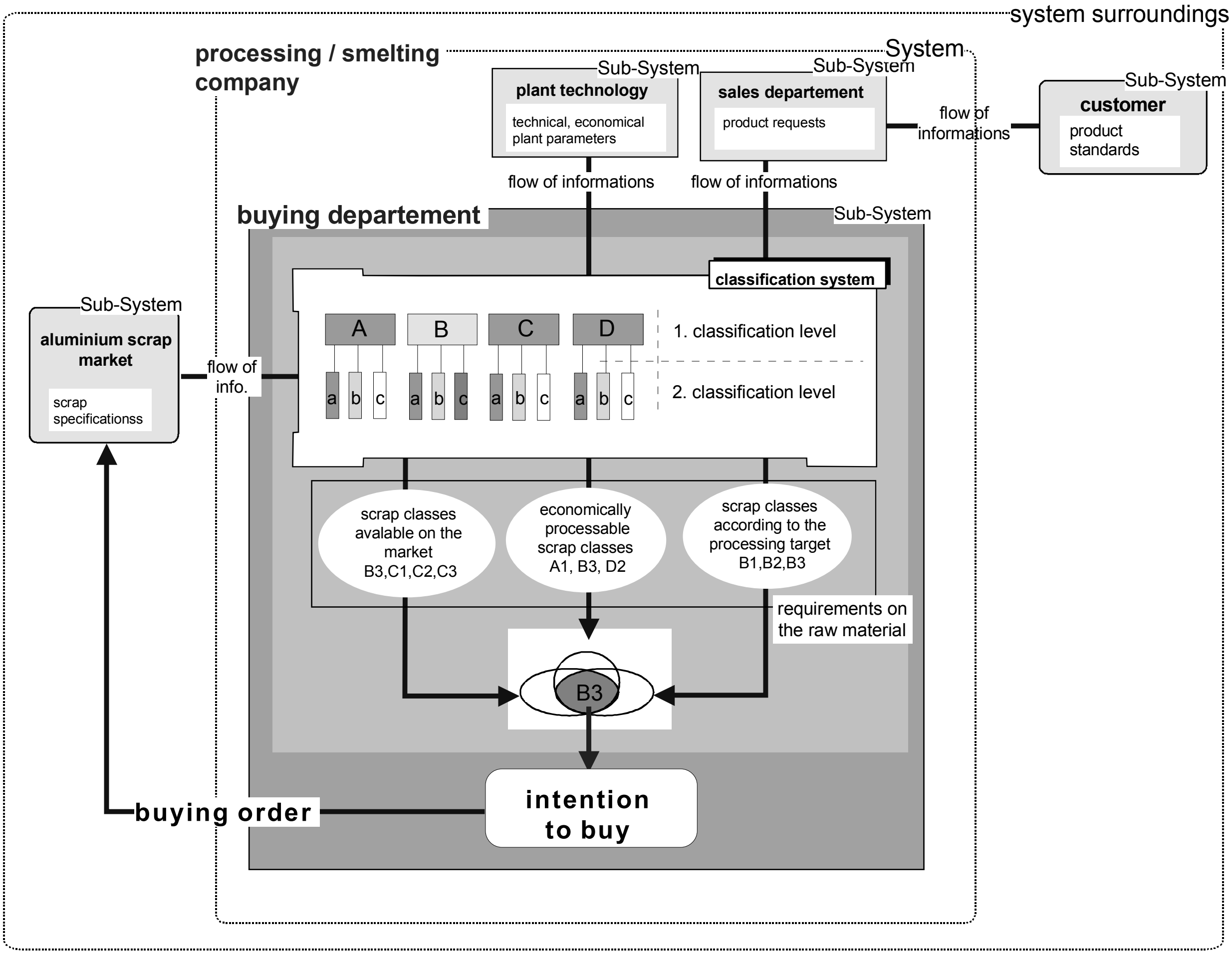

Figure 1: The classification system as an instrument for the purchase of raw material

The classification system should enable the purchase of input material for processing plants with regard to the available technology, the aluminium scrap material available on the market as well as the customer requirements. In this way it is possible to select the aluminium scrap with which the processing aim can be achieved in the most economical way.

To enable the application described above a classification system has to be developed with classes which fulfil the following requirements:

- ⇨ any types of aluminium scrap material can be classified in classes (current and future)
- ⇨ integration of important technical processing and metallurgical characteristic values
- ⇨ material flow with similar characteristics are combined in one class

- ⇨ materials assigned to one class: similar foreign materials contained, same processing- and smelting technology
- ⇨ classes have defined characteristics over a bandwidth as small as possible
- ⇨ aluminium scrap material should be classified in a way that the most economical metallurgical technology can be applied
- ⇨ definition of classes of material which mostly require a remelting

3 Results

In order to define the scrap classes, criteria had to be chosen first. These criteria have to fulfil the following requirements:

- ⇨ criteria have to describe the parameters which are substantial for the system (in this case: processing and metallurgical characteristics of the material flow, which describe the suitability for their use within the different processes or process chains to a sufficient exact extent)
- ⇨ criteria have to permit a significant prediction of the class affiliation
- ⇨ the measurement of sufficiently secured characteristic values has to be possible with small effort

Taking these requirements into consideration, the metallurgical and processing technical criteria for characterising of marking aluminium scrap material and defining classes of aluminium scrap material have been chosen. These criteria are the basis of the classification system. The chosen criteria and their possible variations are listed in Figure 2:

criterion	**possible variations**					
aluminium alloy	wrought	cast	wrought/cast	alloy groups	-	-
Al-content[Gew.-%]	>99	99-90	90-80	80-50	<50	-
format / piece size	compact bundle	large sized, > 50 cm	50-15 cm	15-5 cm	<5 mm	indifferent
thickness [µm]	> 1000	1000-400	400-50	>50	indifferent	-
first combined material	ferrous-metal	non ferrous-metal	organic	inorganic	indifferent	non
type of combination	surface network	layers network	connected components	indifferent	loose	-
second pollution	ferrous-metal	non ferrous-metal	organic	inorganic	indifferent	non
type of combination	surface network	layers network	connected components	indifferent	loose	-

Figure 2: Chosen criteria for the classification of aluminium scrap material

The character of the different criteria is defined within a range of values. Divisions have been found, in order to characterise the aluminium scrap material with regard to the suitable for the different preparation- and smelting-technologies. Thus the different intervals of the criteria define the possible processing-technology.

The aluminium scrap material is classified in different levels according to the importance of each criterion. Within the first level aluminium scrap material is classified according to their metallurgical composition. The second level includes a classification according to the material composition and the physical properties.

A quantity of scrap material consisting of one alloy and being available to a sufficient extent, should be kept into a separate class or assigned to a certain alloy-group. Aluminium scrap material, which consist of different alloys, is assigned to different alloy groups, according to the extend of mixture. Aluminium scrap material of one alloy and arising in a low quantity, is also assigned to these groups. Mixtures of alloys, which cannot be defined, are assigned to the groups “wrought”, “cast” and “wrought/cast”. Aluminium scrap material, consisting of a mixture of similar or of pure alloys, which aren’t available to a sufficient extent for separate storage or processing, are assigned to certain alloy-groups. With the help of clusteranalytic procedures alloy-groups have been defined, taking into consideration the potential quantity of the particular alloys. These groups contain the alloys, which are similar in their metallurgical composition. In this way groups are formed with their metallurgical composition being defined within a bandwidth as small as possible. In the Figure 3 one can see an excerpt of the alloy-groups and their metallurgical composition.

alloy-groups		content [weigth-%]										
		Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Pb	Sn	other
C-AlSi	min	8,000	-	-	0,001	-	-	-	-	-	-	-
	max	13,500	0,800	0,050	0,600	0,375	0,200	0,500	0,050	0,300	0,100	0,050
C-AlSiCu	min	5,000	-	2,000	0,100	0,100	-	-	-	-	-	-
	max	11,000	1,000	5,000	0,400	0,500	0,300	2,000	0,150	0,300	0,100	0,050
C-AlCu	min	-	-	4,200	0,001	-	-	-	0,130	-	-	-
	max	0,150	0,150	5,200	0,500	0,300	0,030	0,070	0,300	0,030	0,030	0,030
C-AlMg	min	-	-	-	0,001	2,700	-	-	-	-	-	-
	max	1,500	0,400	0,030	0,400	5,500	0,050	0,100	0,200	0,050	0,050	0,050

Figure 3: Alloy-groups in the field of castings

After the classification of scrap material in certain alloy-groups, a classification according to the thickness and piece size of the aluminium in the scrap material is done. If a problematic pollution is combined with the aluminium scrap material is classified further according to the particular pollution and the type of combination withe the aluminium.

The classification of selected examples for potential input material of the secondary smelting industry is shown in the Figure 4.

aluminum scrap material	classification
bottle caps from cyrogen-processing	W-AlMg, Al90-99, < 5 cm, 400-1000µm
products of an aluminium shredder plant, input material: collected wrought aluminium scrap	W, Al90-99, 15-5 cm, > 1000 µm
product of an combined aluminium packaging	W, Al90-99, < 5 cm, > 1000 µm
product of an aluminium window preperation plant	W, Al90-99, < 5 cm, > 1000 µm
processed menu trays	W-Al, Al99, compacted, 400-50 µm
Lithosheets	W-Al, Al99, compacted, 400-50 µm
new scrap from the aluminium tape production	W-Al, Al99, compacted, 400-50 µm
product of apreperation plant for household refrigerator	W-AlMn, Al90-99, < 5 cm, > 1000µm
product of a preperation plant for electronic scrap	W-AlMn, Al90-99, < 5 cm, > 1000µm
shredder product, input material: dismantled motors and transmissions from automobile	C-AlSiCu, Al90-99, 15-5 cm, > 1000µm

Figure 4: Exemplary for the classification of aluminium scrap material

4 Conclusions / Outlook

The economical integration of recycling activities or products into the economic system of aluminium production can only be realised by a high standard of quality assurance (reliable quality). Often a material flow cannot be processed in an economical way by a recycling-process, due to a lack of reliably, continuous quality and quantity.

With the help of the criteria defined for the classification of aluminium scrap material, which are scaled over bandwidths, similar scrap material can be concluded into classes. With the classification system the aluminium scrap material is characterised sufficiently exactly with regard to processing-technical and metallurgical aspects. Based on this description a plant in the secondary aluminium industry can conclude on the possible preparation- and or melting-technology enabling the processing of the scrap material.

With the help of this exact and first of all uniform description of the scrap material new sources of secondary raw material can be identified and bundled. This can contribute to the extent of utilisation of the processing plant and can increase the reliability of the quality of the input material.

Therefore the classification system can be used as an instrument for the optimisation of the material flow management of a processing ors melting company.

DEVELOPMENT OF A METHOD TO CREATE A CLASSIFICATION SYSTEM FOR SECONDARY RAW MATERIALS IN THE CASE OF ALUMINIUM

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ABSTRACT[1]

In the field of metal recycling exists a big quantity of different secondary materials which contain aluminium. This is the result of many different applications in various products containing this metal. The character of these fractions differs in a wide range.

A good cooperation between recyclers and metallurgists is necessary to earn economic benefit. The classification system which combines mechanical and metallurgical processing parameters is a very important aspect for analysing metal process chains. Such systems enable the characterisation and classification of all mass streams in the circumstance of the recycling and metallurgical industry.

Therefore, this study develops a classification system for aluminium scraps and alloys. All materials fitting in one class of this system are similar and show the same recycling and smelting behaviour. Thus it is possible to collect and mix bigger quantities of different scraps in one class even before the first processing step.

To ensure that all active parts of the process chain may understand the different classification parameters, a big effort of this study is spend on the comprehensibility and traceability of the system.

The information and results earned within this thesis are further used to develop a non material specific method to set up further classification systems for other secondary raw materials.

[1] Summary of Ph.D. thesis

FUTURE POTENTIAL AND LIMITS OF ALUMINIUM RECYCLING*

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ABSTRACT

The continuously growing importance of the recycling of metals, especially of aluminium as part of the raw material supply is indisputable. Nevertheless there are factors like the impurity level and metal content of secondary raw materials, the multiplicity of alloys, and the increasing amount of composite materials which can limit recycling activities to a certain degree. Further questions result from future development of recycling rates, metal losses during production, manufacturing and use of the materials and their impact on the entire mass flow of primary and recycled aluminium.

This article focuses on recycling potentials of aluminium in Germany concerning the availability and quality of scrap or other secondary raw materials, technological development of material processing and remelting and the efficiency of complete recycling concepts now and in future.

In the same way the limits of aluminium recycling are discussed, depending on scrap condition and availability and technology as well as on quality and ecological aspects. The results can help to identify for example a minimum energy demand at increasing recycling rates of certain secondary raw materials.

KEYWORDS

Aluminium, scrap, secondary material, recycling, recycling potential, metal loss

* Source: Proceedings of EMC 2001

1. Introduction

The topics of discussion about the burdens of production and use of metals are changing. Currently sustainable development is the main subject following life cycle (impact) assessment, eco-auditing, precautionary environmental protection and design for environment. In all these concepts of modern life cycle management recycling plays a substantial role mainly due to following facts:

- The atomic structure of metals ensures their unrestricted recyclability
- Recycling is an important part of the raw material supply
- The saving of energy by re-using the metals content can achieve 95%

The recycled contents of non-ferrous metal production in table 1 clarify the high importance of the recycling for the metal supply of the semi-finished product manufacturers and the foundries. Products of lead and copper have with 51 and 39 % a high recycled content. On the other hand aluminium and zinc show lower values due to their electro-chemically less precious character. The high value for lead results from the application in batteries, where the metal is concentrated and easy accessible for recycling. The values shown are to be interpreted only as order of magnitude, since their calculation are not made uniformly. This aspect is described later.

Table 1: Recycled content of metal production (values in %) [1, 2, 3]

	1990	1995	1997	
	World			Germany
Al	23	26	32	37
Cu	41	42	39	51
Zn	23	27	31	49
Pb	46	48	51	50

The values of the recycled contents in the range of 30 to 50 % point out beside high growth rates in the application of the metals also a large potential for the use of secondary raw materials. If metallic products are returned into the material flow after their use and new alloys are produced out of them, the resulting recycling quotas reach significant higher values of 50 – 95 %. The quota describes thereby the relation of the metal quantity produced during the entire recycling process to the metal quantity available in the end of life product.

2. Availability of secondary raw materials

2.1 Definition of recycling terms

With an exact analysis of the existing metal flow and the used technologies one states the fact that a further problem of the recycling exist in the right use of the recycling terms and thus in the description and evaluation of recycling activities. This article introduces technical-metallurgically based solutions.

The overall recycling quota of metals can be described by the collection quota and the technical recycling quota. This separation clarifies the different levels of the recycling and permits a resource oriented view [4, 5].

- The collection quota CQ is thereby the quantity of available secondary material, which are gathered by collection systems, related to the used product quantity.

$$CQ = \frac{\text{collected quantity}}{\text{used product quantity}} \cdot 100\%$$

- Technical recycling quota RQt: Here the quantity of material is determined, which is actually available for utilisation as secondary metal, i.e. it concerns the yield of the technical process.

$$RQ_t = \frac{\text{amount of remelted aluminium}}{\text{amount of secondary aluminium collected}} \cdot 100\%$$

The technical recycling quota consists of two sections, firstly the processing quota, which indicates, how much metallic aluminium from the collection is supplied for melting, and secondly the smelting yield, which indicates, how much aluminium is won as liquid metal, i.e. herein the losses in the resulting salt cake or dross is considered, see figure 1. Together the recycling quotas from collection, material processing and remelting result in the resource-oriented recycling quota (RQr).

In contrast to the recycling quota the recycled content is the share of secondary metal, which is used for processing. It is usually smaller than the recycling quota because with rising application more primary metal must be produced than it corresponds to the losses during the use phase.

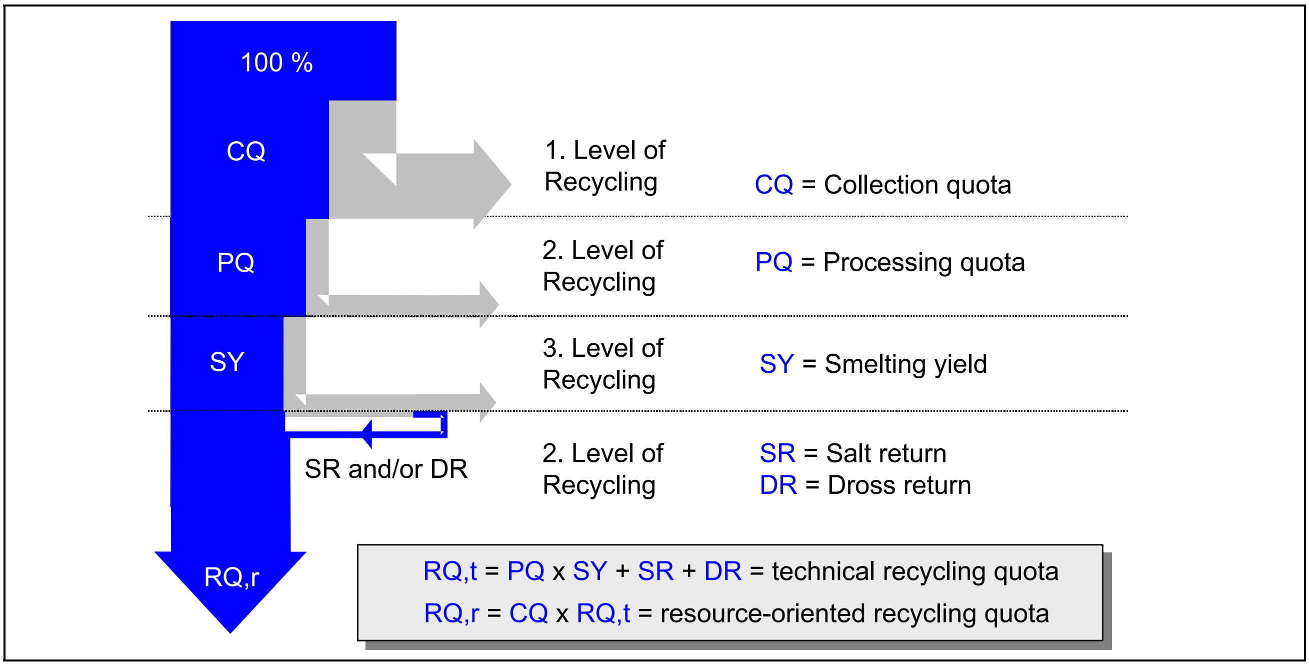

Figure 1: Definition of recycling quotas for collection, processing and smelting [5]

2.2 Current situation

The supply of metal production with secondary raw materials is influenced by various parameters. These are in particular aspects of time and quality, which limit the availability of secondary material.

The difference between the produced and used aluminium quantity in Germany is substantial, like it is shown in the metal statistics, so that the question arises, how is the high metal requirement of the processing industry covered and which role does recycling play thereby. According to figure 2 the recycled content of production would amount to only 18 %, whereby only the secondary aluminium production on cast alloy base is related to the entire metal supply of semi-finished wrought products and castings [1]. This leads undisputed to wrong conclusions.

For a precise assessment of recycling activities a qualitative and quantitative description of scrap flows from the areas of application of aluminium is important, as well as their connection to existing recycling paths. Additionally, aluminium materials have to be distinguished in two groups of alloys. For cast alloys the content of alloying elements, first of all silicon and copper, is high. In contrast, wrought alloys are lower alloyed, usually with magnesium and manganese and should therefore return separately and if possible clean sorted into the recycling cycle.

The material separation however is limited by application and collection. Figure 3 shows the German applications of aluminium differentiated by casting and wrought alloys, which is dominated by the traffic sector [6]. In each of these application areas, with exception of the packaging area, casting and wrought alloys are gathered after the use, which are often mixed.

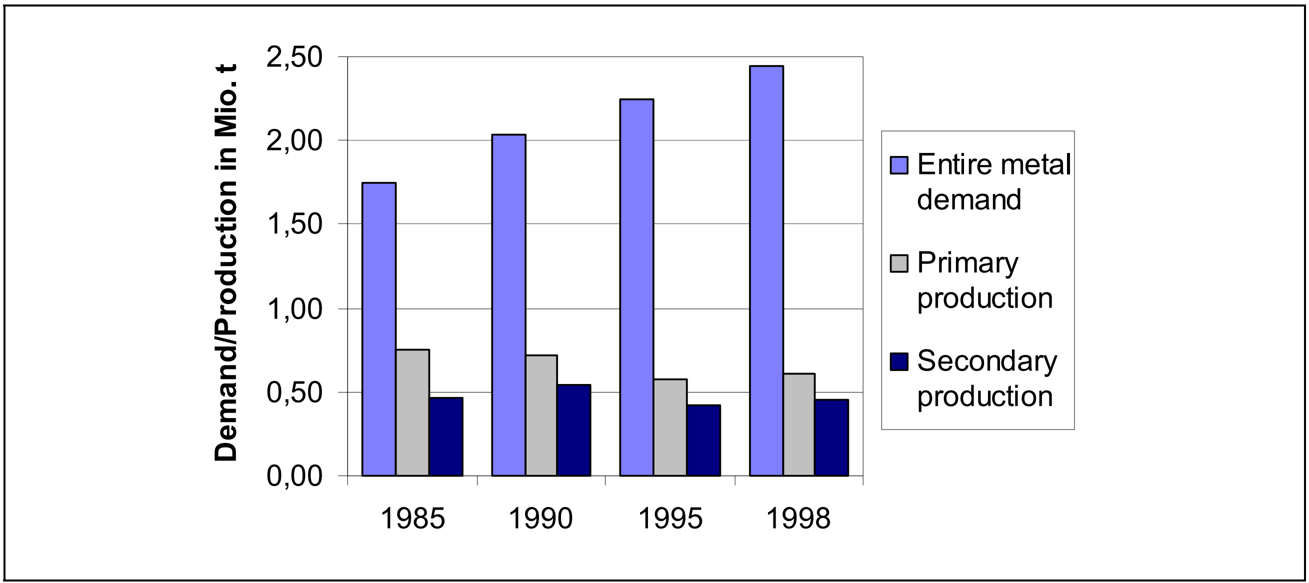

Figure 2: Development of entire metal demand, primary and secondary production of aluminium in Germany [1]

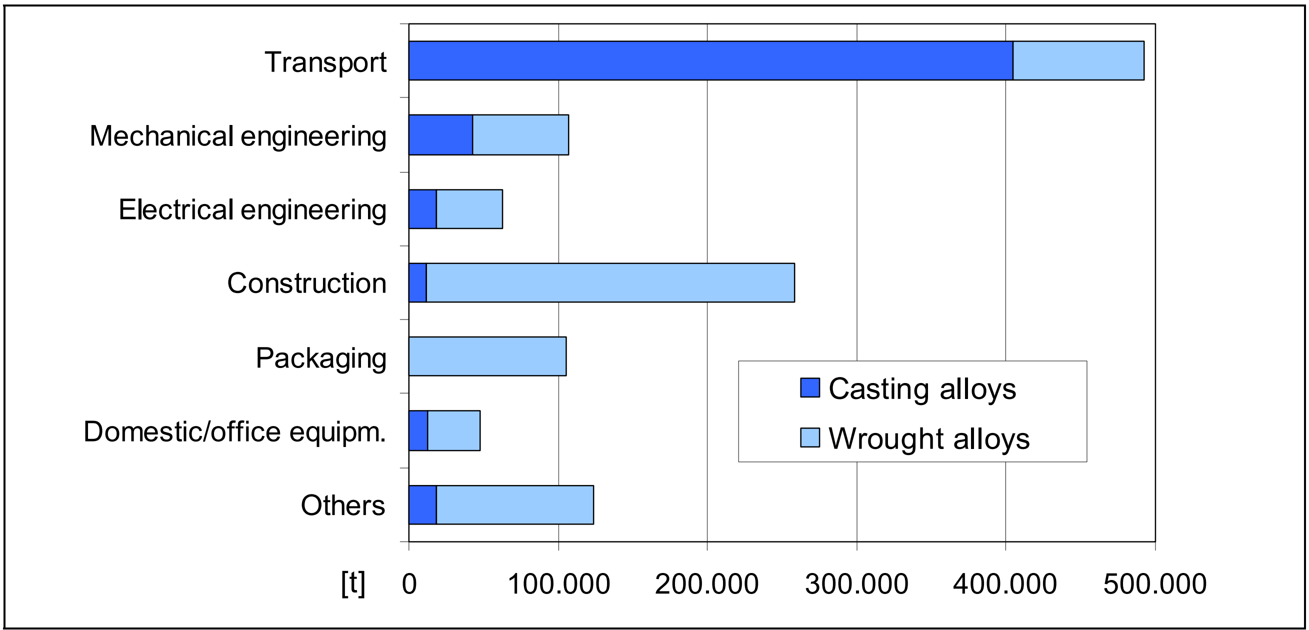

Figure 3: Use of aluminium casting and - wrought alloys in Germany 1997 [6]

Looking on individual areas of application a further distinction must be made: On the one hand closed loop recycling exist, if scraps are supplied to a comparable reapplication, e.g. beverage cans and window frames. Open loop recycling is present, if secondary raw materials after remelting are supplied to another use usually in form of other alloys. Here in particular the secondary smelters (refiner) are mentioned, which produce cast alloys for the automobile industry for example from a mixture of different old and new scraps.

Beside this "idealised" statuses an overlap in material and spatial regard exists. Materially, since also wrought alloys are converted to cast alloys, receiving so a material specific modification. Spatially, since production scraps are not only internally used in the plant, but also externally and thus do not remain in a closed cycle. Pure sorted wrought alloy scraps are selectively reprocessed into rolling and extrusion ingots by the remelting plants (remelter), which dispense then both into closed and into open recycling cycles. Mixed and contaminated scraps are reprocessed exclusively into cast alloys by the secondary smelters (refiner) and attain usually into open recycling cycles [7].

During product use the metal is bound in material storage or depots. The entire depot quantity for aluminium is world-wide estimated on 700 Mio. tonnes. The distribution of the metal is spatially, materially and temporally pronounced. The depot characteristics of aluminium can be described on the basis of selected products, product groups or sections or types of use (table 2). For aluminium packaging for example a high spatial distribution exists with small product size and high dissipation at the same time. The material purity can thereby be highly (menu plate, beverage can), middle (cover caps, painted foils) or small (tetrapack, vaporised chip bags). The dwell is with an average lifetime of a half year comparatively small [8].

Table 2: Depot characteristics of aluminium products in selected application sectors [8].

Depot characteristics		**Packaging**	**Transport** train/plane	car	**Construction**	**General engineering**	**Electrical engineering**
spatially	size	small	high	middle	high	middle	middle
	distribution	high	small	high	middle	middle	high
materially	purity	varied	high	small	high	middle	varied
temporally	dwell	small	high	middle	high	high	varied

The temporal aspect is pointed out in the presentation of production periods, lifetime, recycling quotas, return material quantities of aluminium scraps and the resulting difference to the present requirement in different applications in figure 4.

Today for example scraps from mechanical engineering return, which were produced between 1978 and 1995, thus having a lifetime of 10 to 20 years. Only the mentioned packaging materials return after a short use period in the secondary cycle. By the temporal shift of arising scrap in relation to production the difference between scrap quantity and metal demand becomes larger due to the high growth rates in the aluminium application.

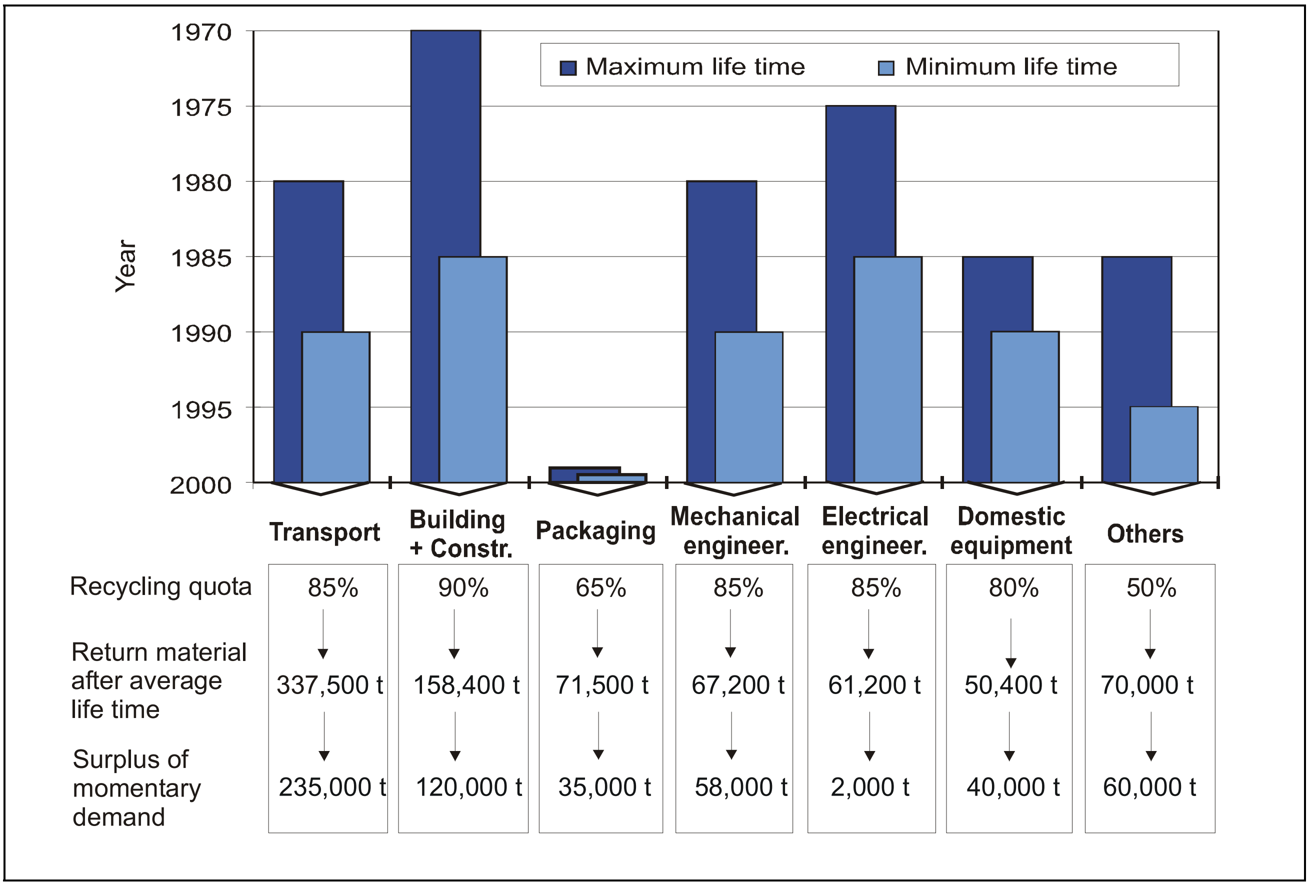

Figure 4: Recycling quotas and return quantities resulting from different lifetimes for different applications under the assumption of complete collection

The determination of the arising scrap amount is based on the depot quantities for individual applications and their recycling quotas. The recycled content, i.e. the share of secondary material of products, resulting from this estimation would amount to 60 % for a complete collection of the scraps.

2.3 Quality influence of secondary raw materials on the recycling

Beside the availability the quality of the raw material, i.e. their condition and especially their alloy composition is of high importance for recycling.

Refining of aluminium is possible only constricted and accompanying elements such as iron, manganese, silicon, magnesium, copper and zinc remain predominantly dissolved in the metal phase (table 3). For this reason during primary aluminium production the refining takes place already before reduction. For recycling this means an exact separation of the scraps before melting with regard to type of alloy and purity. Afterwards only diluting with primary metal or blending of different scraps and melts remain as possibility for the alloy adjustment.

Table 3: Possible melt treatment of aluminium

Refining method	Effect
Use of melting salt	Removal of oxides
Chlorination	Removal of alkalia and earth alkalia
Gas treatment	Removal of H, Li, Na, Mg, Ca, Sr, oxides, carbides and nitrides
Salt refining	Removal of Li, Na, Ca, Sr and oxides
Vacuum distillation	Removal of Li, Zn, Mg, Na
Formation and separation of intermetallics compounds	Removal of Fe, Mn, Si
Addition of primary aluminium	Dilution of accompanying elements
Addition of alloys	Blending, dilution of single accompanying elements

As consequence from the alloy separation in practice two furnace types became generally accepted. Sort-pure scraps and new scraps are usually remelted in large volume open-hearth furnaces, mixed new and old scraps, dross and turnings in smaller, flexible salt bath rotary furnaces. Despite increasing return quantities from production and use the intensified sort-pure recycling of wrought alloy scraps at the remelting plants causes a lack of blend material at the secondary smelters. So their cost situation continues to get worse due to the then necessary increased demand of primary metal. Accordingly, the scrap input of the German secondary aluminium smelters (figure 5) shows a decreasing share of new scrap in the years 1975-1999, while the share of old scrap developes in opposite direction [9].

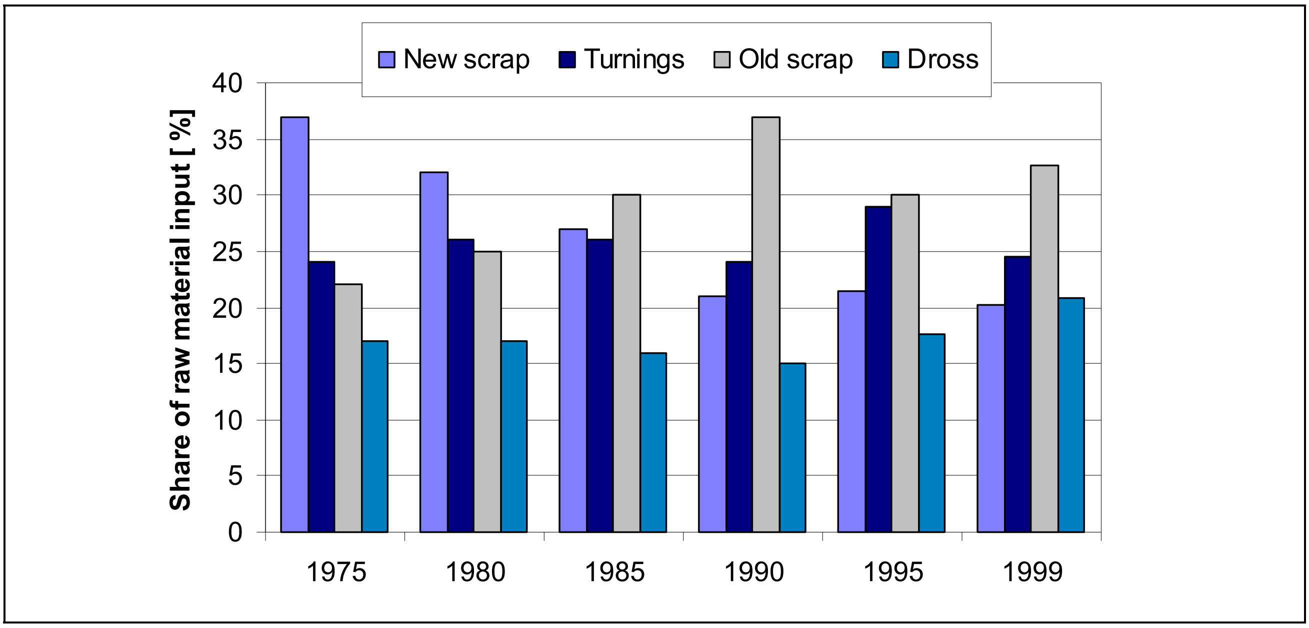

Figure 5: Development of the scrap supply of the German secondary aluminium smelters from 1975 to 1999 [9]

2.4 Quotas of collection and recycling in Germany

With the example of the German packaging recycling the different recycling levels and their corresponding quotas can be explained. In the year 1997 the consumption of light packaging material (LPM) consisting of plastics, tinplate, combined materials and aluminium, amounted to 1,778,198 t, [5]. 1,582,596 t of the used packaging were collected, which corresponds to a collection quota of 89 %. In the sorting plants plastics, tinplate and combined materials are segregated and an aluminium fraction (LPM Al40) is supplied to the further utilisation in the three processes mechanical processing, combined material processing and pyrolysis. The appropriate recycling quotas are shown in table 4. The technical recycling quota reaches 68.4 % and the resource-oriented one 61.7 %.

For the other fields of application of aluminium the quotas are vary significantly [5]. The span of the collection quota reaches from approx. 25 % for aluminium content of the urban waste to almost 100 % of the scrap quantity from the building sector. Therefore the collection becomes the most important parameter for the success of a recycling concept due to the possible utilisation of secondary raw materials.

Considering the collection of secondary raw materials in figure 4 accordingly, the theoretical recycling part decreases from 60 to 46 %. Thus the recycling quota defines the regained metal content of the used materials or components.

Table 4: Technical and resource-oriented recycling quotas for aluminium products [5] *incl. exports

	LPM (DSD)	Building + construction scrap	End of life vehicles	Electronic scrap	Urban waste
Collection quota	89	98	40	84	24
Technical recycling quota	68	92	76	79	12
Total recycling quota	60	90	30	66	3

For the example of aluminium the scrap balance of 1997 in figure 6 clarifies the aspects of scrap availability. First of all a small export surplus can be detected, which consists of old scraps, processing scraps and turnings. For the secondary aluminium production about 400,000 t scrap (Al-content) were used, from which about 70,000 t wrought alloys were remelted separately. Further wrought alloys were remelted in the cast houses of the primary smelters (174,900 t) and the semi-finished product plants (190,000 t) [10, 11]. The amount of production scrap of 920,000 t is directly re-used in the semi-finished product manufacturing as cycle material and is not recorded statistically.

With regard to the shown scrap use, the imported quantity of 168,000 t secondary aluminium and the scrap portion of the foreign primary metal the actual recycled content of total German production results in 37 %. This is a mass-related average value of the individual areas of application.

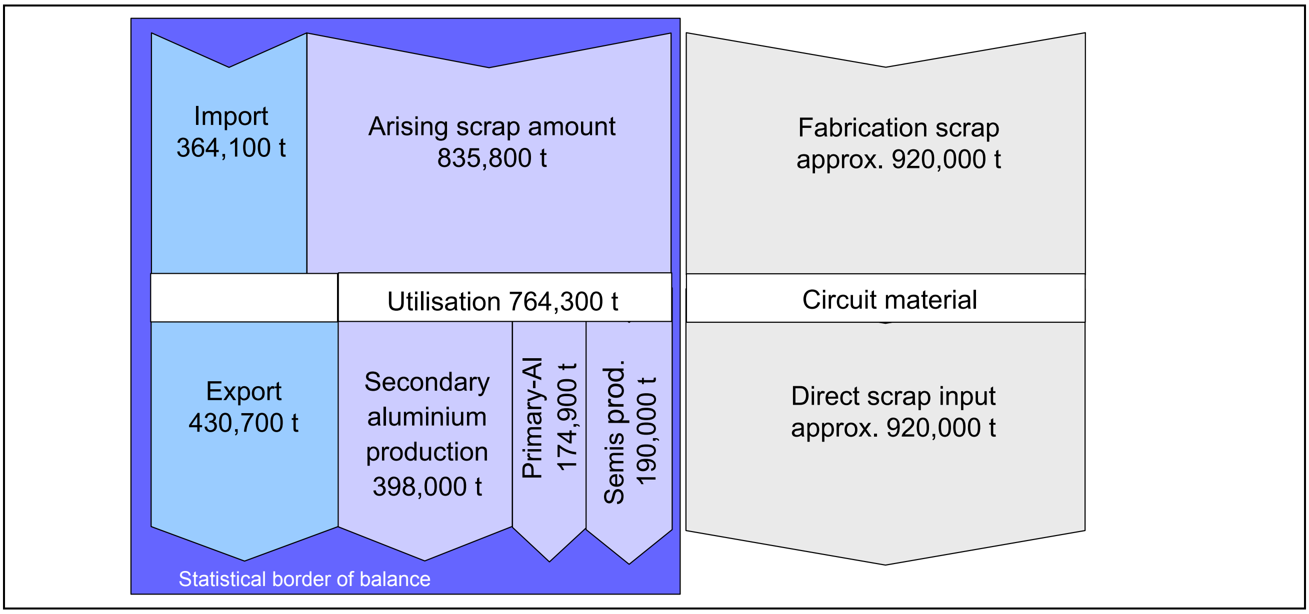

Figure 6: German scrap balance 1997 [10, 11]

2.5 Scrap flows in the aluminium system

It has been shown that the recycled content is unsuitable as scale of valuation for the success of a recycling concept, because it represents a regional situation, which is often strongly falsified by the existing open scrap market and the rising metal requirement in application.

Due to this reason the interaction between the product systems have to be considered. They can be quantified by the existing scrap flows (figure 7). An alloy cascade results, where the recycling activities increase the alloy content of the entire depot. Unalloyed aluminium forms the starting point of this material flow and has therefore the smallest recycling part. Lowering of the alloy status, i.e. a reversal of the usual supplying direction of figure 7 is only possible with high expenditures comparable to the primary metal production.

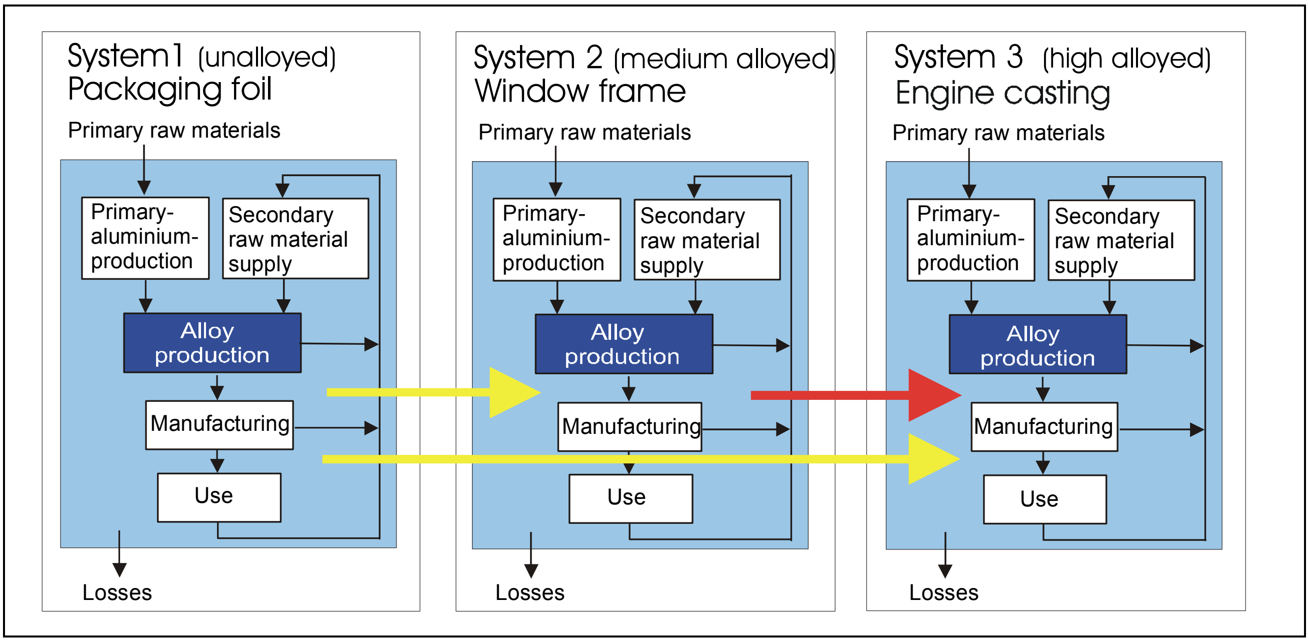

Figure 7: Interaction between the recycling systems

Finally the success of recycling activities can only be measured by the amount of recovered metal and thus the saving of primary metal in the total system of aluminium. It has to be considered that aluminium recycling needs only about 10 % of the energy requirement of the primary smelting. Beyond that the pure sorted collection and material processing work against an enrichment of alloying elements in the recycling cycle and thus receive the maximal utilisation of the secondary raw materials, which are already expensive due to shortage.

3. Technical development

For the example of aluminium packaging potentials of technological development particularly resulting from interactions of processing and smelting can be clarified. Figure 8 shows the existing system of the light packaging recycling. The aluminium fraction from the sorting plants, with 40 %

aluminium content and predominantly organic remainder can not be directly remelted. By the combination of mechanical and thermal processing routes it is possible to obtain a high-quality fraction with about 99 % aluminium which can be remelted with a metal yield of over 90 %. However, the overall processing quota of 73.4 % is relatively low.

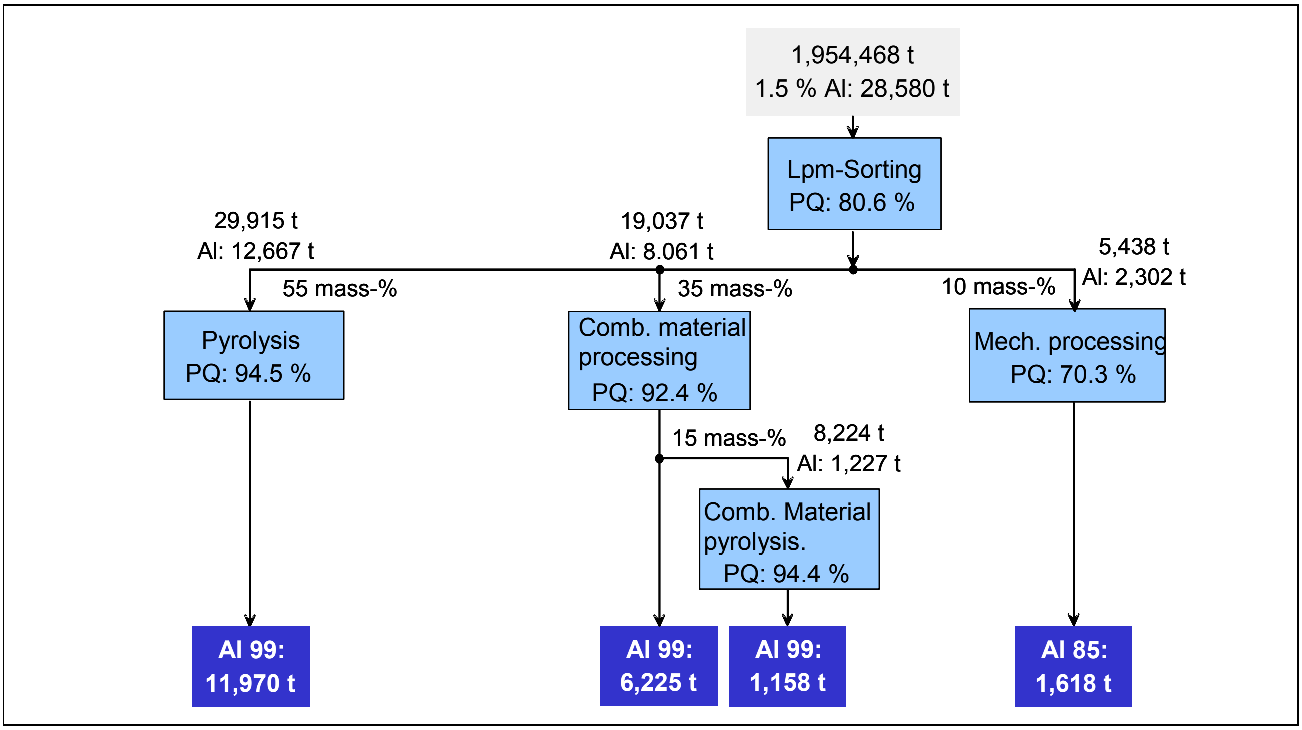

Figure 8: Processing of the Al-fraction of light packaging material [12]

Using a fully automated sorting plant the metal yield of this recycling level would be increased from 80.6 to 94.0 %. Then the process specific energy consumption increases, but related to the larger product quantity this turns to an advantage. Scenario calculations show that in the case of appropriate smelting technique for a future recycling concept NT (exclusively use of newest technology) and its possible implementation in the year 2010 saving potentials of 2,000 respective 1,370 MJ/t of produced alloy result, with an increase of the recovered aluminium amount of 20 and 4 % respectively (figure 9) [12, 13].

These values show an impressive potential, but packaging recycling takes not just done to recover aluminium. The decrease of disposal volume, and the fulfilment of treatment quotas are of main interest for this subventioned system. For the main applications of aluminium, where the scrap contains over 95 % of metal, the material processing and remelting has much smaller improvement potentials, but the processed amounts are much higher, so that every percent point of increased metal yield is a big success.

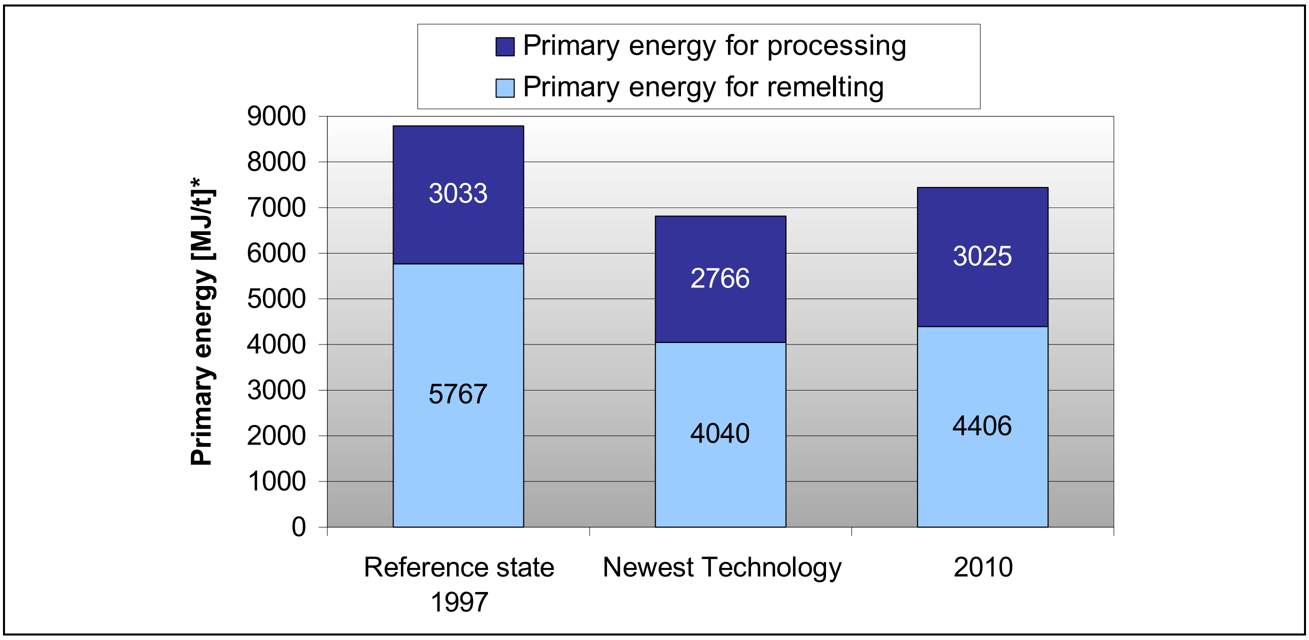

Figure 9: Comparison of the primary energy demand of today's and in the future possible concepts of light packaging recycling (*without Al-recovery from salt slag and dross)[12, 13]

4. Future scrap availability

The growth of aluminium recycling is, unlike primary production, not determined by the industry itself but by the availability of secondary raw materials. Mainly due to improved collection systems for scrap and a strong growth of the amount of present post-consumer scrap recycled aluminium production will increase at a faster rate than that of primary aluminium. This will lead to an increasing share of recycled aluminium of the total aluminium supply in the following years.

The global aluminium demand is estimated to grow about 3 % in average for the next ten years. Of this primary aluminium is expected to grow by 2.7 %, while recycled aluminium should grow by more than 4 % per year in the same period [14].

In Germany the future scrap availability can be estimated on the basis of the produced amounts in the different application sectors and their corresponding life times. Here in contrast to figure 4 not the recycling quota but the future collection quota has to be used to forecast the amount of scrap returning in the recycling system.

Table 5 shows a calculation of scrap amounts for 1998, 2010 and 2020. To estimate the future metal demand in different application sectors yearly growth rates were assumed (line 2). For the evaluation of the different scrap amounts first the reference year of production was determined using the average lifetimes in the application sectors. Then the corresponding metal demand of the sector at the reference year and at 1998 has been taken from the metal statistics [1].

Table 5: Calculation of future scrap amounts in different application sectors in Germany in t

Application	Transport	Gen. Eng.	Elec. Eng.	Construc-tion	Packaging	Home&office	Others	Total
Average Lifetime	12	15	20	25	<1	10	10	
Yearly growth rate	5	3	0	2	1	0	3	
1998								
Reference year	1986	1983	1978	1973	1998	1988	1988	
Amount (ref. year)	387900	65800	61500	150000	104500	63000	121700	954400
Amount 1998	571100	123400	62000	276700	104500	51900	129000	1318600
Collection quota	40	85	80	90	89	50	30	
Scrap amount	**310114**	**80450**	**53080**	**186146**	**95513**	**38622**	**70926**	**834851**
Processing yield	85	95	85	95	75	90	80	
Processed scrap	291809	77834	48181	179993	80768	36338	65564	780487
2010								
Reference year	1998	1995	1990	1985	2009	2000	2000	
Amount (ref. year)	571100	107200	58800	160000	105000	50000	130000	
Amount 2010	1025600	175900	60000	350900	117700	50000	183900	1964000
Collection quota	40	85	80	90	89	50	30	
Scrap amount	**526792**	**121514**	**51024**	**219742**	**100796**	**34000**	**93282**	**1147150**
Improved collection	60	85	85	95	95	60	50	
Scrap amount	607631	123625	53508	228753	105988	37600	111089	1268194
Processing yield	85	95	85	95	75	90	80	
Processed scrap	498438	117444	46334	212755	85884	32120	87204	1080179
2020								
Reference year	2008	2005	2000	1995	2020	2010	2010	
Amount (ref. year)	925182	151782	62000	254000	117040	51900	183180	1745084
Amount 2020	1670600	234460	62000	426118	129580	51900	245100	2819758
Collection quota	40	85	80	90	89	50	30	
Scrap amount	**856872**	**166504**	**53320**	**299085**	**111740**	**35292**	**126110**	**1648922**
Improved collection	60	85	85	95	95	60	50	
Scrap amount	987941	169317	55924	311818	117508	39029	151033	1832570
Processing yield	85	95	85	95	75	90	80	
Processed scrap	810869	160851	48385	288988	95130	33341	117653	1555217

The scrap amount consist of two fractions, the new scrap from the current production and the post consumer scrap obtained from the production at the reference year. Hereby it was assumed that the average amount of fabrication scrap of the end-product manufacturing is about 40 % of the input material and the collection quota of this fabrication scrap is 95 %. The old scrap amount is estimated 60 % of the reference year metal input and the corresponding collection quotas.

The calculation results are presented in figure 10, differentiated by the application sectors. The calculated value of 1998 is in a good agreement with the German scrap statistic (see fig. 6) [10]. The total scrap amount increases from 835,000 t to 1,147,000 t in 2010 and 1,650,000 t in 2020 with an increasing share of scrap form the transport sector, which shows the highest growth rate of 5 %. Further increase of scrap flows results from construction and general engineering.

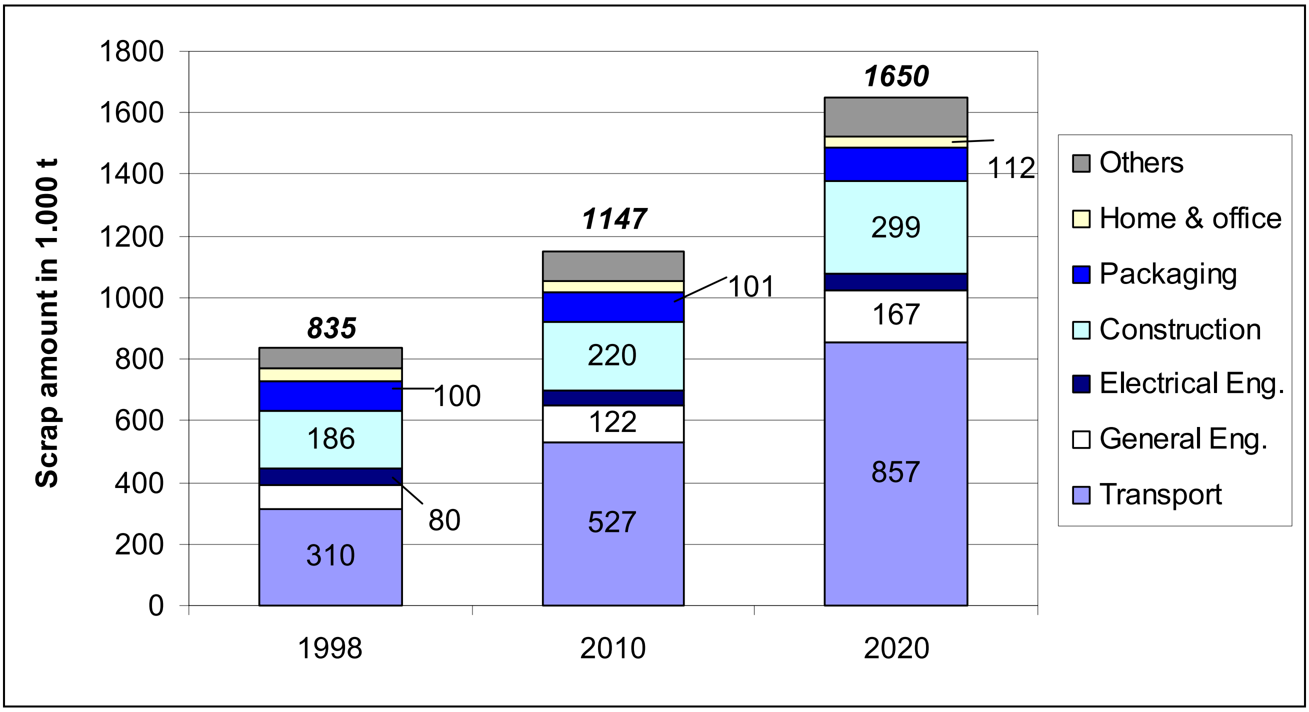

Figure 10: Development of scrap availability differentiated by application sectors

The calculations in table 6 additionally show a further case study of improved collection quotas and the resulting scrap amounts. Main influence on the results again has the transportation sector, where the collection quota is assumed to increase from 40 to 60 % (fig.11). The collection of new scraps will be improved to 98 %. In this case the scrap amount rises about 8 % to 1,270,000 t in 2010 and 1,833,000 t in 2020.

Figure 11 also presents the scrap available for remelting considering the metal yield of material processing. In 1998 780,000 t of processed scrap have been supplied for remelting. The amount will increase to 1,080,000 t in 2010 and 1,550,000 t in 2020 respectively.

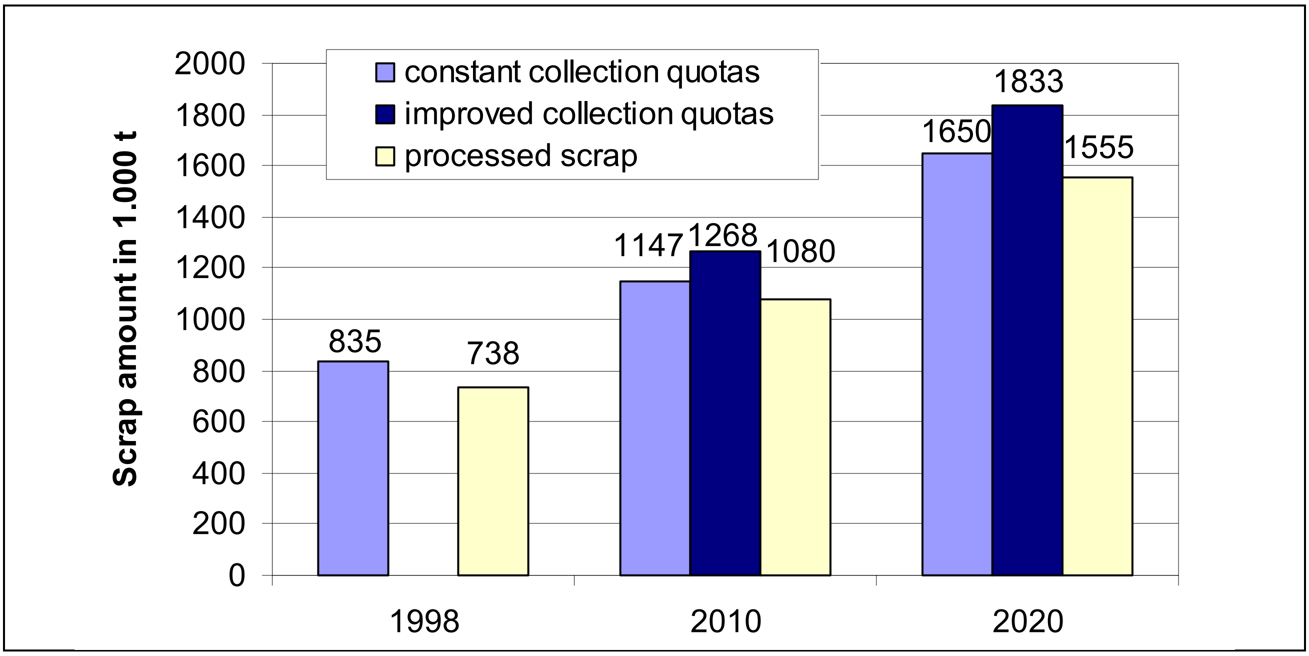

Figure 11: Development of scrap availability with constant and improved collection quotas

5. Summary

This article points out different potentials and limits of aluminium recycling. The scrap availability is located in the focal point of view, which has a major influence on the recycling activities. From this the respective recycled content of the produced metal quantity can be determined, which varies regionally, temporally, product and metal-specifically. On the other hand the recycling quota is a predominantly technique-specific measure for the success of recycling activities, which also has to consider the collection of secondary raw materials. The recycling technique can be described unique over metal yield and energy consumption. Furthermore for the recycled content and the recycling quota the quality of the raw materials, i.e. the condition, the alloy status and the metal content are of high importance. Finally this article estimates the future amounts of scrap arising in the different application sectors. It could be shown that the overall scrap availability increases by 37 % until 2010 and 97 % until 2020. Further calculations now have to identify the share of different alloy groups of these total amounts to support operative recommendations for the secondary aluminium smelters.

6. Acknowledgement

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FUTURE AVAILABILITY OF ALUMINIUM SCRAP*

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ABSTRACT

The continuously growing importance of metal recycling, especially of aluminium, as part of the raw material supply is indisputable. Nevertheless there are limitations resulting from future development of applications, recycling quotas or metal losses during production, manufacturing and use which influence the entire material flow of primary and recycled aluminium. The growth of aluminium recycling is, unlike primary production, not determined by the industry itself but mainly by the availability of secondary raw materials.
This article focuses on recycling potentials of aluminium in Germany and Europe concerning this availability and the quality of secondary raw materials. Different growth rates in each area of application and the product lifetimes will lead to different amounts of both, fabrication and post-consumer scrap. In the analysed case studies also the development and impact of collection efficiency and processing yield are considered.

KEYWORDS

Aluminium scrap, secondary material, recycling, availability of scrap, recycling quota, metal loss

* Source: Proceedings of TMS 2002

Introduction

Often the question arises whether in the next years or decades the availability of aluminium scrap is increasing and if yes, to what extend. Taking the growth rates of application into consideration, it is furthermore of interest whether the share of recycled material of total production will increase or not.
These cannot be answered in general, because every region has its own history and structure of production and use of aluminium.
Due to the fact that aluminium products are mainly used in transport, building industry, and as packaging material, metal demand is strongly related to population and level of prosperity.
Furthermore there are some countries like the USA, Japan or Germany which have a big aluminium manufacturing industry and high export rates. Accordingly, in these countries the availability of fabrication scraps will be much higher than that of post consumer scrap. Latter despite increasing scrap amounts from long-lived products.
Besides the amount itself, the alloy composition of aluminium scrap from different application areas is part of the investigation.
As mentioned before the automobile industry plays a major role in aluminium application. Here future demand for metal and availability of scrap will follow the development of car production.
Besides the amount of scrap and recycled metal supply this article shows the potentials of improved collection, material processing and smelting activities.

Aluminium use in Europe and Germany

Looking on the actual use of aluminium in Europe and Germany in figure 1 there are big differences in the share of application. Europe-wide the three sectors transport, building, and packaging are the big ones which are in the same range of 20 – 30 %. In Germany transport dominates with 41 % followed by building (18 %) and mechanical engineering (8 %) [1-3]. Here packaging plays no significant role because of little use of beverage cans.

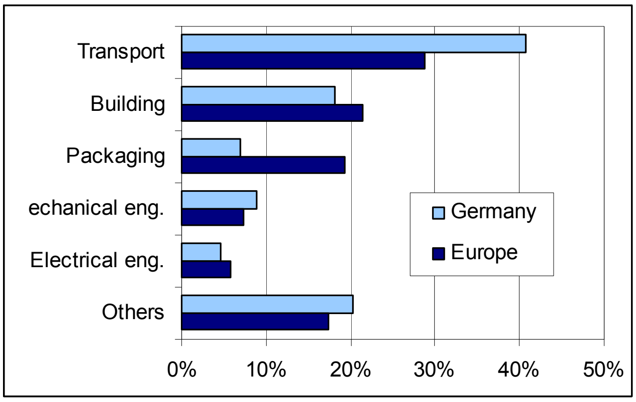

Figure 1: European and German share of aluminium application

Aluminium materials have to be distinguished in two groups of alloys. Casting alloys have a high content of alloying elements of about 5 to 15 %, first of all silicon and copper. In contrast, wrought alloys are lower alloyed (0 – 5 %), usually with magnesium and manganese and should therefore return separately and if possible clean sorted into the recycling cycle.
The material separation however is limited by the kind of application and the collection practise. In each use sector, with exception of packaging, casting and wrought alloys are mixed. Figure 2 shows the German application of aluminium differentiated by casting and wrought alloys [1].

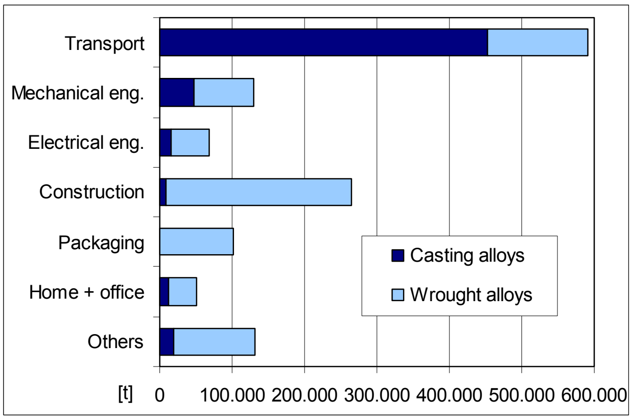

Figure 2: Use of aluminium casting and - wrought alloys in Germany 1998

<u>Parameters of scrap availability</u>

For each area of application amount and quality of future scrap availability depend on growth rates, used alloy composition, lifetimes, share of new and old scrap and collection quotas, metal yield of processing and smelting. Besides actual values the further development of these parameters is estimated.

<u>Growth rates</u>

Main parameter of future scrap availability is the amount of aluminium used in products. To calculate this value following annual growth rates for the different application areas have been estimated, either continuing trends of the last decade in Germany [3] or averaging the growth rate of automotive application, which is explained later (table I).

Table I Annual growth rates for aluminium applications

Transport	3.1 %
General engineering	3 %
Electrical engineering	0 %
Building and construction	2 %
Packaging	1 %
Home and office	0 %
Others	3 %

The overall average growth rate of aluminium use up to 2040 for Germany and Europe is then 2,6 %.
Looking on the particular growth of automotive aluminium in figure 3 the development of car production and the aluminium content per car have to be considered. The amount of produced cars in Germany will reach about 7 million units in the next decades [4] and the average aluminium content of a passenger car will increase from 100 to 250 kg in the same period. Latter curve represents many different estimations of the aluminium industry (Pechiney, VAW, Alcan-Alusuisse, EAA, GDA) and the car industry (PSA Peugeot Citroen, Audi, Ford) up to 2010 [5-8].
In Europe car production will increase from today 19 to about 26 million units per year in the same period.

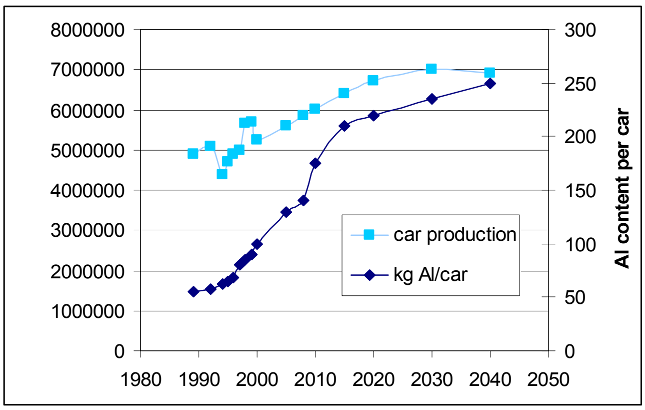

Figure 3: Development of car production in Germany and aluminium content per car

The value of 250 kg aluminium per car for 2040 seems to be achievable considering a total potential of aluminium parts of about 300 kg for a conventional steel based car of which are 160 kg casting alloys and 140 kg wrought alloys [8-14]. The

difference is obtained due to the fact that especially many small cars will not reach this high aluminium content, although some aluminium intensive vehicles will have significantly more.
A comparison of statistics and the calculations of metal demand show that about 80 % of the metal supply of the automobile industry can be found as aluminium product in the car itself. The other 20 % are mainly fabrication scrap of the end-product manufacturing and spare parts. This ratio is assumed to remain constant in spite of improved production technologies, because the increasing share of wrought alloys application with higher scrap rates will compensate this trend. The particular German metal demand is then obtained by multiplying the adapted specific demand per car with the yearly production number, figure 4.

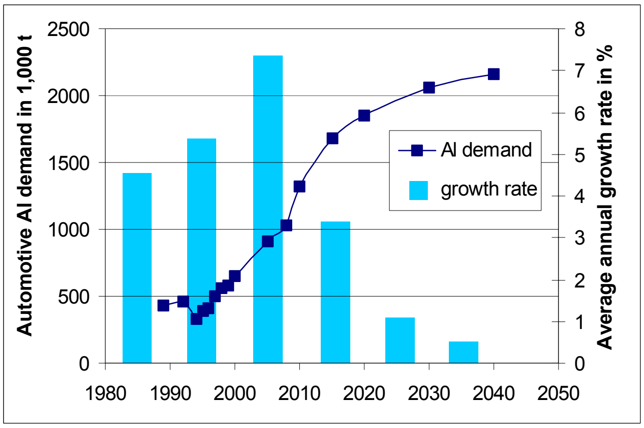

Figure 4: Development of automotive aluminium demand in Germany and the annual average growth rates within the investigated decades

It is obvious that in the ongoing decade the highest average growth rate can be expected, which reaches 7.4 %. In the following decades the growth rate decreases from 3.4 % to 1.1 %, and 0.5 %, respectively.

Alloy composition

For the description of the aluminium demand and supply again cast and wrought alloys have to be distinguished. Due to the fact that 95 % of the aluminium required from the transport sector is used for road transport and about 80 % of the German recycled aluminium is used in this area, the share of produced alloys at the secondary smelters (refiner) is nearly equal to the metal demand of the car manufacturers [1]. The remaining 20 % are so-called primary casting alloys which are supplied from primary smelters. Table II shows the most important casting alloys and their share of production in Germany [10, 13, 15, 16].

Table II Aluminium casting alloys

AA-No.	Notation	Share of production
359	AlSi9Cu3	48 %
356	AlSi7Mg	20 %
361	AlSi10Mg	12 %
-	AlSi12Cu	9 %
413	AlSi12	7 %
332	AlSi12CuNiMg	4 %

The mostly wide used casting alloy for nearly all kinds of application is the AlSi9Cu3 alloy with a share of refiner production of about 50 %. Besides that the eutectic AlSi12 and the AlSi10Mg are the most important alloys with a share of 16 and 12 % respectively, latter has been nearly doubled in the last 4 years.
In the case of the primary casting alloys there is an increasing application of the AlSi7Mg alloy for safety components in passenger cars.
The share of castings will decrease from today about 75 % to nearly 50 % up to 2040. This due to the actual trend of car manufacturers to use, besides aluminium castings for engine, gear box, chassis and suspension, more and more wrought alloys for hang-on parts of the bodywork (figure 5).

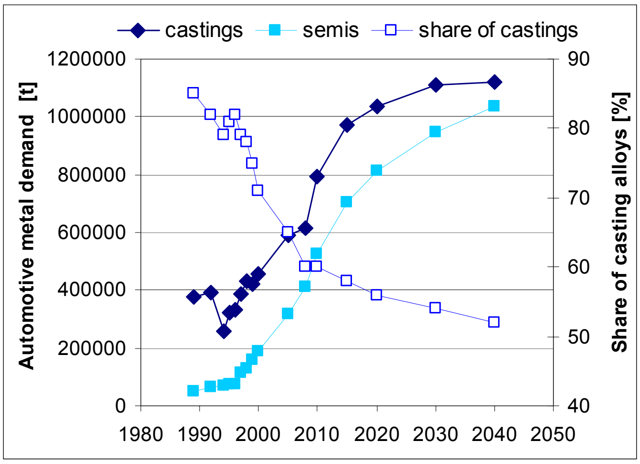

Figure 5: Development of German automotive aluminium demand and its share of casting alloys

The wrought alloy use of the transport sector can be divided into extrusions (35 %), forgings (11 %) and rolled products (54 %). Table III shows the most representative wrought alloys which are used for example for radiators (3003), forged wheels (6082), bumper beams (7020), internal (5182, 5457) and external (6016) structural parts [9, 10, 12, 13, 14].

Table III Automotive wrought alloys, main examples

	AA-No.	Notation	Share of use
- extrusions	6060	AlMgSi0.5	35 %
- forgings	6082	AlMgSi1	11 %
- rolled products	3003	AlMn1	10 %
	5182	AlMg4.5Mn0.4	9 %
	5754	AlMg3	14 %
	6016	AlSi1.2Mn0.4	15 %
	7020	AlZn5.4Mg1	6 %

The increasing share of automotive wrought products causes a much higher growth of semi-fabricated products demand than for the castings, reaching nearly the same value of about 1.1 million tonnes at the end of the investigated period in 2040, see also figure 5. This means a factor 3 of growth for castings and a factor 10 for rolled, forged and extruded parts [4].
For the other use sectors also representative groups of aluminium materials can be distinguished, which distribution was held constant for the calculation. Besides casting alloys (compare table II) following wrought alloys are mainly used in the different applications and can be found in the subsequent scrap mix, table IV [9].

Table IV Representative wrought alloys (AA-Nr.) of use sectors

Use sector	rolled	extruded
Transport (ship, rail, airplane)	5383, 2024, 7075	6082, 6060/61
General eng.	1050/70, 2007/24, 5005, 5754, 7075	6060/82
Electrical eng.	1350/70	1350/70, 6101
Building	3004/5, 3103, 5005	6060/82, 5754
Packaging	1xxx, 8011	-

Finally figure 6 compares the amount of used aluminium materials shared by castings, rolled and extruded/forged products in Europe and Germany 1998 [1, 2, 8].

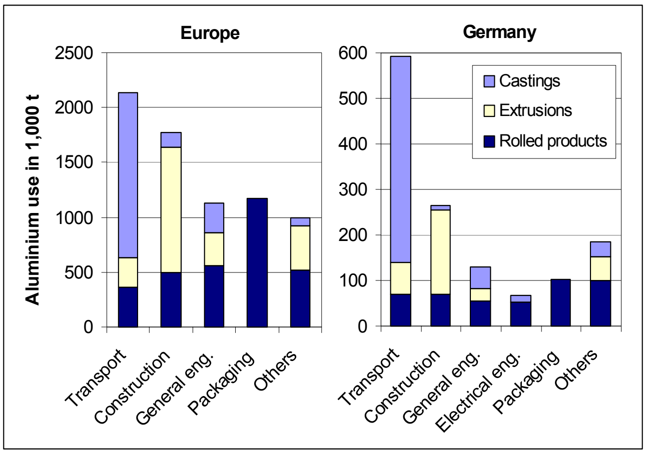

Figure 6: End-use of castings, rolled and extruded/forged products in Europe and Germany 1998

Product lifetime

Due to the average lifetime of aluminium products in the different areas of application the collected old scrap origins from different years of production. The chosen average product lifetime has big influence on the calculation results because of high annual fluctuation of production. This can be compensated by regarding longer time periods. Table V presents the average lifetimes which has been used for the calculation.

Table V Average lifetimes of aluminium products, in years

Transport	12
General engineering	15
Electrical engineering	20
Building and construction	30
Packaging	< 1
Home and office	10
Others	10

Scrap rate of product manufacturing

For the estimation of new and old scraps available it has to be considered that only a share of about 60 % of the particular metal supply is bound as aluminium products in the use phase, the other 40 % return directly as new scrap into the recycling systems. Not included in the scrap amount are in-house scraps of semis production which are circuit material. So the particular scrap mix consists of the portion of post consumer scrap from the earlier production and the fabrication scrap of current production. This average distribution has been used changeless for the different calculations.

Metal yield during recovery

The major parameter of scrap availability and recycled metal supply is the efficiency of the recycling system.
Generally for metal recycling the overall recycling quota consists of the collection quota and the technical recycling quota. This separation clarifies also the different levels of the recycling in figure 7 [17, 18].

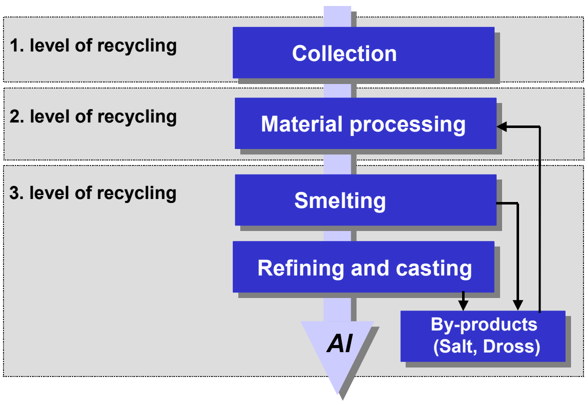

Figure 7: Levels of metal recycling

To distinguish

- the collection quota: It determines the quantity of available secondary material that is obtained in collecting systems, related to the quantity used in the product.
- the technical recycling quota: Here the quantity of material is determined, which is available for utilisation at the end of the process as secondary metal related to the collected scrap amount, i.e. it is the yield of the technical process.

The technical recycling quota consists again of two sections, the processing quota, that is how much metallic aluminium from the collection is supplied for melting, and the smelting yield, which indicates, how much aluminium is won as liquid metal, i.e. herein is taken into account the return flows from salt slag and dross treatment.

For fabrication scrap a collection quota of 95 % is used for the calculation, furthermore a processing and a smelting yield of together 90 %. Latter value seems relatively low, but it includes the metal recovery from dross and turnings, which are also accounted as new scraps. In contrast to that, post consumer scrap has strongly differing collection quotas and also lower processing and smelting quotas due to the impurities and the accompanying materials.

The calculation of future scrap availability also has to consider the improvement of the recycling quotas in each level of recycling. Table VI shows the estimated development of the values for old scrap from each use sector up to 2020. For the following years the values are assumed to remain constant.

Table VI Actual and achievable recycling quotas of used aluminium products in Germany for collection (C), processing (P) and
smelting (S), in %

	1998	2010	2020
Transport	C 40 P 85 S 85	C 40 P 90 S 87	C 40 P 95 S 89
General engineering	C 60 P 95 S 85	C 70 P 95 S 87	C 80 P 95 S 89
Electrical engineering	C 75 P 85 S 90	C 80 P 90 S 91	C 85 P 95 S 92
Building and construction	C 85 P 95 S 90	C 90 P 95 S 92	C 95 P 95 S 94
Packaging	C 89 P 75 S 90	C 95 P 85 S 91	C 95 P 95 S 92
Home and office	C 50 P 90 S 85	C 60 P 95 S 87	C 70 P 95 S 89
Others	C 30 P 80 S 85	C 40 P 85 S 87	C 50 P 90 S 89

For Europe similar values can be used with the exception of packaging material, where the collection quota only reaches about 50 % due to a missing collection system.

One of the most significant values is the collection quota of end-of-life vehicles (ELV), which currently amounts to 40 % of the deregistered cars in Germany [18]. This is due to a high share of exports of used cars, damaged cars and dismantled spare parts. This value is assumed to remain constant in future due to the high technical standard of German and European cars and the resulting export potential to eastern and south-eastern Europe, the Middle East and Africa.

Calculated scrap amounts

The main results of the calculation are the developments of total scrap availability, resulting recycled aluminium amount and future demand for aluminium in Europe and Germany.

The European domestic demand for aluminium materials will reach 21.5 million tonnes in 2040 and 4.2 million in Germany. At the same time the amount collected and processed scrap increases from 3.6 to 13.2 million tones and 0.7 to 2.6 million, respectively. Table VII shows the corresponding values.

Furthermore the amounts of collected and processed old scrap from end-of-life products are shown, which reach about 40 % in 2040 in Europe and Germany. The overall aluminium recovery is described by the recycled aluminium amount used for new castings and wrought products. These amounts increase from 3.2 to 12.0 million tonnes in Europe and from 0.7 to 2.3 million in Germany.

Nevertheless these total numbers have to be analysed in detail to get valuable information about future scrap availability. In particular the areas of application, the distribution of alloy groups, technical improvements along the process chain and the resulting recycling potential for domestic production are considered.

Table VII Calculated aluminium demand, scrap amount and recycled aluminium amount for Europe and Germany

		Total scrap amount	Old scrap amount	Recycled aluminium	Domestic demand
Europe	1998	3610430	869500	3194180	7213000
	2010	6005070	1572360	5372870	11665040
	2020	8527700	2712300	7700400	15303670
	2030	11113130	4151100	10014700	18321060
	2040	13226900	5050500	11913650	21516780
Germany	1998	749840	240790	668050	1439600
	2010	1281470	390450	1158730	2449800
	2020	1780720	600380	1628850	3216160
	2030	2238790	864920	2044760	3730450
	2040	2568630	1020060	2345510	4195170

Scrap amounts from use sectors

The total values of old and new scrap available can be distinguished by the different use sectors. It has to be mentioned that the shown trends only can give orders of magnitude mainly determined by the assumed growth rates of production (table I). Furthermore it has to be considered that the estimated new scrap amounts do not include in-house fabrication scraps from the semi-finished production. This circuit material is not accounted in statistic data.
In Europe the biggest increase of future scrap amounts can be expected for the transport sector followed by construction and general engineering, figure 8. In 1998 scrap from packaging materials has a comparable level to the other applications, but does not reach their high values in the next decades. This due to the estimated moderate growth in demand.

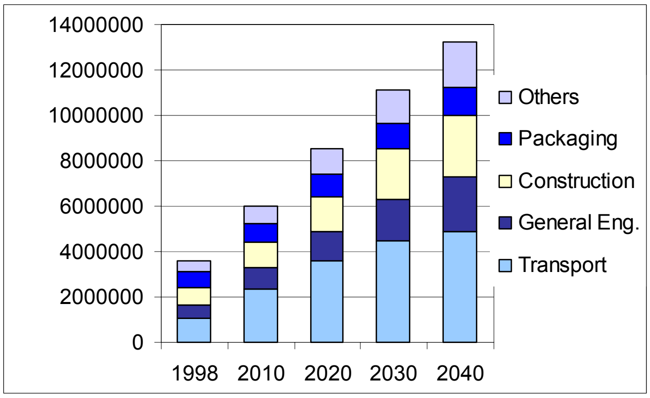

Figure 8: Development of European scrap availability distinguished by use sectors

For Germany, the results show a similar picture but with different shares, figure 9. Here the major scrap amounts also arise from transport application, increasing from 40 to 53 % of total. Construction and engineering scraps follow with 19 and 9 % for 1998 changing to 17 and 11 % up to 2040. The share of packaging scrap decreases from 11 to 6 % at a lower level than in Europe (18 – 9 %). This indicates the disproportionate growth of automotive aluminium in Germany.

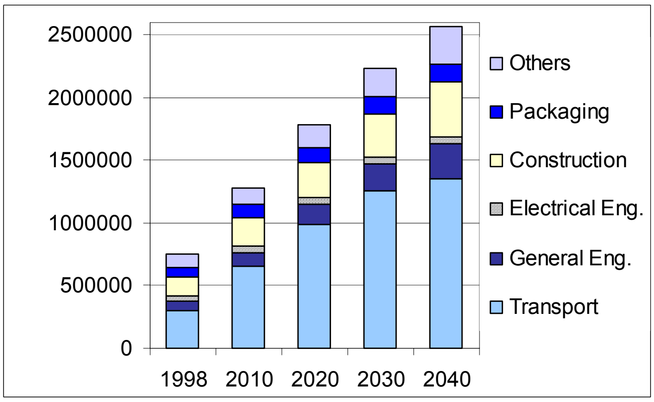

Figure 9: Development of German scrap availability distinguished by use sectors

Share of alloy groups

Resulting from the different aluminium applications the amounts of old and new scrap of castings, rolled and extruded products can be distinguished.
In Europe (figure 10) rolling alloys have the biggest share of scrap available, with 42 % in 1998 and 41 % in 2040 remaining nearly constant. Due to the expected change in automotive application the scrap share of casting alloys decreases from 33 to 29 % and the one of extrusion scrap increases from 25 to 30 % of the total values. Also increasing recovery rates at the construction (mainly extrusions) and packaging (foil and strip) area support these developments.

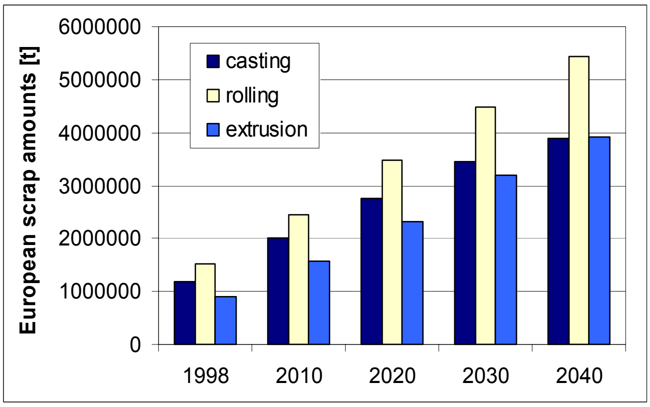

Figure 10: Development of scrap amounts for casting, rolling and extrusion alloys in Europe

In Germany again the picture is different, figure 11. The biggest amount are casting alloys. For the estimated conditions the amount of casting scrap loose its dominating part of 41 % catched up by rolling scrap in 2040 (now 32 %), both then reaching 35 %. The share of extrusion alloy scrap will also increase slightly from 27 to 30 %. Here especially the influence of changed automotive application with more sheets and profiles will be responsible. Compared with the European figures, rolled products and their corresponding scrap have a much lower share of total scrap availability. Probably an increasing use of aluminium beverage cans could change these values.

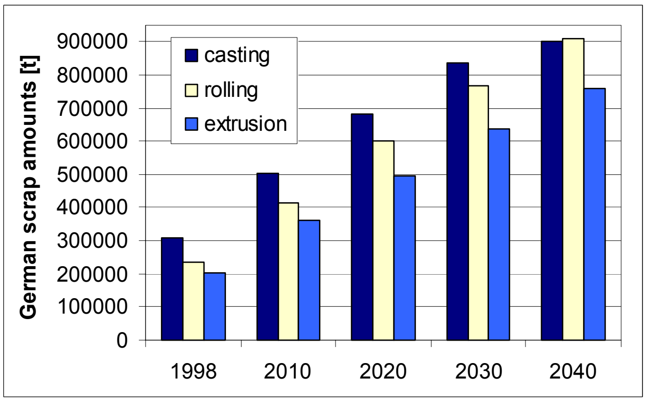

Figure 11: Development of scrap amounts for casting, rolling and extrusion alloys in Germany

Availability and use of old scrap

Besides the presentation of total values of old and new scrap it is interesting to separate the availability of post-consumer scrap in each use sector due to their different condition and resulting recycling processes.
Figure 12 shows the overall old scrap share and two varying examples of single applications, transport and construction. The slight decrease of the total old scrap share can be explained by the high growth rates of aluminium use in the next decade. The resulting new scraps thereby outnumber the also increasing old scrap amounts from current and previous use.
Main reason for this development is the strongly growing automotive aluminium demand, shown in the lower curve. Here the old scrap share decreases from 26 to 19 % up to 2010. Thereafter more old scrap from ELV returns into the recycling system and the share of old scrap increases to 33 % in 2040.

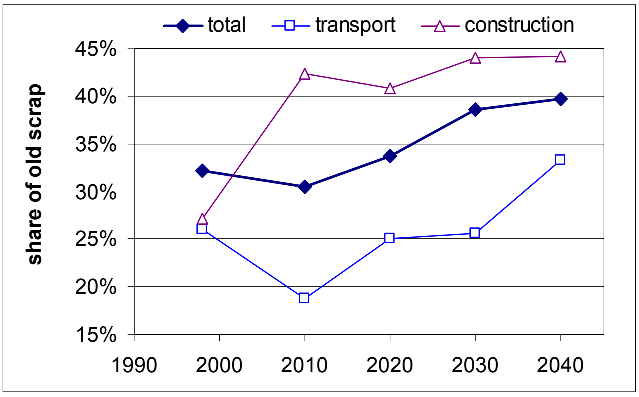

Figure 12: Share of total old scrap amount in Germany in comparison with old scrap shares of transport and construction

The construction area shows an opposite picture. Due to the long lifetime of these products of about 30 years today only small old scrap amounts arise, but considering the high collection and processing quotas of these types of secondary material the share will increase to about 44 %.

Since old scrap is the biggest raw material source for recycled aluminium alloys, especially casting alloys, figure 13 shows whether this part will change and to what extend. Today about 40 % of the casting alloy demand could be covered by old scrap (metal content), up to 2040 this value increases to 70 %.

Looking on ELV scrap as raw material source for casting alloys, metal supply will theoretically increase even to 90 %. Both numbers do not consider the smelting yield but indicate clearly the rising necessity of scrap sorting to guarantee an usable raw material mix for the secondary smelters and a maximum substitution of primary wrought alloys.

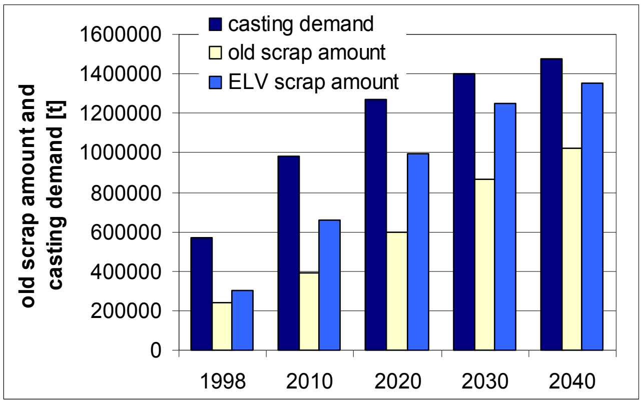

Figure 13: Comparison of casting alloy demand and availability of old scrap and ELV scrap in Germany

Improvements of the recycling system

To describe the efficiency of recycling activities besides collection and pre-treatment of secondary raw materials the smelting processes are of interest. Taking their corresponding metal yield into account the amount of recycled aluminium can be determined (see table VII).

To isolate the effect of improved recycling quotas at all three levels of recycling the calculation of German scrap availability has been carried out four-fold with constant quotas, improved collection, improved processing and improved smelting (compare table VI). Table VIII shows the values for constant and entirely improved recycling. It can be found that the technical development has a share of about 10 % of the recycled aluminium amount in 2040, of which 4 % result from better collection and each 3 % from more efficient processing and smelting. This means an remarkable absolute surplus of 53,000 tonnes of recycled aluminium already in the year 2010.

It has to be mentioned that a further improvement of aluminium recovery can be reached by improved collection quotas, which still have the biggest optimisation potential. Here national or regional regulations or a scrapping credit for used cars, recently proposed by the German car industry could for example increase the collection quota for ELV to 50 %. This would increase the recycled metal amount in 2010 by additional 54,000 t alone.

Table VIII Development of German scrap amount with constant and improved recycling quotas

	constant quotas	improved collection, processing and smelting
1998	668,046	668,046
2010	1,105,679	1,158,733
2020	1,488,209	1,628,850
2030	1,856,804	2,044,760
2040	2,121,584	2,345,513

Future recycling potentials

To describe the recycling potential of the investigated systems the recycled aluminium amount has to be related to the particular metal demand for aluminium products. The resulting so-called recycled content can be derived concerning either the overall production for domestic use and export or the domestic use only. Latter has been done in the present article since future exports of products and imports of metal can not be estimated simply. Furthermore the results for Europe and Germany can be compared.
The graph drawn in figure 14 shows the increasing recycling potentials.

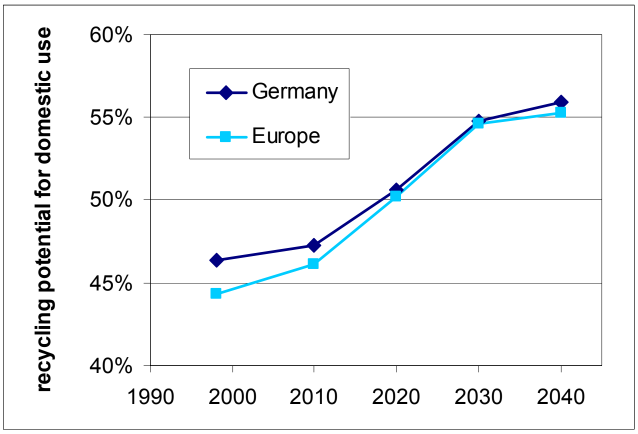

Figure 14: Future recycled aluminium contents of domestic aluminium demand for Europe and Germany

In Germany about 46 % of the aluminium demand for domestic use can be obtained from recycled metal. (Considering today's imports of aluminium alloys and exports of semi-finished products the actual recycled content of the total German metal demand is 37 %) Between 2010 and 2030 the recycling potential increases significantly from 47 to 55 %.
The European picture looks similar although starting from a lower value (44 %). This due to nearly the same assumptions of recycling quotas and growth rates.
This result can be interpreted in several ways. Firstly it shows that in the ongoing decade no significant increase of scrap availability will take place. Furthermore the subsequent growth is smaller than expected often in public discussion so that the shortage of secondary raw materials will only decrease slightly in spite of highly increased absolute scrap amounts.
Considering that the gap between metal demand and scrap supply of now 4 million tonnes in Europe will already reach 6 million tonnes in 2010 and about 9 million in 2040, future supply strategies of primary aluminium should be discussed by the aluminium industry. In Germany 1998 nearly 800,000 t of primary aluminium were needed to cover only the domestic demand, reaching 1.3 million in 2010 and 1.8 million in 2040. This again clarifies that the main growth of aluminium demand will take place in the next ten years.

The particular values for the different alloy groups in figure 15 are very similar to the ones of the total recycling potential. Only the recycled content of casting alloys decreases from the highest value (48 %) to the lowest one (46 %) up to 2010. Since casting alloys are mainly connected to the automotive application, the expected growth in this area will decrease the recycling potential of castings first, before more scrap will be obtained in the following time span. For rolled and extruded products this trend is compensated by the rising scrap flows from the construction and packaging sector.

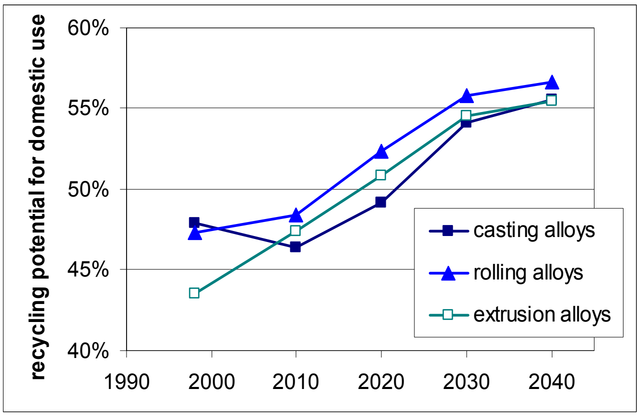

Figure 15: Recycling potential for casting, rolling and extrusion alloys in Germany

Finally in figure 16 the fact is considered, that about 80 % of the casting alloys in Germany are produced from secondary raw materials, i.e. old and new scrap, dross, and turnings. If the refiners will keep that unchanged they have to cover their demand for scrap with rolling and extrusion alloys which then have a remaining recycling potential of only 26 and 21 % in their own alloy group. Up to 2040 the recycling potential for rolled and extruded products for domestic use will increase to 44 and 41 %.

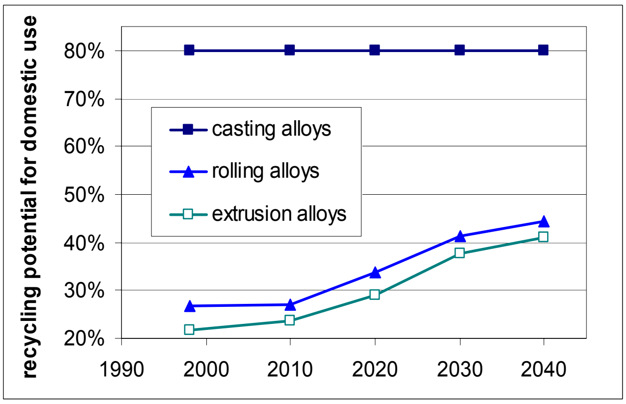

Figure 16: Recycling potential for rolling and extrusion alloys in Germany at constant recycled contents of casting alloys

Conclusion

In this article the future availability of scrap is shown in absolute values and the resulting recycling potential. The calculation results are strongly dependent on the assumptions, first of all the growth rates of the use sectors. Nevertheless trends and orders of magnitude can be shown. The results are dominated by the automotive application of aluminium, especially in Germany. The long term view of the investigation also includes the effects of long-lived products in the construction sector. It has been shown that the collection of used aluminium materials has the biggest potential to improve the recycling system. In the stage of material processing sorting of the increasing amounts old scrap and ELV scrap will become more important.
In general the results show, that no significant increase of scrap availability can be expected, in contrast to the often stated opinion. Taking the estimated growth of aluminium products into account the biggest demand for metal in Germany and Europe will occur within the next decade and will cause big changes of the supply situation.

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ALUMINIUM RECYCLING IN GERMANY
-STATUS AND POTENTIAL-*

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ABSTRACT

This article confronts requirement and feasibility of the aluminium recycling. The scrap availability is the focal point of the view, since it exerts an influence on the recycling activities, equally important for all metals. From this the recycled content of the used metal quantity can be determined, which varies regionally, temporally and product-specifically. The recycling quota is in comparison a predominantly technique-specific measure for the success of recycling activities, with which depending upon the selection of the definition also the collection of secondary materials must be considered. For recycled content and quota is the quality of the raw materials, i.e. the condition, the alloy composition and the metal content of importance. The recycling technique can be described over the metal yield and the energy requirement, whereby as possible an entire recycling concept with processing and melting technique has to be evaluated and not an individual process.

Future developments will have to aim at the increase of the efficiency of collection and utilisation of secondary raw material sources up to an optimum. The energy expenditure for the recycling represents however only one element, which are usually consulted in connection with the resulting emissions for the ecological evaluation. In order to arrange a sustainable development of the metallurgy, also economic and social aspects of the resource management are to be included into the view.

KEYWORDS

Sustainable development, recycling, secondary raw materials, availability of secondary material, technological development, collection, processing and re-melting

* Source: Light Metal Age, Aug./2001, pp.66-75

Introduction

Recycling of metals is an important source of raw materials for the increasing applications since beginning of its use. It has always been worthwhile to use the economic value of metal bearing wastes from processing and used products to recycle metals. Ecological aspects apart from the economic interest are today:

- saving of resources
- reduction of emissions and wastes
- reduction of dumps and
- saving of energy

Increasingly recycling is included also into the discussion about a sustainable development in metal-industry. With the recycling of aluminium even renewable raw materials are discussed as well as a generation contract regarding the energy used for primary aluminium production. In the long run any use of products leads to a material distribution of the used metals, this should be regarded as a challenge for the development of collection, processing and remelting technologies.

Despite the undisputed economic and ecological advantages of metal production from secondary raw materials there is a set of factors, which limit expenditure and use of recycling. These are, among other things, minimum metal contents of the secondary materials, the production of secondary wastes, the multiplicity of the different types of alloy and pollutants, a rising number of composite materials and the effects of user-specific material treatment on the achievable metal quality. However the different quality and availability of the raw materials for the production of the different product alloys show that for an evaluation of recycling systems the technical operating parameters are not sufficient alone as criterion for the selection of certain procedure versions or alternatives.

The availability of secondary raw materials

The supply of metal production with secondary raw materials is subject to various influences, which are described in the following. These are in particular time aspects and aspects of quality, which limit the availability of secondary material. With an exact analysis of the existing metal flows and the assigned technologies develops a further problem of the recycling, the definition of the recycling quota and the recycled content which describe and evaluate recycling activities. This abstract presents technical-metallurgically based solutions for these problems.

The difference between the aluminium quantity used and the quantity produced in Germany is substantial however according to the metal statistics. The question arises how the high metal requirement of the processing industry is covered and which role thereby plays the recycling. According to figure 1 the recycled content of the production would amount only to about 18 %, whereby only the secondary aluminium production on cast alloy base is compared with the entire in the semi-finished material and casting area assigned metal quantity [1]. This leads undisputed to false conclusions.

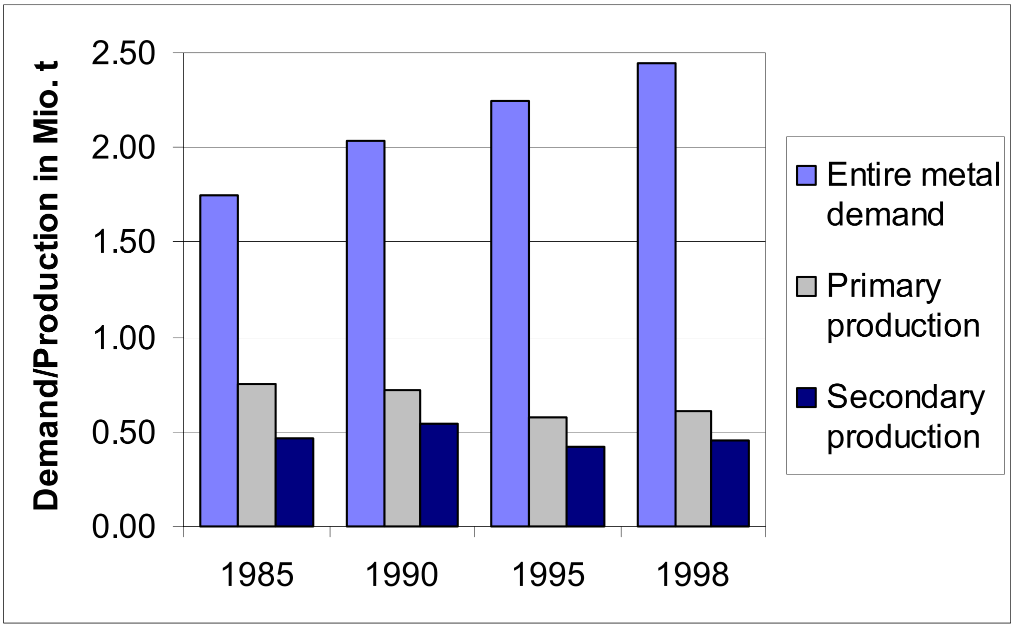

Figure 1: Development of entire metal demand, primary and secondary production of aluminium in Germany [1]

For the correct definition of the term “recycling” at first a qualitative and quantitative description of the scrap flows from the areas of application is important, as well as their connection to existing recycling routes. Therefore a division of Aluminium materials in two groups of alloys is important. In cast alloys the content of alloying elements, above all silicon and copper, is rather high, wrought alloys in comparison are lower alloyed, usually with magnesium and manganese and should therefore be separated and if possible should arrive pure sorted in the recycling cycle. Figure 2 shows some basic differences.

Casting alloys:
- **relatively high alloying contents (Si, Cu, Mg, Zn)**
- **AlSi7Mg, AlSi12, AlSi6Cu, AlZn5Mg**
- **casted engine parts, wheel rims, doorhandels, pans**

Wrought alloys:
- **relatively low alloying contents (Mn, Mg, Cu, Ni, Zn, Si, Fe)**
- **AlMn1Mg1, AlSi1Mg, AlCuMg, AlZnMgCu,**
- **tins, foils, extruded shape, conducting material**

Figure 2: Comparison of casting and wrought alloys

The material separation is limited by application and collection inclusive trade. Figure 3 shows the German application divided by aluminium casting and wrought alloys, that is dominated by the traffic sector [2]. In each of these ranges of application, with exception of the packing area, casting and wrought alloys often are mixed after use.

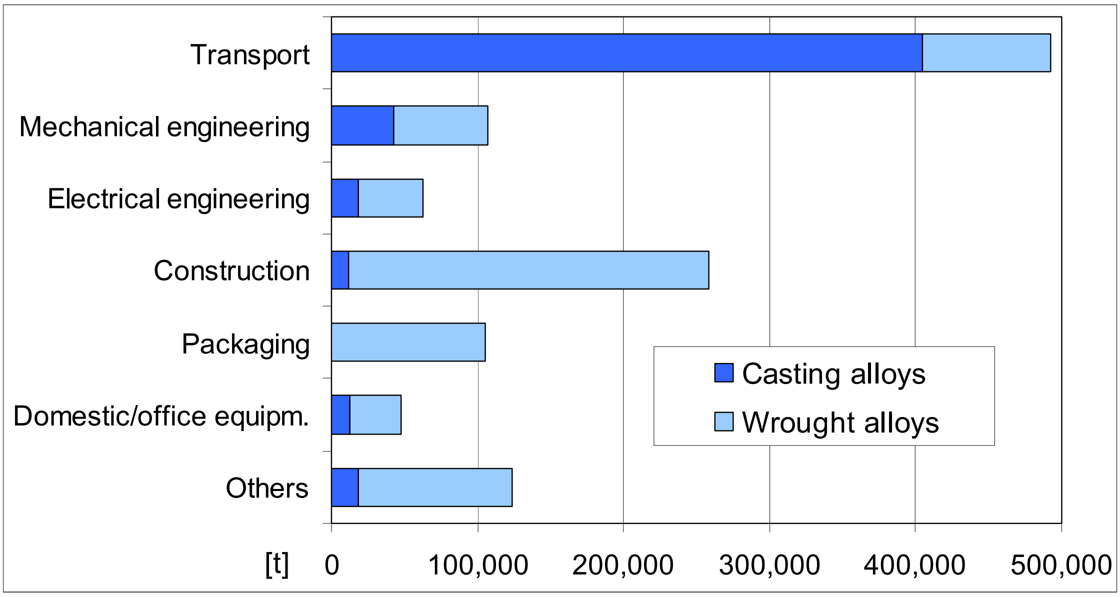

Figure 3: Use of aluminium casting and - wrought alloys 1997 [2]

Apart from this rough division in casting and forgeable alloys exists a further distinction in group of alloys, which results from type and quantity of the mainly used alloying elements. Figure 4 shows an division of aluminium alloys commonly used in statistics. These can be mixed only within close limits among each others and are collected individually if possible.

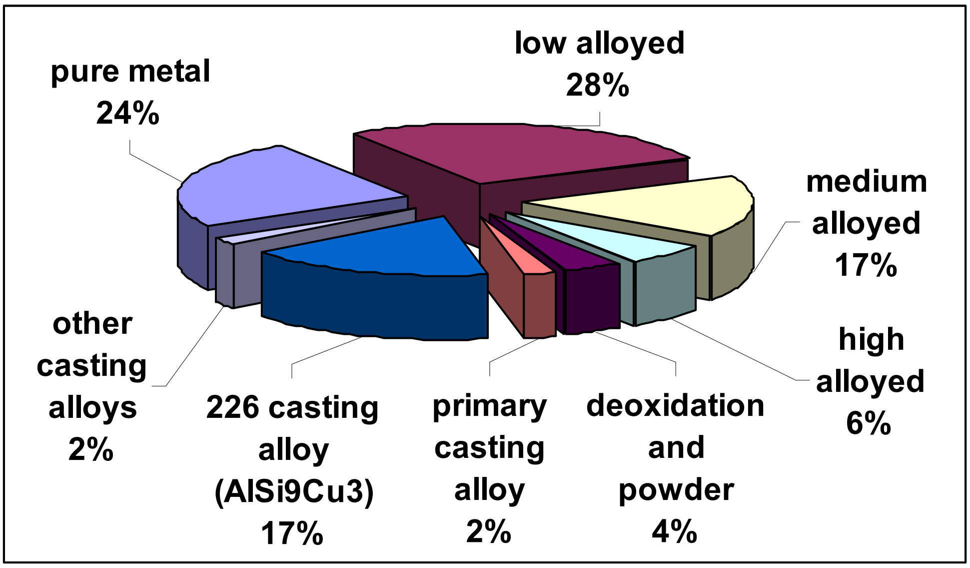

Figure 4: Alloy shares of aluminium application in Germany

With the view of individual ranges of application further distinctions must be made: On the one hand closed recycling cycles exist, so called closed loop recycling, if scrap is supplied to a same-alloy reapplication, e.g. with beverage cans and window frames. Open recycling cycles, so called open loop recycling, exists if secondary raw materials are after smelting supplied to another use also in form of other alloys. Here in particular the refiner (secondary smelters) should be mentioned, which produce cast alloys for the automobile industry exemplary out of a mixture of different old and new scrap (figure 5).

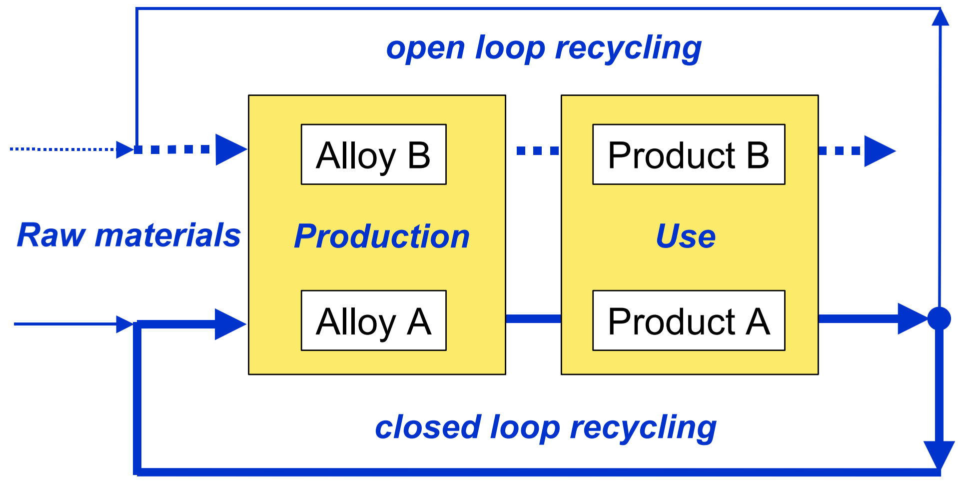

Figure 5: Open and closed recycling cycles

Besides this idealised cases a transient area in material and spatial regard exists. Materially, since also forgeable alloys are converted into cast alloys and so achieve a material-technical modification. Spatially since production scrap is recycled externally not only in-house, and thus not remain in a closed cycle. Sort-pure wrought alloy scrap is recycled directly by the remelters to rolling and extrusion ingots, which go then into closed and open recycling cycles. Mixed and contaminated scrap is exclusive recycled by the refiners into cast alloys and go usually into open recycling cycles [3].

While the product is in use the metal is bound in so material stock. The overall stock quantity of aluminium is estimated to 600 - 700 millions t world-wide. The distribution of the metals and the return flow into the production cycle are thereby spatially, materially and temporally different. The stock characteristics of aluminium can be described on the basis of selected product groups, products, product sections or types of use (table 1). Aluminium packaging for example was a high spatial distribution with small product size. The material purity can be high (menu bowl, beverage can), middle (cover caps, painted foils) or low (multi layer foils, vaporised bags). The retention time is small with an average life span of half a year [4].

Stock characteristics		Packa-ging	Transport		Con-struction	General en-gineering	Electrical engineering
			train/plane	car			
spatially	size	small	high	middle	high	middle	middle
	propagation	high	small	high	middle	middle	high
materially	purity	varied	high	small	high	middle	varied
temporally	retention time	small	high	middle	high	high	varied

Table 1: Stock characteristics of aluminium products in selected use areas [4]

The temporal aspect is shown in the next figure of production periods, life span, recycling quotas, return flow quantities of resulting aluminium scrap and the resulting difference to the present requirement in different applications, figure 6.

Today for example scrap from mechanical engineering arises, which was produced between 1980 and 1990, thus has a life span of 10 to 20 years. Only packing materials arrive back into the secondary cycle within half a year. By the temporal shift of the scrap flow in relation to the production the difference between resulting scrap quantity and necessary metal becomes larger. This is still enlarged by the high growth rates in the aluminium application.

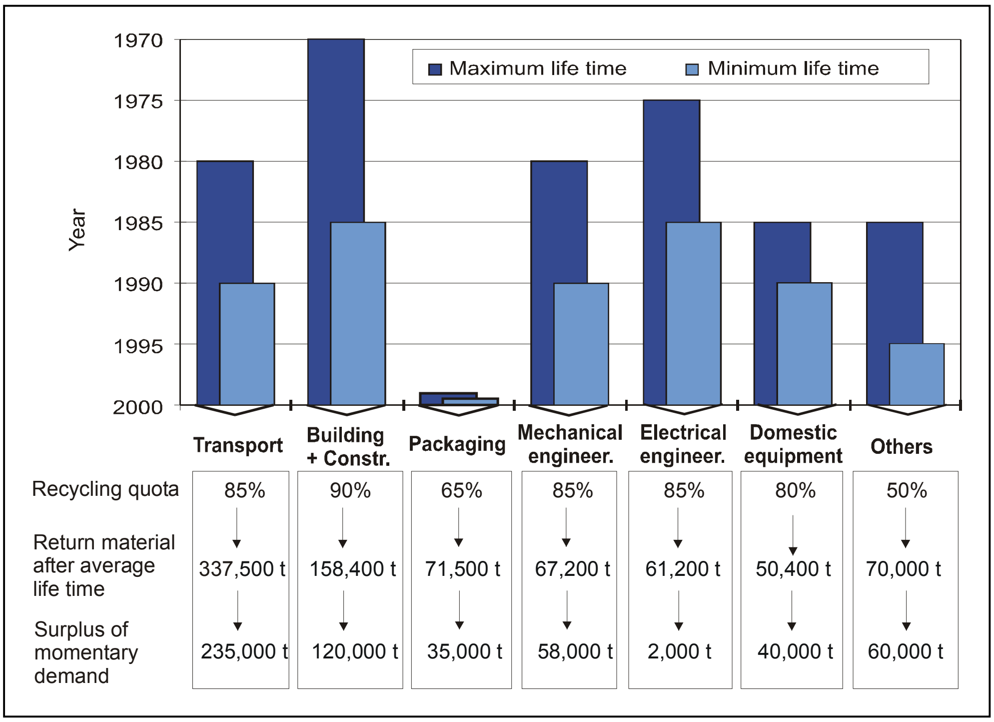

Figure 6: Recycling quotas and return quantities resulting from different lifetimes for different applications under the assumption of complete collection

The determination of the scrap amount is based on the depot quantities of individual applications and their recycling quotas. The recycled content resulting from this estimation would amount for a complete collection of the scrap to 60%. Reason for the difference to the value of 18%, specified before, is alone the determination of the recycling quota. Following some definitions [5, 6]:

For metal recycling the recycling quota consists of the collection quota and the technical recycling quota. This separation clarifies also the different levels of the recycling in figure 7, their knowledge represents the basis for a resource-oriented view.

To distinguish

- the collection quota CQ: It determines the quantity of available secondary material that is registrated in collecting system, related to the quantity used in the product.
- the technical recycling quota RQ_t: Here the quantity of material is determined, which after the collection and recycling actually is available for utilisation at the end of the process as secondary metal, i.e. it is the yield of the technical process.

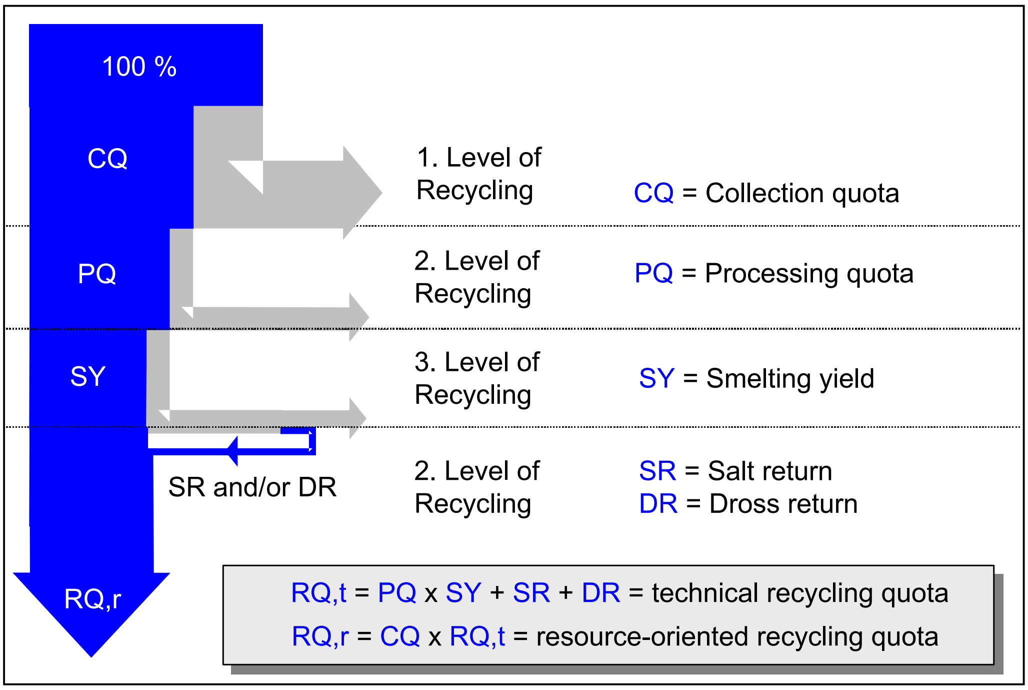

Figure 7: Definition of the recycling quotas for collection, processing and smelting [5]

The technical recycling quota consists again of two sections, PQ, which indicates the processing quota, that is how much metallic aluminium from the collection is supplied for melting; and the smelting yield SY, which indicates, how much aluminium is won as liquid metal, i.e. herein is taken in account the return flows from salt slag and dross treatment (SR, DR).

By the example of the German packaging recycling the different levels of the recycling can be explained.

In the year 1997 consumption of light packaging material (LPM) that are plastics, tinplate, composites and aluminium, amounted to 1,778,198 t [6]. Of the used packaging material 1,582,596 t collected, which corresponds to an collection quota of 89 %. At the same time 389,525 t of other materials arrived by false collection into the LPM mixture. In the sorting plant plastics, tinplate and composites are separated and an aluminium-bearing fraction (LPM Al40) is supplied to the further utilisation in mechanical processing, composite processing and pyrolysis. This amounted in 1997 to about 55,000 t.

The appropriate recycling quota is calculated in figure 8. The technical recycling quota amounts to 68,4 % and the resource-oriented recycling quota is 61,7 %.

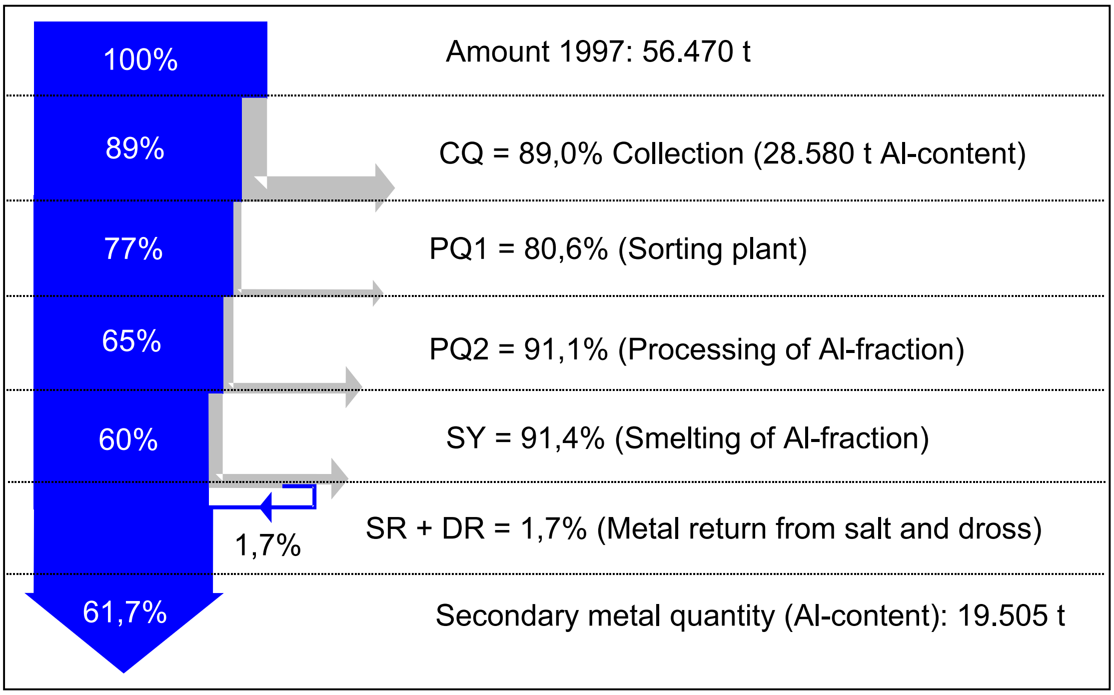

Figure 8: Determination of the recycling quotas for Aluminium light packaging material [6]

For the different areas of use for aluminium the determined quotas vary [4]. The span of collection reaches from approx. 25% for the aluminium content of urban waste up to almost 100% of the quantity from the constructing sector, in such a way it becomes a crucial element for the success of a recycling concept in regard for a most efficient utilization of secondary raw materials (figure 9).

The resource-oriented recycling quota defines thus the recoverable metal content of the assigned materials or components.

In contrast to it the recycled content is the share of secondary metal, which is used for processing. If the collection quota of secondary raw materials is considered for the determination of the theoretical recycled content, it is reduced from 60 to 46% (viz. figure 6). The recycled content lies usually below the recycling quota, since with rising metal consumption more primary metal must be produced, than is corresponded to the losses during usage.

The recycled content however is unsuitable as standard of valuation for recycling success, since it represents a regional valve, which is often strongly falsified by the existing open scrap market and the rising metal demand of application.

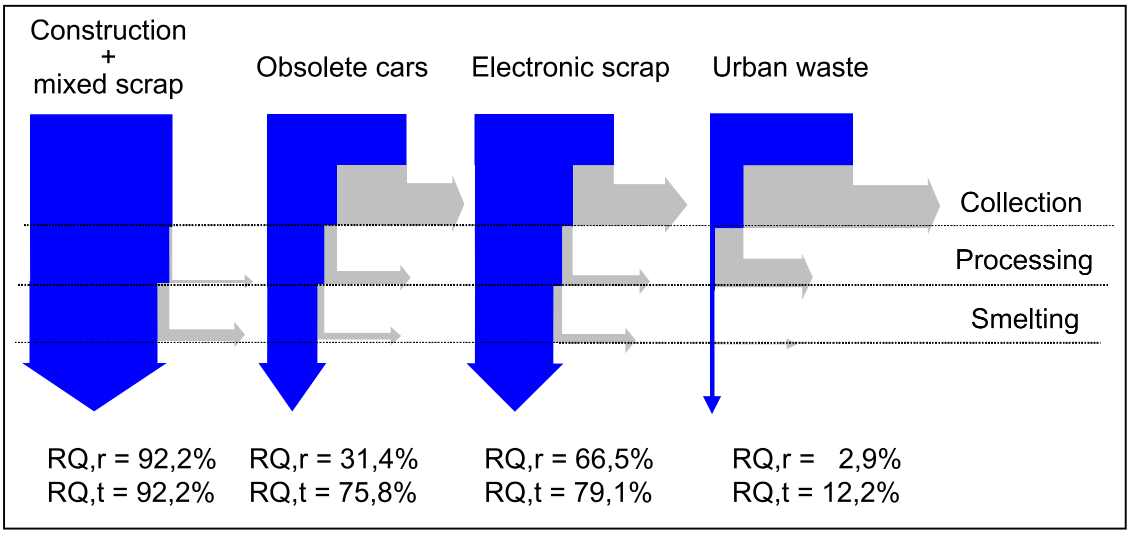

Figure 9: Technical and resource-oriented recycling quotas for aluminium products [6]

Quality influence of secondary raw materials on the aluminium recycling

Apart from the availability also the quality of the feed materials is of crucial importance for the recycling, i.e. their condition and above all their alloy composition.

Refining of the very ignoble metal aluminium is only possible within very small limits (table 2) and accompanying metals such as iron, manganese, silicon, magnesium, copper and zinc remain predominantly soluted in the metal phase. For this reason during primary aluminium production refining is done before reduction, for recycling this means an exact separation of the scrap concerning type of alloy and purity must be done already before melting. If this is not succeeded only a diluting with primary metal or blending of different melts as a possibility for alloy adjustment remains.

As consequence from the alloy situation in practice two types of furnaces became generally accepted. Sort-pure scrap and new scrap are usually melted in large volume open-hearth furnaces, mixed new and old scraps, dross and turnings are melted in smaller, more flexible salt bath rotary furnaces. This distinction is also found in the different procedure routes of the second and third recycling level (figure 10).

Kind of refining	Effect
Use of melting salt	Removal of oxides
Chlorination	Removal of alkalia and earth alkalia
Gas treatment	Removal of H, Li, Na, Mg, Ca, Sr, oxides, carbides and nitrides
Salt refining	Removal of Li, Na, Ca, Sr and oxides
Intermetallic precipitation	Removal of Fe, Mn, Si
Vacuum distillation	Removal of Li, Zn, Mg, Na
Addition of primary aluminium	Dilution of accompanying elements
Addition of alloys	Blending, dilution of single accompanying elements

Table 2: Possible melt treatment of remelted aluminium

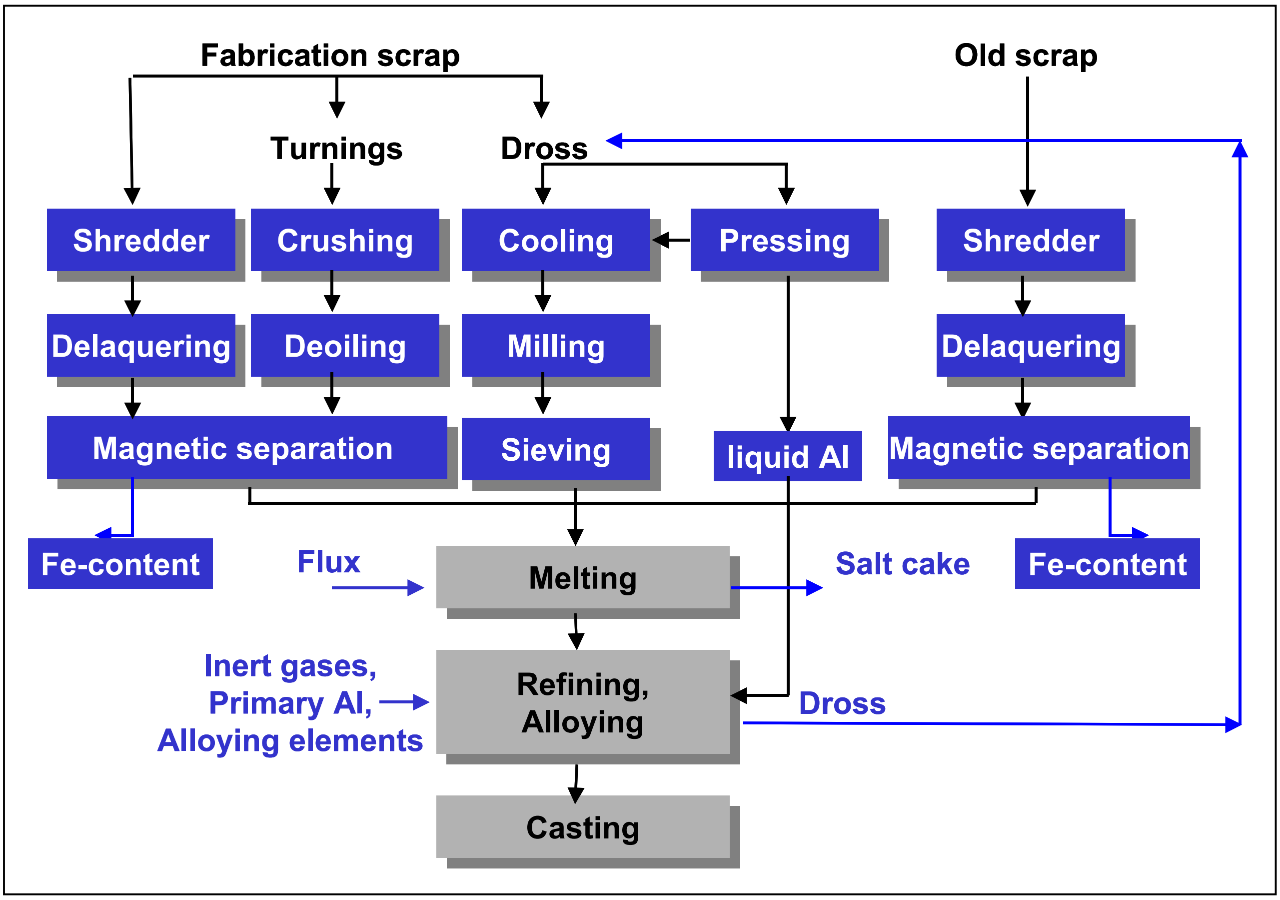

Figure 10: Flow sheet of the aluminium recycling (level 2. and 3.)

Despite of rising return quantities from production and use the intensified sort-pure recycling of forgeable alloy scrap from refiners leads to a lack of diluting material for the secondary smelters. Through their necessarily increased application of primary metal their cost situation is getting more difficult.

Accordingly, the scrap application of German aluminium refiners (figure 11) shows decreasing shares of new scrap in the years 1975-1999, whose share was reduced to 30 %, while the share of old scrap developed in opposite direction [7].

For the example of aluminium the scrap balance of 1997 in figure 12 clarifies the aspects of scrap availability and quality. First a small export surplus is to be detected, which consists of old scraps, fabrication scraps and turnings.

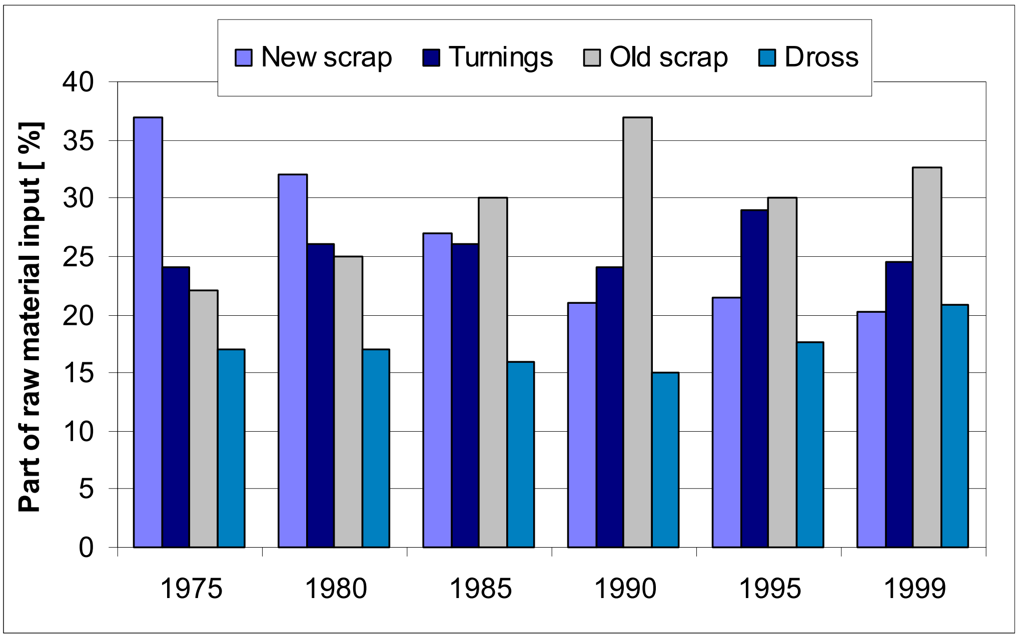

Figure 11: Development of the scrap supply of the German secondary aluminium smelters from 1975 to 1999 [7]

For the secondary aluminium production approx. 400,000 t scrap (Al-content) were used, of that about 70,000 t of wrought alloys became remelted pure sorted. Further wrought alloys were remelted in the cast houses of primary smelters (174,900 t) and the semi-finished material plants (190,000 t) [8, 9]. The amount of approx. 920,000 t of fabrication scrap is re-used directly in the semi-finished material manufacturing as cycle material and is thus statistically not registered.

The shown scrap application plus an imported quantity of 168.000 t secondary aluminium and the scrap share of the foreign primary metal results in a real recycled content of the German total production of 37 %. This is a mass-referred average value of the individual areas of application.

The interaction between the product areas can be quantified by the existing scrap flows (figure 12). An alloy cascade results, whereby the recycling activities increase the alloy content of the entire stock. Unalloyed aluminium forms the starting point of this material flow and has therefore the smallest recycled content. Lowering of the alloy status, i.e. a reversal of the usual supply direction in figure 13 is only possible with a high expenditure, comparable to the primary production.

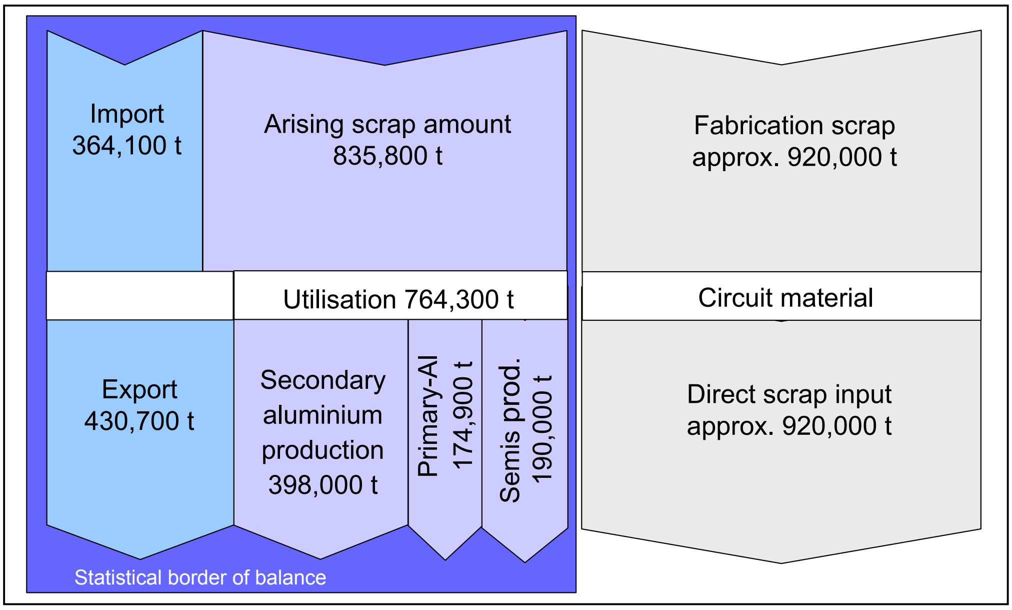

Figure 12: German scrap balance 1997 [8, 9]

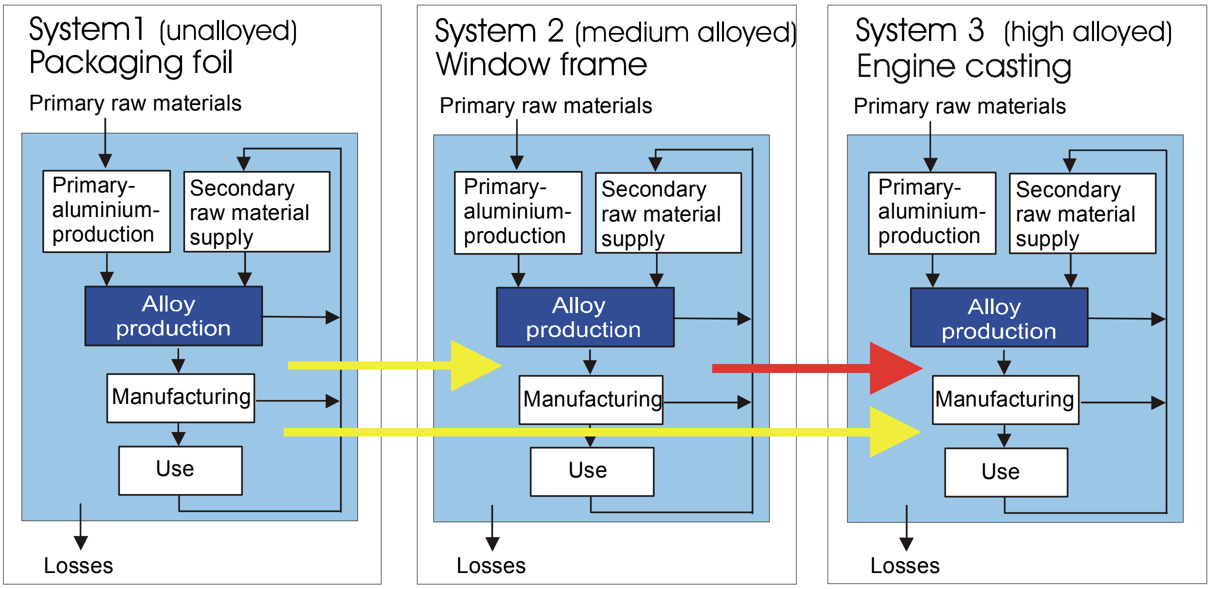

Figure 13: Interaction between the recycling systems

In the long run the success of recycling activities can only be evaluated by the metal quantity recovered and thus by the saving of primary metal in the total system of aluminium, whereby only about 10 % of the energy expenditure of the primary production is needed. Beyond that the sort-pure collection and processing works against an enrichment of alloying elements in the recycling cycle and save thus the maximal applicability of the secondary raw materials that is expensive anyway by its shortage.

Energetic evaluation

For the energetic evaluation of recycling first the question of the optimal technique for the processing of the different materials is to be answered. Thereby the energy expenditure of every material sinks with rising recycling quota, or rising recycled content of a closed product cycle shown in figure 14. An increase of the recycling ratio leads however starting from a certain limit value to very strongly rising expenditures, since then the specific energy consumption rises super proportionally with the high expenditure for collecting and processing.

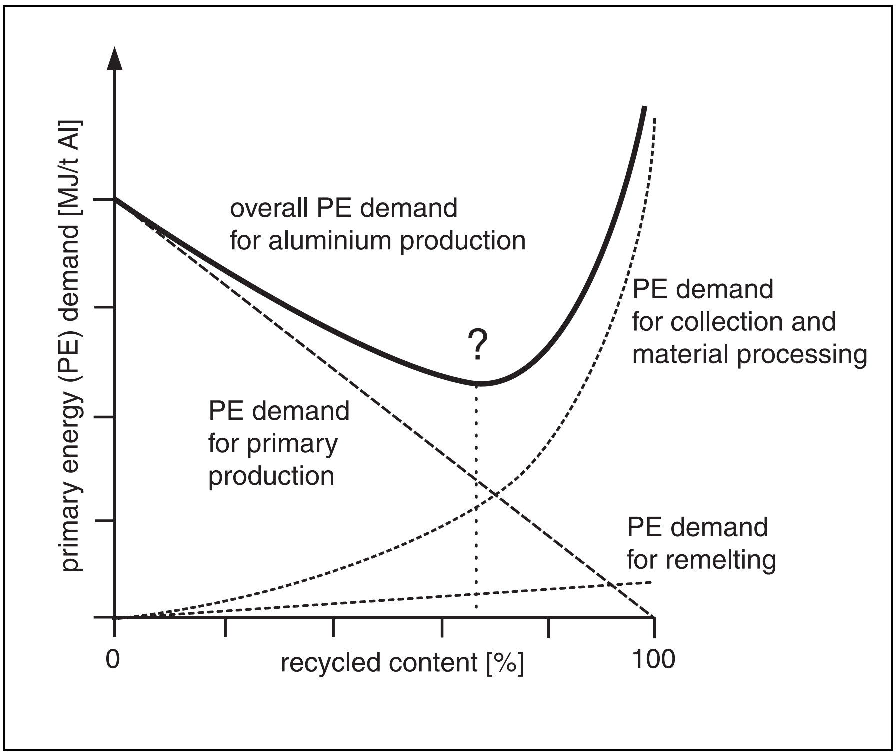

Figure 14: Qualitative determination of an optimal recycling ratio regarding the primary energy expenditure

Beyond that the condition of the scrap and in particular their aluminium content intends the power requirement for the remelting. Figure 15 shows a strong rise of the energy requirement below approx. 80 % aluminium content. Below that value the accompanying substances of the aluminium decide on the application in which respective melting or processing unit they are treated. In melting practice an optimal melting yield is achieved only by special material mixtures.

An example of aluminium-poor raw materials is the aluminium fraction won from light packaging materials. Here also the potentials of the technological development and in particular the interaction between processing and melting practice can be clarified. Figure 16 shows the existing system of the packaging material recycling. The aluminium fraction from the sorting plant, with 40 % aluminium content and predominantly organic residues can not be processed directly pyrometallurgically. With the combination of mechanical and thermal processing routes a high-quality fraction with approx. 99 % of aluminium content is obtained which can be processed with a melting yield of over 90 %. The average processing quota is situated however with about 73.4 % relatively low.

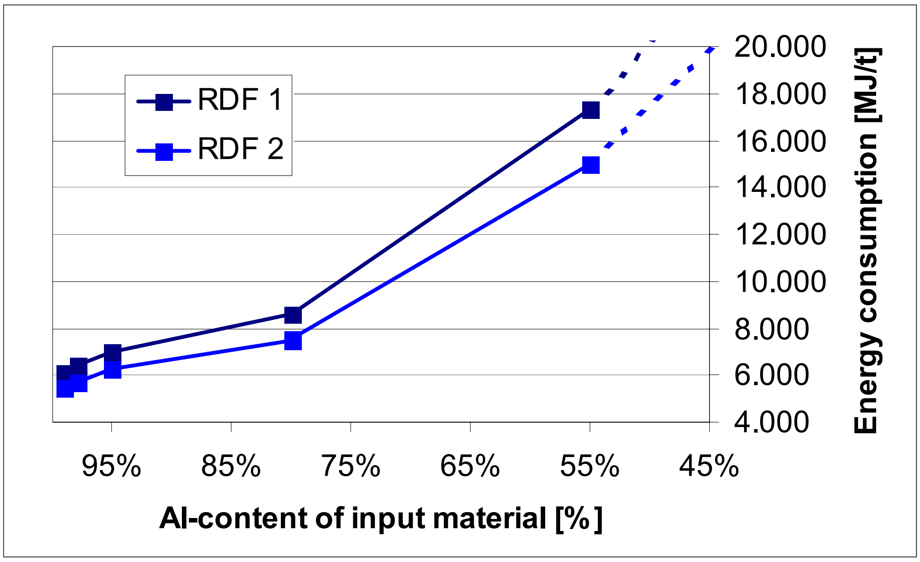

Figure 15: Dependency of the melting on the aluminium content of the materials

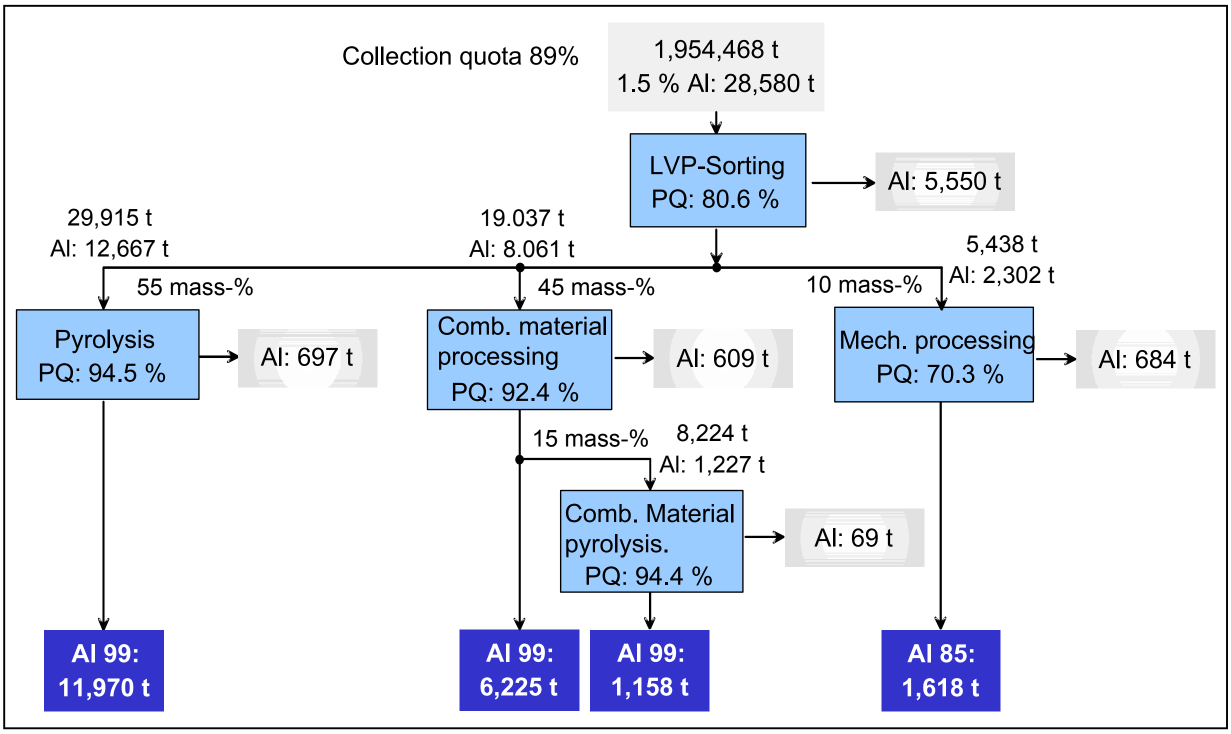

Figure 16: Processing of the Al-fraction of light packaging material [10]

Alone by the application of a fully automatic sorting plant the yield of this level could be increased from 80,6 to 94 %. Then process specifically the energy consumption rises, related to the larger production however this turns into an advantage. Scenario calculations show that in the case of appropriate melting technique for future recycling concepts NT (exclusively newest technology) their possible usage in the year 2010 saving potentials result of 2000 or 1370 MJ/t of produced alloy, with an increase of the aluminium quantity around 20 or 4 % (figure 17) [10, 11].

Beyond that detailed analysis of the recycling processes by means of process chain modelling points out further important, often not obvious aspects of the recycling or individual processes.

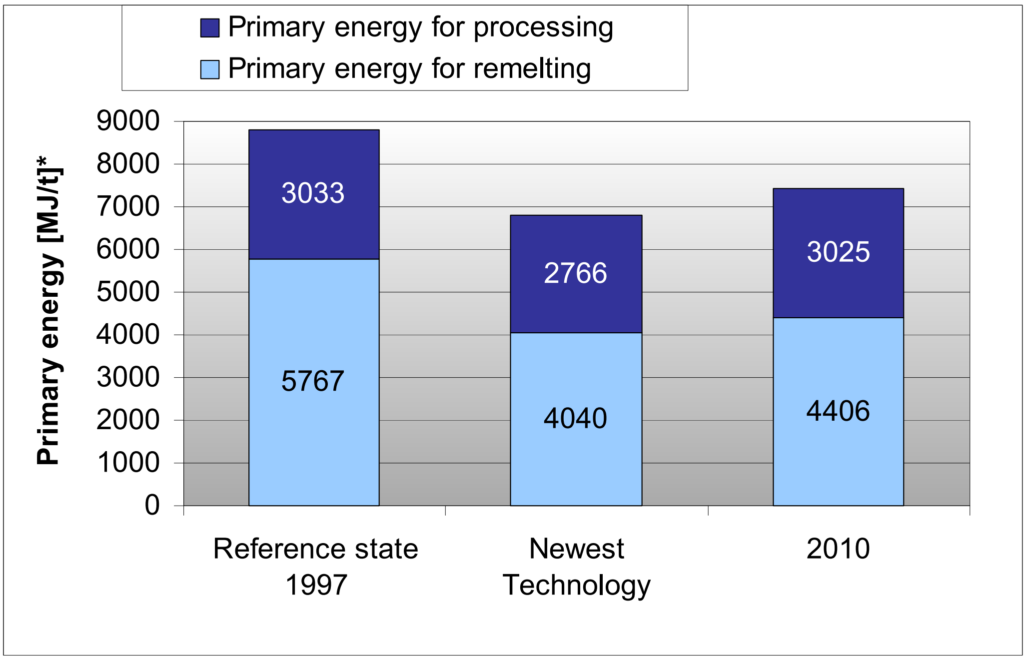

Figure 17: Comparison of the primary energy demand of today's and in the future possible concepts of light packaging recycling [10, 11]

Figure 18 shows besides the allocation of the primary energy the distribution of the final energy exemplarily for the energy carrier Diesel. It shows how important the transportation during the collection and afterwards to the sorting plants is. Likewise the utilization of the aluminium fraction in the centralised pyrolysis operations in Southern Germany is connected to high transport expenditures.

Summary

This article confronts requirement and feasibility of the aluminium recycling. The scrap availability is the focal point of the view, since it exerts an influence on the recycling activities, equally important for all metals. From this the recycled content of the used metal quantity can be determined, which varies regionally, temporally and product-specifically. The recycling quota is in comparison a predominantly technique-specific measure for the success of recycling activities, with which depending upon the selection of the definition also the collection of secondary materials must be considered. For recycled content and quota is the quality of the raw materials, i.e. the condition, the alloy composition and the metal content of importance. The recycling technique can be described over the metal yield and the energy requirement, whereby as possible an entire recycling concept with processing and melting technique has to be evaluated and not an individual process.

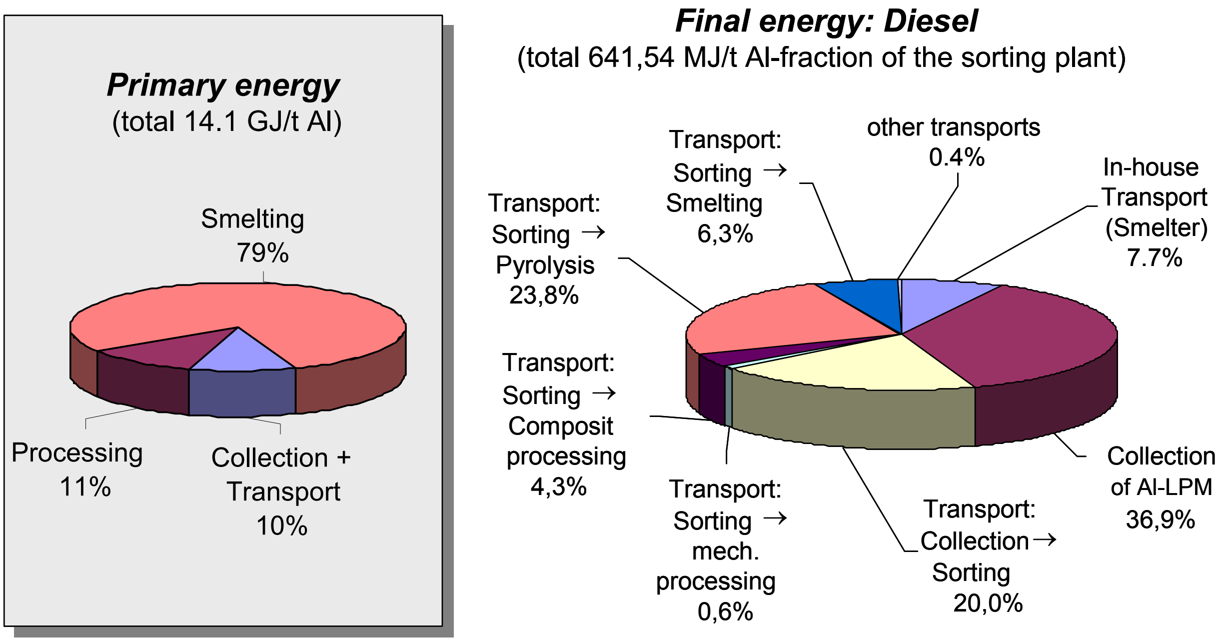

Figure 18: Classification of the primary and final energy consumption for the packaging recycling by the example of Diesel fuel [10]

Future developments will have to aim at the increase of the efficiency of collection and utilisation of secondary raw material sources up to an optimum. The energy expenditure for the recycling represents however only one element, which are usually consulted in connection with the resulting emissions for the ecological evaluation. In order to arrange a sustainable development of the metallurgy, also economic and social aspects of the resource management are to be included into the view.

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A SCENARIO TO OPTIMISE THE ENERGY DEMAND OF ALUMINIUM PRODUCTION DEPENDING ON THE RECYCLING QUOTA*

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ABSTRACT

Re-melting aluminium requires about 5-10% of the energy used for primary production, so that recycling is very attractive from an energy point of view. Beside smelting secondary aluminium production includes other processes like collection and material processing. The energy demand for these processes rises with an increasing recycling quota because of lower metal contents and greater specific mass flows respectively. So in a closed loop recycling system there is a minimum energy demand of mixed aluminium production from primary and secondary raw materials. In this article a first approximation of this optimal recycling quota is given. As an example the recycling system of lightweight packaging material (LPM) in Germany is analysed and its overall energy input is determined. Based on this analysis, a scenario is developed to study the energy demand at recycling rates higher than the present one. Additionally several options to calculate the energy demand of secondary aluminium production are discussed.

KEYWORDS

Secondary aluminium production, lightweight packaging recycling, energy consumption, recycling quota

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1. Introduction

This study aims at an energy-related discussion and evaluation of improved aluminium recycling concepts. As a basis for the analysis the energy consumption and recycling quota of light weight packaging recycling in Germany are assessed using a process chain model. A scenario is developed for increased recycling achieved with alternative or improved processes.

The evaluation starts with the determination of primary energy equivalents of electricity and fuel consumption of different processes as well as their combinations. In the next step an additional energy input materials is considered, which is supplied by the energy content of the secondary raw materials, i.e. the fraction of aluminium oxidised during remelting and the accompanying organics. In the third step the system is extended to the incineration of that part of packaging materials which is treated together with the household waste. Finally a credit system for power produced in incineration plants is used. Different calculation methods are discussed to show the energetic limits of recycling activities and the difficulties of process evaluation.

Packaging material is chosen as an example because of the competitive ways of material processing and the existing optimisation potentials in all stages of the recycling process.

In order to model the complex system of metal production and recycling an integrated resource management system is used. This system has been developed by the Collaborative Research Centre CRC 525. This research institution has been established in 1997 at the Aachen University of Technology and the Forschungszentrum Jülich. Here nine departments co-operate in order to achieve a "Resource-Orientated Analysis of the Material Flow of Metallic Raw Materials" [1].

The integrated approach of the CRC 525 provides support for finding decisions based on the concept of sustainable development. The goal of the research program is the identification of options for resource-sensitive supplying and processing of metallic raw materials considering the conflicts between technical developments, economic and ecological aims.

2. Determination of recycling quotas

For metal recycling the recycling quota consists of the collection quota and the technical recycling quota. This separation clarifies the different levels of recycling and permits a resource-orientated point of view [2].

- The collection quota *CQ* is the quantity of secondary material, which is recovered by collection systems, related to the total quantity of used products:

$$CQ = \frac{\text{quantity of collected products}}{\text{quantity of used products}} \cdot 100\%$$

- The technical recycling quota RQ_t is the relation between the remelted and the collected quantity and describes the yield of technical processes:

$$RQ_t = \frac{\text{remelted quantity}}{\text{collected quantity}} \cdot 100\%$$

The technical recycling quota consists of two sections. First, the processing quota indicates, how much metallic aluminium of the collected quantity is supplied for melting. Second the smelting yield describes, how much of the aluminium supplied is won as liquid metal, i.e. here the losses in the resulting salt cake or dross are considered.

The product of CQ and RQ_t results in the resource orientated recycling quota RQ_r:

$$RQ_r = \frac{\text{remelted quantity}}{\text{quantity of used products}} \cdot 100\%$$

In contrast to the quota, the recycled content is the share of secondary metal, which is used for product manufacturing. It is usually smaller than the recycling quota. Due to an increasing aluminium demand more primary metal must be produced than would be required for replacing the losses.

3. Methodological approach

The primary energy demand of remelting aluminium amounts to only 5-10% of that for primary production. To produce primary aluminium large amounts of electricity are required for electrolysis while for mining, transport and production of alumina and anodes only minor amounts of energy have to be supplied. For remelting just the melting energy has to be supplied, which is mostly done by natural gas combustion. Beside remelting, collection and material processing are necessary steps in the process chain of recycling. The energy consumption for those processes depends on the recycling quota. For high recycling quotas the material flows to be processed reach very large scales in relation to the metal content. So due to the high efforts of complete material collection and processing the overall energy consumption for aluminium recycling rises disproportionate at high recycling quotas and goes to infinity for a quota approaching 100% (see dotted lines in figure 1).

Furthermore, the energy demand of the production of one ton of aluminium depends on the recycled content. To handle both, the recycling quota and the recycled content, a closed loop recycling system is assumed. So the recycling quota is equivalent to the maximum recycled content of that closed system. A further assumption is necessary due to different metal qualities obtained from different process alternatives. The amount of aluminium obtained from each recycling path is assumed to substitute primary aluminium. Material depending metal losses during remelting are considered but the quality of the obtained alloy is neglected, so that cast alloys are assumed to substitute primary aluminium in the same way as wrought alloys.

Combining the dotted curves in figure 1 to an overall primary energy demand, it decreases with an increasing fraction of secondary aluminium at low recycling quotas. With growing recycling quotas the influence of increasing energy consumption for the material processing of secondary raw materials exceeds the decrease due to lower contents of energy intensive primary metal. This results in a point of minimum primary energy demand for aluminium production at a certain recycled content. One approach to obtain this optimal recycling quota of light weight packaging is presented in this article.

4. Recycling of aluminium packaging material in Germany

The use of aluminium as packaging material is still increasing. The variety of its application ranges from combined coffee-packaging to beverage cans. In Germany, aluminium packaging is recycled together with other lightweight packaging material (LPM) by the Duales System Deutschland AG (DSD). LPM is collected separately from household waste and recycled afterwards.

The system for the recycling of aluminium can be divided into three levels. First the secondary raw material is collected. Second, the material has to be processed in order to achieve an aluminium product which can be remelted. Third, the processed material is remelted. At each level of recycling different technical processes are linked together by transportation steps which are also taken into consideration.

4.1. Current LPM recycling practice

Figure 2 shows the process chains of the LPM recycling as it is currently done in Germany. At the first level LPM material is separated from other household waste by the consumer itself. It is collected in special bags or bins and regularly picked up by the garbage collection system. In the year 1997 the German consumption of light weight packaging material (LPM) consisting of plastics, tinplate, combined materials and aluminium, amounted to 1.78 Mt [3]. 1.58 Mt of the used packaging were collected, which corresponds to a collection quota of 89%.

On the second level of recycling first an aluminium fraction is separated from other packaging material in so-called sorting plants. A drum sieve separates large volume items, foils, and films. Before the foils and films are pressed to bales and transported to a plastic recycling plant, impurities are sorted out by hand. After the sieve all ferrous material is separated. A magnet extracts packaging containing iron such as tinplate cans, bottle caps and jar lids. Lighter packaging as paper or plastics are separated by pneumatic separation. Next the recyclable material is sorted by hand. Beverage cartons, plastic packaging, and composites are separated. The last step of the sorting plant is the separation of aluminium from the remaining sorting rest. This is done by an eddy current separator. As the resulting aluminium fraction has an aluminium content of app. 40%, further processing is necessary prior to remelting.

Currently this is done using three different techniques which are mechanical processing, pyrolysis and decomposition of combined material with subsequent pyrolysis. The production shares are 10%, 55% and 35%, respectively.

For the mechanical treatment the material is shred into pieces smaller than 50 mm. Comparable to the steps of the sorting plant, an aluminium fraction is sorted out. Since the shredded pieces are smaller, a more exact sorting is possible.

In the pyrolysis process the Al40 fraction, which consists of approximately 40% aluminium, 40% plastics (PP, PE), water, oxides and paper, is processed. At temperatures around 550°C the organic mass is carbonised and evaporated in a non-oxygen atmosphere. The energy content of the carbonised gas is used for heating the pyrolysis process.

The third installed process is the mechanical decomposition of combined material. In a high speed mill, the composites are split up into two fractions, an aluminium fraction of high quality, which can be remelted directly and another fraction of low aluminium concentration. The latter needs further treatment, which is done by pyrolysis.

Finally, remelting of the aluminium fractions takes place at secondary aluminium smelters. The aluminium is molten in two different types of furnaces, the multi chamber furnace and the rotary drum furnace. During remelting a certain amount of metal is lost in dross or salt cake due to oxidation.

The efficiency of the recycling system for aluminium packaging in Germany can be described for collection, processing and remelting. Each level of recycling causes losses of metal (see table 1) so that the overall recycling quota (collection, processing, remelting) is 59% and the technical recycling quota (processing, remelting) is 67% [4].

4.2. Automated LPM sorting

Beside the existing processes a new technology is considered in the calculation representing technical progress of the recycling concept. The so-called Sortec 3.0 is a fully automated sorting plant for mixed packaging materials as they are collected by the DSD. It can be subdivided into a dry-mechanical pre-sorting stage, a wet processing stage and a plastics beneficiation stage. The products of the first stage are tinplate, beverage cartons and PET which are compressed for further utilisation.

The light weight fraction of the LPM-fraction is processed in the wet part of the plant. By using a wet dissolving step in combination with a subsequent comminution the wet processing separates combined packaging material. Aluminium is recovered by eddy current separation. A further product of the wet processing are paper fibres. The aluminium product which contains 85% of metal is recovered with a yield of 94%.

The plastics beneficiation stage includes separation of different plastic types, drying, agglomeration and granulation [5].

The aluminium fraction is subsequently treated by pyrolysis.

For this process chain, the overall recycling quota (collection, processing, remelting) reaches 76.3% and the technical recycling quota (processing, remelting) 85.7%.

If the Al85-fraction is remelted directly without the pyrolysis step the overall recycling quota decreases to 60.8% and the technical quota to 68.3% respectively. This impressively shows the benefit of further aluminium concentration before remelting.

4.3. Aluminium recovery from waste incineration plants

In this evaluation steps all packaging material which is not utilised by the DSD, is assumed to be collected via municipal waste collection. Beside disposal in landfill sites one third of the municipal waste is incinerated. Two thirds of the incineration slag are processed for further utilisation e.g. for road construction [6]. Therefore the metallic content must be extracted. This is done in a slag treatment plant which mainly consists of a shredder, sieves, a magnetic separator for ferrous metals and an eddy current separator to recover the non-ferrous metals (see figure 3). Since most of the metal in the slag is ferrous, the plant is optimised for the extraction of ferrous metal and the non-ferrous metal fraction is a by-product. The non-ferrous fraction consists of aluminium, copper and zinc, which are separated in a sink-float process. The aluminium fraction is molten in a rotary drum furnace.

To improve the metal yield of the incineration path it seems useful to install further eddy current separators (ECS) in the slag treatment plant in order to extract non-ferrous metals from the slag product. Since they work best, when the piece size of the raw material does not vary too much, sieves are installed to gain fractions with defined piece sizes (see figure 4). In this way non-ferrous metals are extracted from the slag product, so that the aluminium loss is reduced close to the technical loss.

5. Calculation steps and system boundaries of the scenario development

Based on the analysis of the current LPM recycling system in Germany a scenario of increasing recycling quotas is developed in several steps. The presented differentiation and evaluation of the technical potential allows statements about an optimal recycling quota from an energy-focused point of view.

5.1. Scenario calculation for LPM-processing

The calculation starts with representing the current recycling system for aluminium in LPM comparing the different technologies of material processing and remelting. Then technical development is introduced by implementing the Sortec process in the recycling chain. The following steps have been calculated:

1. Individual analysis of the three process chains of mechanical processing, pyrolysis and processing of combined material with subsequent pyrolysis
2. Calculation using the existing capacity weighted process mix considering the 1997 reference state
3. Exclusive LPM-recycling by fully automated separation (Sortec) and rotary drum furnace for remelting the resulting Al85 fraction
4. LPM-recycling by fully automated separation (Sortec) with subsequent pyrolysis and multi chamber furnace for remelting the resulting Al99 fraction with best metal recovery

5.2. System extension by inclusion of aluminium recovery from incineration slag

Beside the recycling system of DSD the remaining 11% of the used packaging material are collected as a part of the municipal waste of which currently one third is incinerated. The extension of the assessment to the waste incineration has to consider the collection efficiency of the complete German system. So all further calculations now refer to the resource-orientated recycling quota (RQ_r) instead of the technical quota (RQ_t).

The extended system is calculated according to the following steps:

5. Current situation with one third of the municipal waste being incinerated (including 11% of LPM) and two thirds of the resulting slag being processed, DSD processing by the 1997 process mix

6. Partial incineration as in step 5 but use of the Sortec process for DSD processing instead of the 1997 process mix
7. Installation of a pyrolysis plant following the Sortec process of step 6 and use of a multi chamber furnace for remelting instead of the rotary drum furnace
8. Sortec and incineration combination according to step 7 but assuming an increase of slag processing from two thirds to 100%
9. Installation of an additional treatment for the slag product within the improved system of step 8

5.3. Improvement of LPM recovery

For further increase of the amount of recovered material and the resource-orientated recycling quota of LPM respectively there are 3 theoretical options. First the packaging fraction could be separated from the municipal waste, which does not seem realistic due to the huge amount of waste material. A second option could be the complete waste incineration of the LPM-fraction contained in the municipal waste without a preceding sorting process. This is assumed for a further calculation step of the scenario. The expenditures of incineration of the LPM-fraction are allocated by mass to the aluminium and the other non-ferrous metal fraction which consists mainly of brass.

The third theoretical possibility to increase the amount of collected material beyond the current collection quota of 89% is to improve the consumer's behaviour, which means a better individual separation practice of LPM already in the private household and an increasing collection quota of the DSD.

The latter two options lead to further calculations, which define the two extreme situations of complete collection:

10. Increase of the recovery rate to 100 % by complete incineration of household waste for the optimised system according to step 9.
11. Increase of the collection quota of LPM by the DSD according to step 4 from 89 to 100% with the processing technology of Sortec and subsequent pyrolysis.

6. Energetic evaluation of the scenario steps

All processes of the LPM recycling, including transport, processing and remelting have been balanced by mass and energy flow analysis within the work of the CRC 525. The resulting process chain model was used for the calculation of the energy demand of the different existing and possible process systems.

Beside the final energy inputs (gas, diesel, electricity etc.) listed in table 1 aluminium, oxidation during smelting and the organic content of packaging material during both processing and remelting supply a considerable energy input to the recycling system.

To show the impact of the different energy inputs on the calculation result, the overall energy demand was determined in four case studies:

(a) Primary energy calculation from natural gas, diesel and electricity consumption of the processes

To compare the energy consumption of the various process steps, each using different forms of energy, the final energy requirements of the processes were converted into primary energy demand considering the efficiency of power and fuel supply (see table 2). The energy supply is based on the German energy carrier mix in 1997. The power supply for electrolysis reflects a contract mix, which differs from the national grids because in each case the contractual power supplier and his base load mix is considered [10]. The sources of primary metal available in Germany consider indigenous production as well as imports from different countries [1, 4].

(b) Primary energy consumption including reaction heat of aluminium oxidation:

During smelting processes in fuel fired furnaces the oxidation of metal cannot be avoided. To this reaction a heat value can be assigned. For aluminium it amounts to 31.05 MJ/kg, which supplies a considerable contribution to the energy input. For the aluminium fraction of LPM processing the specific loss by oxidation amounts to 5-15%.

(c) Primary energy consumption including aluminium oxidation and combustion of the organic content of the LPM-fraction:

For the recycling of aluminium with pyrolysis as a concentration process more energy is needed than for the other recycling paths. For this process the energy content of the organics is used. Since this energy could be used in another way (for example for the production of district heating) it must be considered as an energy input to the pyrolysis process. The organic content of the feed material for the pyrolysis varies from 15 to 85% but at about 40% an autothermal operation i.e. without any additional fuel supply can be achieved. So the advantage of the Sortec plant reaching a highly enriched aluminium fraction turns into a disadvantage from an energy point of view. Due to the small amount of organics additional heating of the subsequent pyrolysis is necessary. In practice a blending of input materials is common.

(d) Primary energy consumption including aluminium oxidation and organics combustion equalised for an autothermal condition:

Considering the industrial practice of blending input material, the different pyrolysis processes with their different input qualities have to be offset against the autothermal condition. Therefore the difference between the actual organic input and the one necessary for autothermal operation is either added in case of a lower organic content or subtracted in case of a higher content.

Extending the system to municipal waste incineration the question of accounting energy contents changes to a fundamental one concerning the preference of thermal dissipation or material utilisation. Since aluminium is a minority component in the waste, it is necessary to allocate the combusted energy content in both cases.

In case of thermal dissipation the following boundary conditions have been assumed. First the amount of incinerated material is limited to the fraction of packaging material. Second the energy content of the LPM fraction is allocated by mass between the aluminium and the brass fraction of the slag product. Furthermore it is assumed that the aluminium yield of the incineration slag treatment is the same for all the different origins of the metal and therefore also applies to the aluminium from packaging material.

Further case studies have been calculated:

(e) Addition of the energy content of LPM-fraction in incineration plants to the energy consumption of the recycling process

The average heat value of the LPM-fraction is only about 17 MJ/kg due to the high content of water (20%) and inert oxidic materials. Only plastics (40%) and paper (2%) supply a heat input. The scenario contains additional process steps according to step 9 assuming aluminium as the target product. In this case the expenditures e.g. energy inputs can be allocated to the aluminium content.

(f) Energy credit for power production from LPM incineration:

Usually the off-heat of waste incineration is used for production of electricity, process heat and/or district heating. This important point has not been considered in the calculations so far. In order to keep calculations inside the system of aluminium production waste incineration plants are assumed to produce electricity exclusively. This electric energy is then to be consumed by German primary smelters for aluminium electrolysis to replace recycling metal losses. The conversion efficiency of waste incineration power plants is app. 15% [7]. So the partial substitution of nuclear and lignite fired power stations which actually generate electricity for the German aluminium smelters with about 33-35% conversion efficiency results in a considerable rise in primary energy demand for aluminium electrolysis.

In case of material utilisation due to calculation 11 the energy demand is calculated following case (d). Since the German LPM recycling system produces other secondary raw materials than aluminium, material and energy flows of the sorting process are allocated by mass.

7. Results

7.1. Energy consumption of existing recycling systems

The overall energy consumption for the different ways of recycling are shown in figure 5.

7.1.1. Conventional calculation method

Usually Life Cycle Inventories consider fossil fuels and electricity as energy inputs. Applying this method for LPM recycling most energy (20 GJ/t) is needed for the recycling path of mechanical processing. Two concentration processes are needed for this way of recycling, which both consume energy. Furthermore this process chain comes with the lowest specific aluminium output of about 44% which makes it the most unfavourable system for recycling. The best technical recycling quota of nearly 70% within the current DSD system is reached by decomposition of combined material with partial following pyrolysis (see figure 2). The fuel and power consumption of 12.7 GJ/t is only little higher than that of the system's average with 11.6 GJ/t.

7.1.2. Consideration of aluminium oxidation

Assessing additionally the oxidation heat of aluminium the energy demand rises considerably by 6 GJ/t for the paths of mechanical processing and Sortec. Here the aluminium fraction Al85 causes high oxidation losses of 15%, whereas only 5% of the Al99 fraction, obtained by all other process chains, oxidise during remelting. Consequently aluminium oxidation contributes with only less than 2 GJ/t to the energy input.

7.1.3. Consideration of organics

Assigning the energy content of organic adhering completely to the overall energy demand for the existing LPM recycling system results in a higher energy input (case c). For the current two process chains with pyrolysis and an organic content of 60% the energy demand is four times higher. The mechanical processing and Sortec without following pyrolysis supply a fraction with an organic content of only 15% which is oxidised during remelting and only adds about 5 GJ/t to the overall energy demand.

7.1.4. Normalisation of pyrolysis processes

Finally considering the current industrial practice of blending the pyrolysis input material to operate the process auto-thermally and thereby only assigning an organic content of 40% to the energy input reduces the demand considerably once more (case d). This is most obvious for the decomposition path because here the pyrolysis input consists of 85% organics. On the other hand the energy input rises for the Sortec process followed by pyrolysis. In this case the input's amount of organics does not meet the conditions for auto-thermal operation so that additional energy is needed. The calculation shows a nearly equal overall energy demand for both Sortec alternatives, with and without following pyrolysis, the latter being favourable due to its better recycling quota.

Altogether the current German recycling system for aluminium in LPM reaches a technical recycling quota of 67% consuming 11.6 GJ primary energy due to electricity and fuel demand per tonne of secondary metal. Applying a new technology of fully automated sorting followed by pyrolysis processing the technical recycling quota can be increased up to 85.7% while using 20% less primary energy.

In principle all energy contributions, i. e. both, external inputs of electricity or fuels and material-bound energy contents like organics, must be considered for the overall energy balance. Thereby the primary energy demand of the current DSD system approximately doubles to 23.3 GJ/t and the overall energy consumption of the Sortec/pyrolysis recycling path triples. With 25.5 GJ/t it slightly exceeds the energy demand of the current system. But with the overall energy demand of primary metal production, which amounts to 165 GJ/t for aluminium available in Germany, switching to the new technology in order to improve the recycling quota is advantageous from the energy point of view.

7.2. Energy consumption of improved recycling systems

In order to further increase the recycling quota, the collection process has to be considered, because of its aluminium loss of 11%. The technical potential of the processing steps seems to be exhausted by reaching a metal yield of 94% in the Sortec process. For that purpose figure 6 provides overall quotas and primary energy demand of the different recycling systems described above. Here the primary energy demand has been calculated according to the case studies a, d and e explained above.

Regarding first the recycling efficiency the resource orientated quota can be increased from 59% to 76.3% replacing the current DSD system exclusively by the combination of fully automated sorting and pyrolysis. Processing 100% of waste incineration slag instead of only 2/3 only adds 0.7 per cent points to the quota. But improved slag processing shifts the overall efficiency up to 79%. Further large increase by another 5.5% per cent points is achieved recovering 100% of LPM in household wastes by incineration and improved slag processing. The hypothetical case of complete collection of LPM by the DSD results in a resource orientated recycling quota of 85.7% which naturally corresponds to the technical quota of the Sortec/pyrolysis system.

Considering only energy inputs by electricity and fuels the systems do not differ considerably. Even with material-bound energy contents taken into account and pyrolysis calculated autothermally the overall energy demand of around 25 GJ/t stays nearly constant. Thereby it seems reasonable to incinerate all LPM not collected by the DSD but with the household waste, to recover aluminium from the slag and to reach finally an overall recycling quota close to the technical one.

7.2.1. Consideration of incineration

For balancing waste incineration in analogy to the other processing steps again material-bound energy content has to be considered. Doing so the overall energy demand for secondary aluminium production generally nearly doubles to about 46 GJ/t. In spite of the quite small share of aluminium recovered from incineration slag the influence of incineration on energy balancing is enormous. The non-ferrous metal content in LPM only amounts to 5% but the whole energy content of the fraction is assigned to this share. Due to the same reason the overall energy demand doubles to 88 GJ/t for 100% recovery by incineration. Thus this method to increase the recycling quota seems questionable from an energy related point of view.

7.3. System extension to total aluminium production

The use of incineration heat for power production must not be neglected. In order to calculate appropriate energy credits the balancing system has to be extended to primary aluminium production. The inclusion of the incineration plant results in the additional system's output of electrical energy. To avoid allocation by system extension an energy credit for power production from LPM incineration is given for the electrolysis applied for primary aluminium production.

In figure 7 the appropriate values per ton aluminium made from primary and secondary raw materials are represented, as they correspond to the resource-orientated recycling quota.

Considering the energy inputs by electricity and fuels the values decrease up to the highest quota. The same applies to the adapted values for autothermal pyrolysis.

Taking into account the energy content of the LPM-fraction, when assessing waste incineration, the energy demand again increases above 79% for both calculations (e, f). This minimum indicates that at this point there is an optimal recycling quota concerning energy consumption. The energy credit for electricity production from incineration lowers the energy demand of the total system from 74.2 to 67.1 GJ/t.

8. Conclusion

The recycling of the aluminium content of LPM in Germany is actually done at a resource orientated recycling quota of 59%. The presented calculations show that by increasing the recycling quota to the optimal one concerning energy demand, 27.6% of the energy, which is required now, could be saved. A further increase of the resource orientated recycling quota over 79% would not be reasonable concerning the overall energy demand including primary energy as well as the heat content of burnt materials. Although remelting of aluminium requires less energy than primary production also at high recycling quotas the results identify a turning point. Above that point methodological and social aspects (like consumer behaviour) influence the recycling practice and therefore the calculated results.

It must be emphasised, that the results can only be seen under the assumptions made. The development of the scenario concentrates on increasing the recycling quota. Here the new technology of fully automated sorting is a big step towards highly efficient metal recovery and reduced energy requirement. At the same time further fractions of usable materials are won. Reaching higher sorting selectivity of one of these materials might result in quality losses of the other ones. Also pyrolysis can be identified as an important part of a material efficient process chain. Beside the technical improvement new strategies to increase the overall recovery rate of secondary raw materials have to be considered. Here the collection quota shows potentials to increase recycling efficiency.

Other target values to determine an optimal recycling quota such as economical, social or ecological ones are not considered in this paper and will have to be subject of further research.

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Tables

	Al loss	electricity input	gas input	diesel input
LPM collection	11,0%			245 MJ/t Al
sorting	19,4%	37 kWh/ t Al		
mechanical processing	29,7%	234 kWh/t Al		125 MJ/t Al
decomposition	12,1%	152 kWh/t Al		244 MJ/t Al
pyrolysis 1	5,5%	343 kWh/t Al		
pyrolysis 2	5,5%	121 kWh/t Al		866 MJ/t Al
pyrolysis 3	5,5%	121 kWh/t Al		
rotary drum furnace 1	22,0%	93 kWh/t Al	9646 MJ/t Al	159 MJ/t Al
rotary drum furnace 2	5,8%	42 kWh/t Al	6426 MJ/t Al	95 MJ/t Al
rotary drum furnace 3	7,6%	44 kWh/t Al	5244 MJ/t Al	107 MJ/t Al
rotary drum furnace 4	6,9%	107 kWh/t Al	12304 MJ/t Al	154 MJ/t Al
twin chamber furnace	4,5%	59 kWh/t Al	3884 MJ/t Al	76 MJ/t Al
Sortec	6%	116 kWh/t Al		
multi chamber furnace	4,5%	59 kWh/t Al	4879 MJ/t Al	76 MJ/t Al
slag treatment	95,1%	5 kWh/t Al		
sink-float plant	1%	265 kWh/t Al		
slag product processing	20,8%	241 kWh/t Al		

Table 1: Al loss and energy inputs of the different process steps [5, 9]

electricity (national grid)	gas	diesel
32,7%	91,1%	92,2%

Table 2: overall efficiencies for energy supply in Germany [8]

Figures

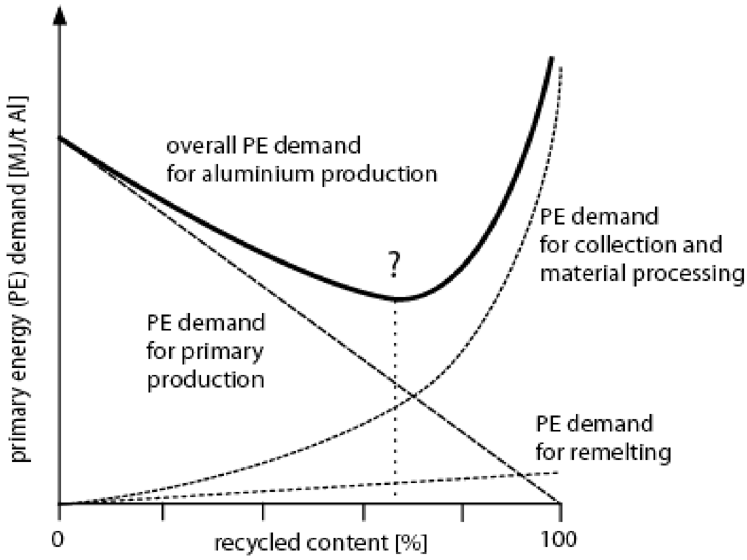

Figure 1: Qualitative representation of an optimised recycling quota concerning the primary energy demand

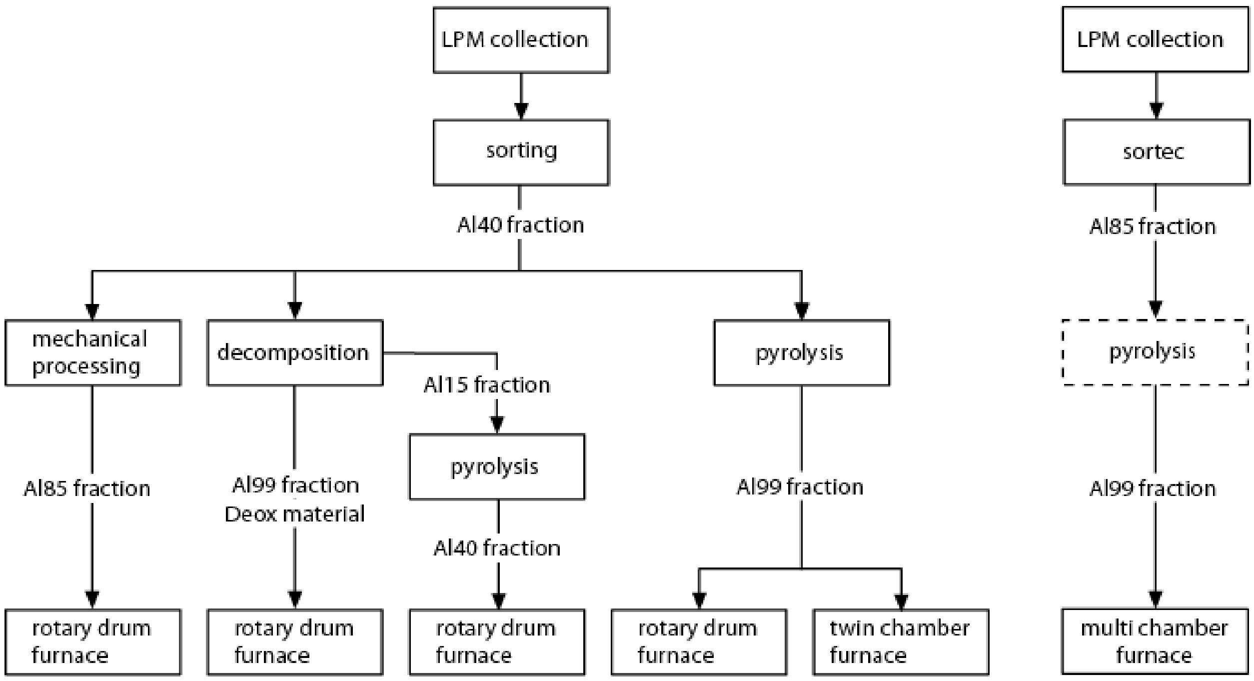

Figure 2: Process chain of the current and improved DSD recycling system for aluminium in LPM

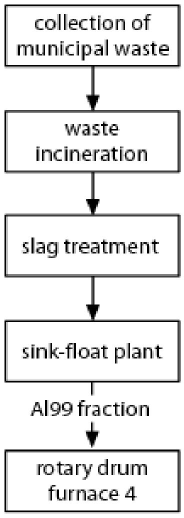

Figure 3: Process chain of aluminium recovery from incineration plants

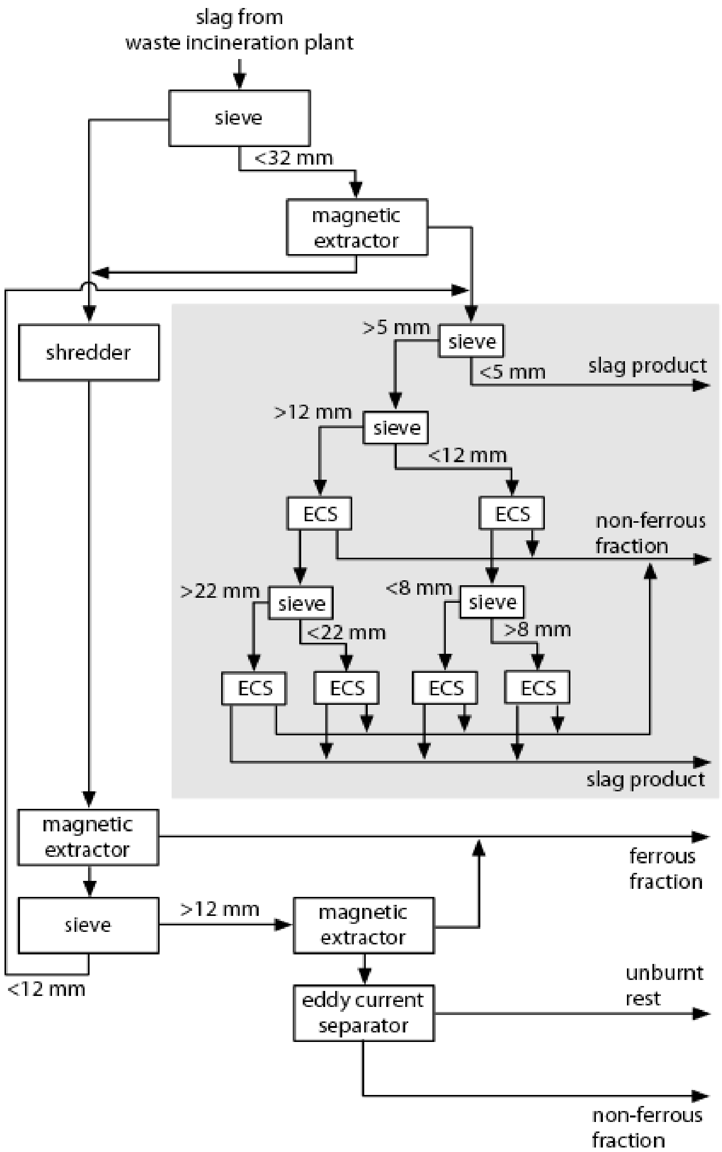

Figure 4: Process chain of slag processing with additional steps of metal recovery

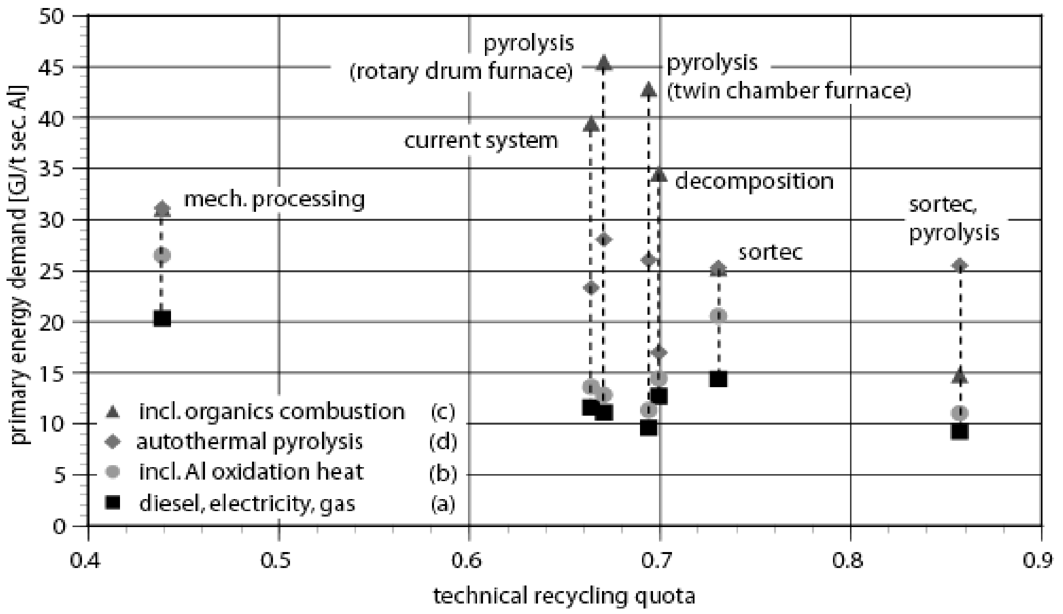

Figure 5: Technical recycling quota of different recycling paths and their primary energy demand depending on the applied method of energetic evaluation

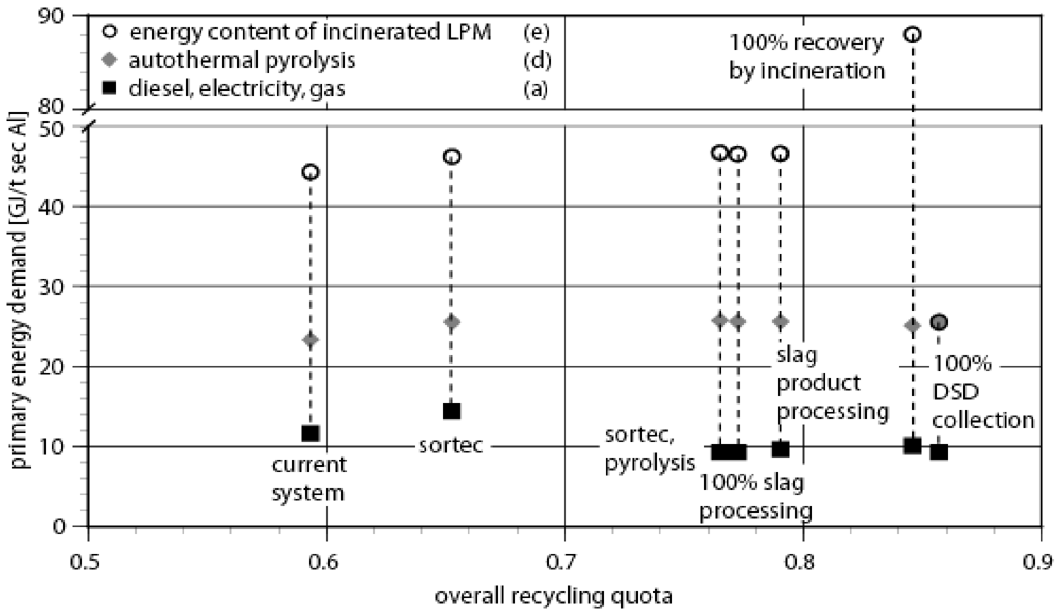

Figure 6: Overall recycling quota of the scenario recycling paths and their primary energy demand depending on the applied method of energetic evaluation

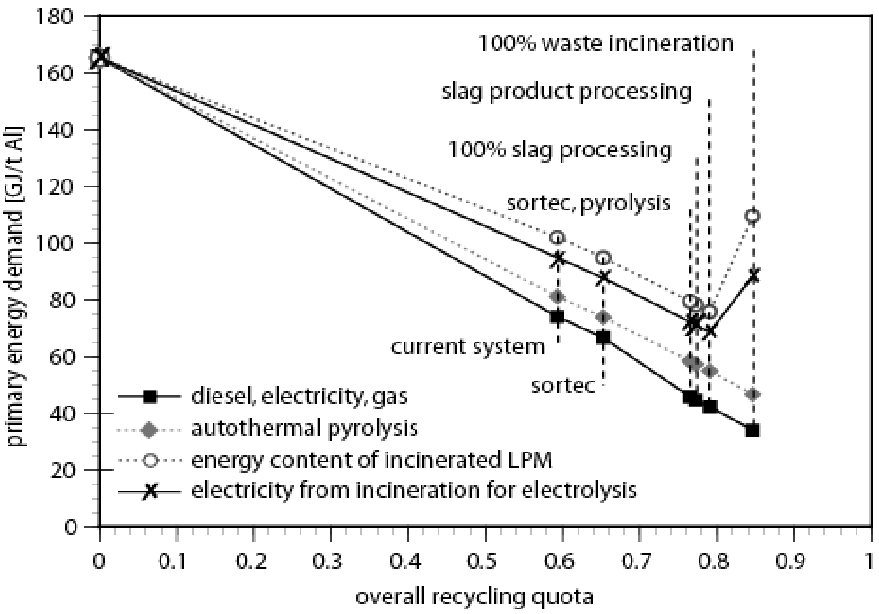

Figure 7: Primary energy demand of aluminium production depending on recycling quota and energetic evaluation

RECYCLING ACTIVITIES FOR ALUMINIUM PACKAGING IN GERMANY INCLUDING THE PREPARATION FOR THE RE-MELTING PROCESS*

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ABSTRACT

Aluminium is often regarded as a material which is very suitable for recycling i.e. due to large energy savings compared to primary production. When recycling of aluminium is discussed the focus point is mainly in the area of re-melting and refining. Nevertheless, the processing of scrap material prior to its reuse in secondary smelters becomes more and more important as aluminium and its alloys are typically used in combination with other materials.

Within this paper the most important recycling activities taking place in Germany in the field of aluminium packaging are presented.

First the different possible input materials are described under the aspect of raw material properties e.g. metal content, average piece size, impurities etc.

Then an overview of the different technical processes of recycling of aluminium is given with some examples. For measuring the success of such recycling activities there are some factors used like metal yield, energy and labor.

Finally the technical possibilities in preparing the input materials to get better results in the re-melting process are shown.

KEYWORDS

Recycling module, packaging, scenario, recycling quota,

* Source: Proceedings Light Metals 2001, New Orleans

Introduction

The studies to this article are made from the subproject 4 and give an overview of the work of the Collaborative Research Center 525 which was established in 1997 at the Aachen University of Technology and is funded by the Deutsche Forschungs-gemeinschaft (DFG). The long-term goal of the research program is the identification of options for resource-sensitive supplying and processing of metallic raw materials considering technical developments and economic and ecological aims.

In the year 1997[1] [1],[2] the total amount of sales packaging forwarded for recycling was about 1,95 million tons. The mixture of materials is heterogen and contains aluminium, different plastics, paper, tinplate and composites of all these components. This means 39.565 tons[2] of aluminium has been collected. 1.954.468 tons of light packaging with an average of 1,5 w.-t.% Aluminium, i.e. 28.580 tons of aluminium are recycled. The composition of this material is of a very different nature. Most important characteristic is the metal content. It indicates indirectly, how high the portion of impurities (organic/inorganic) is. Besides this, piece size, the format, the middle wall thickness, apart from the metallurgical composition, are important raw material characteristics as decision criteria for the choice of the recycling process as best preparation for the following remelting process. The metallurgical composition is with the production of aluminium from secondary materials of crucial importance, because alloys or alloy elements can be removed only to a very small extent on fusion metallurgical path.

[1] All numbers in this article are based on the year 1997

[2] This amount of aluminium is a mixture over all materials form the PMD containing aluminium. The aluminium content of "real" aluminium packages has to be more then 95%. Other packages with an aluminium content less then 95% are called aluminium composites

Different materials are used for foils and thin bands as it acts with the used alloys over very low alloyed Aluminium wrought alloys:

- foils, 12-15 µm, weak: Al (1000 series)
- thin band, 70-100 µm, weak: Al (1000 series)
  AlMn (3000 series)

To qualify in the recycling process, the metal yield, the primary energy and the qualities of the aluminium product as a calculation of the process and the scenarios are selected. After this the recycling modules under the focus of technical details are explained and the most important parameters are given. Later on the three scenarios as "Basic Scenario", "NT", and "2010" as a buildup of the different modules are visualized. Thereafter the parameters of the different scenarios are collated and the reasons for the arbitration to choose the scenario "2010" as it is are performed. The last step will be the analysis and discussion of the results and the prospects will be discussed.

Recycling Modules

The following paragraph gives a review of the recycling for the aluminium packaging recycling existing in Germany. The recycling of PMD Packaging is reduced to these modules which gives a good overview about the actual situation. The data to build and calculate the modules are recorded from meetings with people of the recycling business and the results of accounting the important plants within a period of three years of the scientist working in the subproject 4 of the Collaborative Research Center 525. The modules are used later to compose the scenarios describing the situation right now and the possibilities for the future. The output products are seen under the angle of aluminium recycling and the given numbers are orientated on this point of view.

The concrete values of the parameters which are shown later on are generated with the software Gabi 3 of PE Product Engineering GmbH, Germany.

The numbers such as yield or technical recycling quota (the product of the yield and the metal yield) [3] or metal yield received from the modules or scenarios are referring to the aluminium content in the material.

Light Packaging Sorting

After the collection by the dual system the light packaging is mixed with the other materials contained in the "yellow bags"[3]. The Lightweight Packaging Sorting (PMD) takes place in approximately 300 plants all over Germany. There the material mixture is sorted in the typical fractions plastics, tinplate, composites and aluminium packaging. The most important assigned sort technology is hand sorting. The tinplate by mean of magnetic separation and the aluminium fraction by mean of eddy current separator is won. Additionally different classification steps such as air classifiers are used to substitute the hand sorting. After the assortment, remains are discarded, either deposited or supplied to waste incineration.

The aluminium fraction consists of aluminium, aluminium composite and non aluminium packaging. The average aluminium content is too low with 42,3%, in order to be re-smelted directly, so that a large processing is necessary. Before the material is transported to the next processing plant it is injected into bundles with a baler, in order to receive a bulk density more favorable for transport. The process yield is 80,6% and the output material in the aluminium fraction is Al40[4] compact, foils and thin band. The energy consumption to process one ton of output material is 36,8 kWh/t.

Mechanical Processing

With the mechanical processing only the fraction of full aluminium packaging from the material mixture, which is delivered by the PMD, is segregated.

First the material is crushed in a single shaft shredder down to <50 mm in order to achieve the liberation necessary for the following sorting. Within the liberation air classification takes place to separate the light materials. Here it focuses primarily on plastic foils and scrap of paper which have to be dumped or supplied to waste incineration.

In the second sorting step, the material stream becomes now eddy current divorced whereby the eddy current separator is so adjusted that it sorts only thick-walled aluminium in the metallic fraction. Composite are not processed and dumped on domestic refuse dumps or burned in the waste incineration [4]. The output material in the aluminium fraction is Al85 small, coarsely, foils and thin band. Yield is 70,3% and energy consumption is 200 kWh/t.

Composite Processing

The composite processing is based on a mechanical process including a large liberation of composite containing aluminium, plastics and paper. First the aluminium fraction from the PMD is crushed in a single shaft shredder. Afterwards an aluminium free fraction is separated by an air classifier and will be deposited on domestic refuse dumps or burned in the waste incineration. The remaining material is given to the elementary module in this process, the turbo-rotor mill. The material is liberated on grinding bodies at the inside wall of the mill. One by high air speeds caused strong turbulence guarantees the large liberation.

After liberation the material is screened. The different size ranges are separated by air tables and the aluminium fraction is the heavy media fraction in this process. The light media con-

[3] Lightweight packaging manufactured from plastics, composites, tinplate and aluminium is generally collected in yellow bags from The Dual System in Germany

[4] Al40 means that 40 w.-t. % of the material is aluminium e.g. 400 kg aluminium of a 1000 kg sample

taining liberated composite has to be processed in the Pyrolysis. The output material in the aluminium fraction is Al99 fine, foils and thin bands. The yield is 92,4% and the energy consumption is 65,3 kWh/t.

Sortec 3.0

Sortec 3.0 represents a fully industrial sorting plant with a dry and wet mechanical processing of different mixed packaging materials as it is contained in the yellow bags. The dry mechanical sorting and the wet mechanical liberation are running in three steps and are combined with liberation and refinement of plastics. In the dry cleaning step after a bundle opening of the yellow bags and sieving with air classification the light plastic parts and the foils of paper are blown out. This so called "light fraction" is given directly to the central material detachment. With infrared technique and magnetic separation the fractions PET-mixture, beverage cartons[5] and tinplate are won. In the wet separation part of the plant the paper is recovered after dissolving. The aluminium is won by eddy current separator. The different plastic materials are separated with working media in a scroll (centrifuge). So the polyolefins (PO) is won as agglomeration and produced polyethylene (PE) as well as polystyrene (EPS) yield by extrusion. With this kind of assortment, a new form of the creation of value and secureness of salvage can be created [5], [6].

The output material in the aluminium fraction is Al85 fine and coarsely, foils and thin band. The yield is 94,0% and the energy consumption is 98,8 kWh/t [7].

Pyrolysis

In order to get material for the re-melting process from the aluminium composite after the PMD this material is given to the pyrolysis to get the containing aluminium. Therefore the material is crushed in a single shaft shredder and given to a kiln. In there the material is heated up to 500-580 C° in reduced atmosphere. The materials are decomposed in gas and coke. The gaseous decomposition are burned and this energy is used to operate the process autotherm.

After the pyrolysis itself the material is screened in a revolving screen < 5 mm whereby a majority of the coke is separated as fine material in the underflow. The coke fraction is used for the production of coke masses for example as electrodes. Because on the surface of aluminium coke still remains, the material is put into a glow chamber in which under regulated air supply the coke is burned. Subsequently remaining ash is separated from aluminium by screening. Ashes contain aluminium only in oxidized form and have to be dumped.

The resulting aluminium product exhibits a very thin wall thickness and is milled again in fine mills, screened and homogenized. It is used e.g. as powder for steel smelting or as pyrotechnically aluminium powder or aluminothermical alloys in steel.

The flue gas from the pyrolysis process is cleaned in a flue-gas scrubbing. For the quench fresh water is needed. The mud resulting in the flue gas purification is deposited on special refuse dumps.

In addition to the processing of the output of the PMD Sorting the Pyrolysis is used to process the composites of the Composite processing. After our calculation of the scenarios there has to be a pyrolysis of the output material of the Sortec 3.0 plant. The pyrolysis processes are similar and are distinguished mainly in the input material.

[5] These beverage cartons have a special geometrical form in Germany so they are called "Tetrapack". Because of this automatical detection was developed to sort them out because they are made of three materials (paper, plastic and aluminium) and have to be processed in a special way

The output material in the aluminium fraction is always Al99 fine and coarsely, foils and thin band. The yield is for all three pyrolysis the same with 94,5% but the energy consumption is different. For the Pyrolysis after the PMD Sorting and the Pyrolysis in future after the Sortec 3.0 the energy consumption is 120 kWh/t output. The Pyrolysis of Composite uses 340 kWh/t output material.

Scenarios

These scenarios are tools to give an overview of the existing technical standard and the possibilities in recycling for the future. The "Basic Scenario" stands for the actual technique in the processing of light aluminium packaging. The scenario "NT-Newest Technology" represents the latest technical standard i.e. state of the art in processing of packaging. On the assumption of the same basic conditions and conversions of the technical possible innovation the Scenario "2010" was used [8].

Basic scenario

The actual PMD Sorting in Germany follows the arrangement of the recycling modules as it is shown in picture A1[6] in the appendix.

All material is given to the PMD Sorting. After that 55 w.-t.% of the aluminium content (correlative is the amount of all packaging material; to simplify the weight the aluminium content is given) is going to be processed in the pyrolysis. 35 w.-t.% is given to the Composite processing. The composites resulting from this sorting are going to be handled in the Composite Pyrolysis. The output material of all these process steps is Al99. The last 10 w.-t.% of aluminium content from the PMD Sorting are upgraded to Al85 in the Mechanical Processing. The mineral processing is the preparation of the re-melting process. Actually the products after the pyrolysis are given to the twin chamber furnace or the rotary kiln furnace. There are different types of these furnaces existing in Germany with different input materials. The other aluminium products are given to the rotary kiln furnaces.

Table 1 shows the important parameters as described in the →Introduction.

Table 1: important parameters to show the efficiency of the Basic Scenario

parameter	value	unit
manpower	8,9	[h/t]*
yield	73,4	[%]
re-melting yield	91,4	[%]
technical recycling quota	67,1	[%]
primary energy processing	3.033	[MJ/t]*
primary energy re-melting	5.767	[MJ/t]*

* oriented at one ton of output as shown in picture A1 in the appendix

New Technology (NT)

The picture A2 in the appendix shows the technical state of the art in light packaging sorting in Germany.

This fully industrial plant is running in Hannover and has the name Sortec 3.0. The advantages of the plant is the sorting of all components, contained in the yellow bags, into products which can be reused. The different fractions are described under → Recycling Modules → Sortec 3.0. Compared to the other ideas of processing PMD packaging this plant is running fully automatically and does it very effec-

[6] The three flow sheets of this lecture are put into the appendix to provide the reader with another layout of the pages the possibility to get the content of the small icons and arrows

tive. After the aluminium was sorted by the plant it has to be put into a Pyrolysis.

Table 2: important parameters of the scenario NT

parameter	value	unit
manpower	5,9	[h/t]*
yield	88,8	[%]
re-melting yield	90,8	[%]
Technical recycling quota	80,6	[%]
primary energy processing	2.766	[MJ/t]*
primary energy re-melting	4.040	[MJ/t]*

* oriented at one ton of output as shown in picture A2 in the appendix

After the Pyrolysis the material is taken to the twin chamber furnace and the Scenario NT is calculated with the parameters of this furnace. The existing systems of this type can be upgraded. Compared to the very good tilt type rotary furnace the yield is only about 0,4% points worse but the energy consumption for this specific material is lower. This system is for aluminium output with the same quality like it is lower on energy consumption and the metal yield is better than the other furnaces as e.g. used for the Basic Scenario.

At this point in the scenario it is ideal to calculate with one furnace. The actual situation because of the change from the actual processing to the Scenario NT will be carried out in many steps such as scenario 2010. No smelting plant will have furnaces specifically for this small mono batch. They will give this material mixed with other aluminium containing material in existing systems so that this argument is another advantage for the use of the twin chamber furnace.

Scenario 2010

The material flow of aluminium in the Scenario 2010 follows the flow sheet in picture A3.

Compared to the Basic Scenario some important changes take place. This part of the mechanical processing no longer exists any more. This technology is compared to the other modules in the first preparation step[7] not efficient enough in important parameters like it is pictured in table 3.

Table 3: comparison of recycling modules

modules	primary energy [MJ/t]*	yield [%]*	man-power [h/t]*
PMD Sorting	420	80,6	2,2
Fully industrial plant	1.128	94,0	1,7
Mechanical processing	2.284	70,3	1,8

* oriented at one ton of process output

The PMD Sorting seems quite effective with the energy consumption of only 420 MJ/t. But the output Al40 has to be processed with the combination of Composite Processing and Pyrolysis Composite. After this the energy balance is worse than the combination of Sortec 3.0 and Pyrolysis Sortec 3.0. This and the yield are the most important reasons to expect that in future for recycling of light packaging much more recycling systems such as the Sortec 3.0 will be used. The idea to give 10 w.-t.% of the aluminium content in the Sortec 3.0 comes with the capacity of the plant. Within its actual size and design it can process 25.000 tons of light packaging material per year. With a progressive

[7] There are two preparation steps in each scenario pictured in one line in the flow sheet. In the Scenario 2010 the first step is e.g. “PMD Sorting” and “fully industrial plant”

and optimistically point of view there will be up to eight plants during a ten year period standing for processing this 10 w.-t.% of aluminium. The details resuming of modeling the Scenario 2010 are shown in table 4.

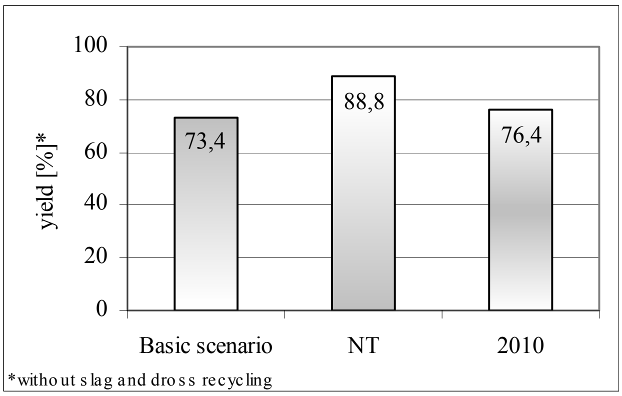
Table 4: parameters to show the results of the Scenario 2010

parameter	value	unit
manpower	9,7	[h/t]*
yield	76,4	[%]
re-melting yield	91,2	[%]
technical recycling quota	69,7	[%]
primary energy processing	3.025	[MJ/t]*
primary energy re-melting	4.406	[MJ/t]*

* oriented at one ton of output as shown in picture A3

Results

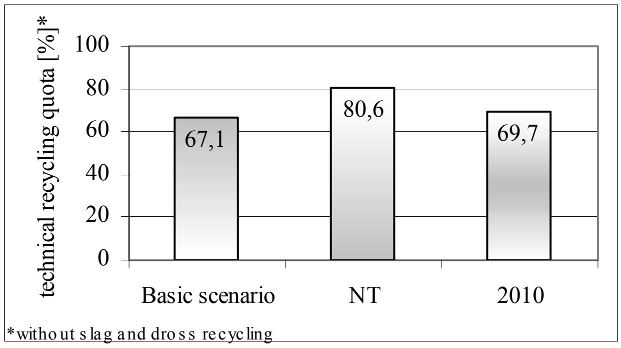
In the following the numbers resulting from the scenarios concerning manpower, yield, technical recycling quota and energy consumption are given in the pictures 1-4.



Picture 1: Yield of the scenarios for processing

With 88,8% the yield of the scenario NT shows the high efficiency of this combination of the modules Sortec 3.0 and Pyrolysis Sortec 3.0. The yield of Basic Scenario and the Scenario 2010 are quite close. The better yield of the Scenario 2010 comes with the regeneration of easy and not effective processes like the Mechanical Processing as one advantage.

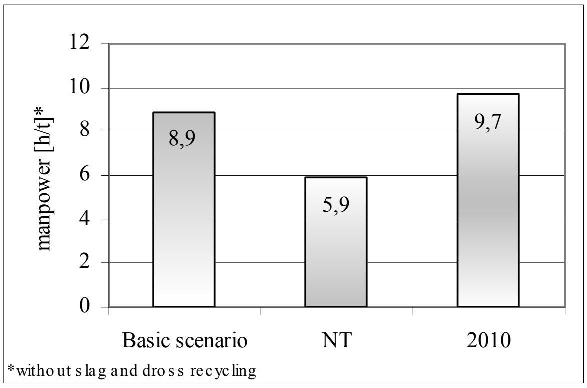
In picture 2 the technical recycling quota as a product of yield and metal content is pictured. The different metal yields for the scenarios are similarly and therefore the proportion is like it is in picture 1. Beside this another important quota is the collection quota which indicates the ratio between collected secondary raw aluminium and aluminium which came to the phase of use. The product of the technical recycling quota and the collection quota finally is the so called resource orientated recycling quota. The collection quota in the year 1997 for aluminium in light packaging in Germany was 89,0%.



Picture 2: Technical recycling quota of the scenarios

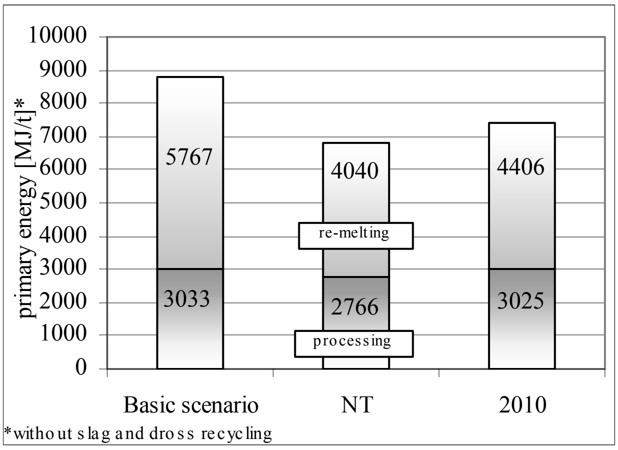
In picture 3 manpower is given as a unit of hours per ton of output. Regarding this number as a real important value as it is e.g. in Germany the operating costs are remarkable quantified by the manpower per ton. In other countries e.g. China other numbers are much more important. In the Scenario 2010 the value is higher than in the Basic Scenario. This fact is based on the allocation of the material to the two different processing steps. The path of Composite Processing and combination with

Pyrolysis Composite is very labour-intensive and has to be reduced in the next years to get more efficiency.



Picture 3: Manpower of the different scenarios

A Comparison of the energy consumption of the three scenarios is done in picture 4. This parameter is still one of the most important signs to evaluate a process or a combination of processes with the same output product. By calculating the number of scenarios the recycling of slag and dross wasn't considered. The Basic scenario needs the most energy to produce the same product like the scenario NT or Scenario 2010.



Picture 4: Comparison of the different energy consumption of the scenarios differing in energy used for processing and re-melting visualized in a batch diagram

The scenario NT has the best yield and technical recycling quota and demands the lowest energy wastage of the three scenarios. This result together with the possibility to get products as single material fractions which can be reused or brought back to the production side from a mixture of different packaging materials as it is containing in the yellow bags is an evidence that the recycling of PMD material is on the right way. Another advantage of the Scenario NT is the fully automatically plant in the processing step of sorting the material.

It will need years or maybe decades for the Scenario NT as the state of the art technology in light packaging recycling to become reality. Under this point of view the Scenario 2010 is quite realistic as one step of this process under the assumption of same basic conditions and conversions. The yield and the recycling quota of the Scenario 2010 are not that much better than they are in the actual situation. The manpower is worse than it is today. But the consumption of energy is with 7.431[8] [MJ/T] compared to 8.800 [MJ/t] a lot more effective. The energy of only 6.806 [MJ/t] to produce one ton of aluminium with the same quality shows that the development is on the right way.

Perspectives

After the interpretation of the numerical values of the different tools for measuring the efficiency of the scenarios a lot of questions concerning the methodical approach appear:

- Which criteria should be consulted for the best determination of the process chain, the scenario "NT"?
- How is the best evaluation of a single criteria to get a meaningful rating of the whole process?
- How will the changing of use and different situations of material and energy prizes take influence of the scenario calculation?

[8] All this numbers in relation to the pictures 1-4

The criteria which had been chosen for this analysis are each for itself very important and expressive. It does depend on different perspective of companies or organizations which have the power to decide if a new technology is the best for their actual situation or not. In some areas or countries the manpower is with high costs a very important criteria. In other countries it doesn't matter yet, there energy is the most important carrier of costs. In Germany for example the object of optimization to reduce the costs is the fact of a very good and effective combination of the criterias manpower, energy consumption and yield. At the end the costs are the tractive force for companies in within the scope of laws to invest in some new technologies. For us as the subproject 4 of the Collaborative Research Center 525 of the University of Technology in Aachen the results of the presented calculation are a task to develop new methodology to determinate the best scenario as part or totally and new methodology to evaluate and classify the secondary raw material.

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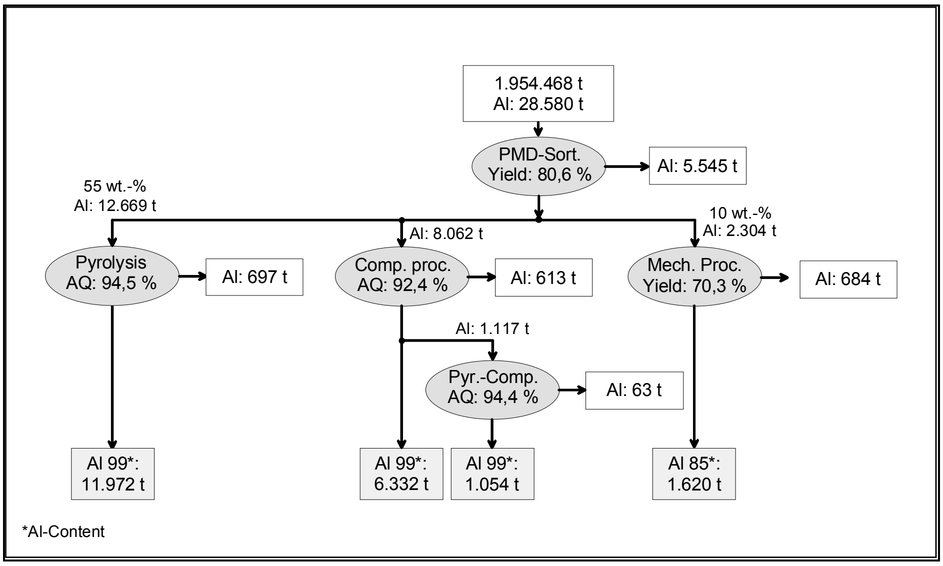
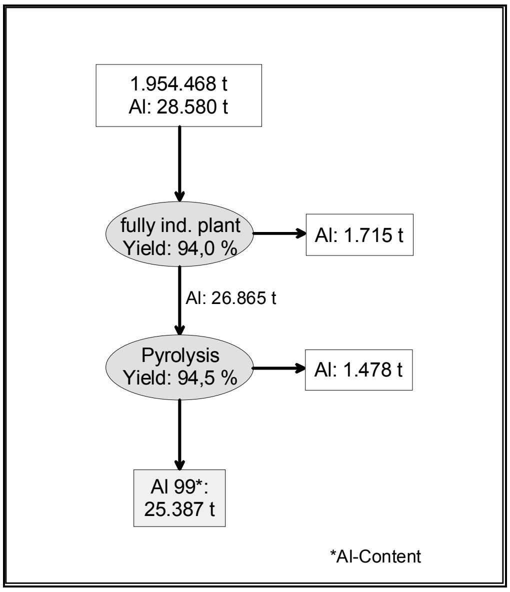
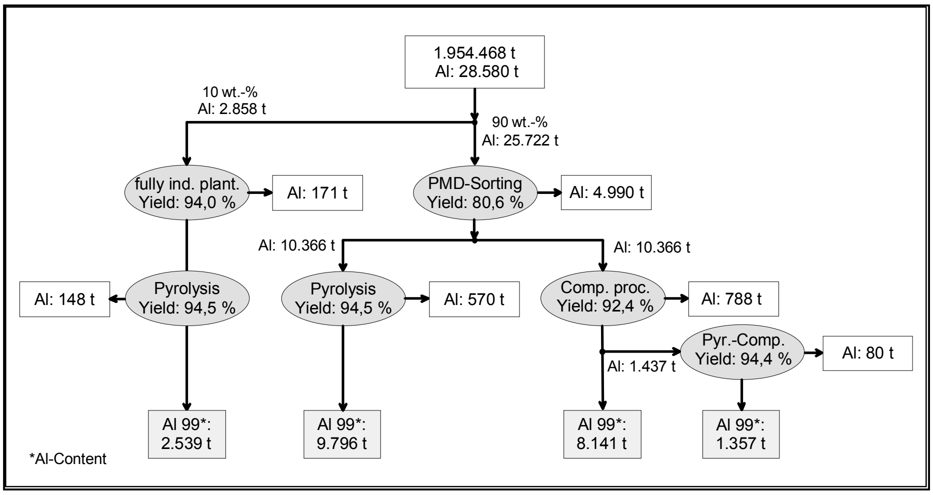
Appendix



Picture A1: Basic scenario as a picture of the actual PMD Sorting in Germany



Picture A2: Scenario New Technology representing the state of art in PMD Sorting



Picture A3: Scenario 2010 in PMD Sorting on the assumption of same basic conditions and conversions

VERHALTEN MINERALISCHER PIGMENTE BEIM ALUMINIUMRECYCLING *

(BEHAVIOUR OF MINERAL PIGMENTS DURING ALUMINIUM RECYCLING)

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ABSTRACT

With increasing quality demands for secondary aluminium materials production processes for recycling of pure sorted wrought alloy scrap are increasingly gaining importance. Especially for these alloys with their low tolerances in chemical composition metal quality is determined by type and amount of impurities. Due to increasing recycling rates and repeated participation in recycling loops even small amounts of inorganic impurities from lacquering pigments can reduce the ability of recycling when accumulated in the liquid metal during remelting. In this work metallurgical effects and conditions of pigment metal enrichment during recycling are investigated. Special interest is taken in effects type and amount of pigment, temperature and fluxing salt addition will have on accumulation in aluminium. The study shows that the interactions between the working conditions during remelting determine the accumulation reactions rather than the chemical reaction potential

KEYWORDS

Aluminium, closed-loop recycling, pigment metals, accumulation in recycling loops

* Source: Erzmetall 53 (2000), Nr. 2, pp 98-105

Im Zuge steigender Qualitätsansprüche an die Sekundäraluminiumproduktion gewinnen die Verfahren zum sortenreinen Recycling von Knetlegierungsschrotten an Bedeutung. Die Metallqualität wird aufgrund niedriger Toleranzen durch Art und Menge der Verunreinigungen bestimmt. Bei steigenden Recyclingmengen und mehrmaligem Durchlaufen der Recyclingzyklen können auch geringe Mengen metallischer Verunreinigungen, die aus den Lackpigmenten stammen, die Recyclierbarkeit des Aluminiums einschränken, sofern sie sich im Aluminium anreichern. In dieser Arbeit werden die Auswirkungen und die physikalisch-chemischen Ursachen für einen Eintrag der Pigmentmetalle während des Recyclings untersucht. In Versuchen wurden die Einflußgrößen Pigmentart und -menge, Temperatur und Salzzusatz auf die Anreicherung im Aluminium ermittelt. Es zeigt sich, daß weniger die chemischen Potentialdifferenzen als vielmehr die Arbeitsbedingungen während des Umschmelzens für eine Anreicherung verantwortlich sind.

1 Einleitung

Aluminium ist eines der wichtigsten Gebrauchsmetalle. Neben den werkstofftechnischen Vorteilen wie geringe Dichte, hohe Festigkeit und hohe Leitfähigkeit liegt ein weiterer in der Recyclingfähigkeit und der damit verbundenen Energieeinsparung gegenüber der Primäraluminiumerzeugung. Die Energieeinsparung führt dazu, daß auch minderwertige, verunreinigte und beschichtete Schrotte selbst bei geringen Metallgehalten wirtschaftlich umgeschmolzen werden können.

Werden verunreinigte Aluminiumschrotte bzw. Mischschrotte umgeschmolzen, können die geforderten Toleranzen der Ziellegierung nur mit einer aufwendigen Gattierungsrechnung durch Verschneiden verschiedener Schrottpartien erreicht werden, da für Aluminium nur begrenzte Raffinationsmöglichkeiten bestehen. Um einer aufwendigen Aufbereitung vermischter Schrotte zu entgehen, den Einsatz von Hüttenaluminium zur Verdünnung zu begrenzen und Qualitätsverluste zu vermeiden, sollten die Schrotte bereits möglichst sortenrein erfaßt und einem Schmelzprozeß zugeführt werden.

Auch beim sortenreinen Recycling können sich bei gleichem Wiedereinsatz, besonders bei wiederholtem kurzen Recyclingzyklen, Verunreinigungen im Metall anreichern. In dieser Arbeit wird der Eintrag von Verunreinigungen mineralischer Pigmente aus lackierten Schrotten untersucht, der einen äquivalenten Wiedereinsatz begrenzen kann. Hierzu wird die während des Umschmelzens auftretende elementspezifische Anreicherung der Pigmente im Aluminium bestimmt. Die Einflüsse von Pigmentart, Schmelztechnik und Salzzusatz werden diskutiert.

2 Werkstoffbeeinflussung durch Legierungs- und Begleitelemente

Aluminium findet überwiegend in legierter Form Anwendung. Knetlegierungen haben insgesamt einen relativ geringen Legierungselementanteil (Tabelle 1) [1].

Die verschiedenen metallischen Zusätze oder Verunreinigungen beeinflussen die Aluminium-Knetlegierungen in vielfältiger Weise. Bereits Spuren dieser Metalle haben Einfluß auf Gefüge, Festigkeit, Zähigkeit, Warm- und Kaltverformung etc.. In den anorganischen Pigmenten liegen Metalle als Oxide, Hydroxide, Hydrate, Salze, Mischkristalle, deren Gemischen oder elementar vor (Tabelle 2) [2]. In dieser Arbeit wird das Verhalten von Titan, Chrom, Blei, Antimon, Eisen, Kobalt und Zink untersucht, wenn sie in Form von Pigmenten einer AlMn1Mg0,5-Schmelze (AA3005) zugesetzt werden. Die oberen Grenzgehalte dieser Elemente sowie deren Auswirkungen sind in Tabelle 3 zusammengefaßt [1, 3].

Durch die niedrigen Grenzgehalte z.B. in Dosen- und Fassadenblechlegierungen kann bei einer Anreicherung dieser Elemente aus Beschichtungen und Anhaftungen ein äquivalenter Wiedereinsatz auch nach sortenreinem Recycling eingeschränkt sein. Bei hohem Recyclinganteil können sich auch geringe Anreicherungen pro Recyclingzyklus bemerkbar machen, da sich diese durch fehlende Raffination addieren. Dies ist besonders beim Recycling von Produkten mit kurzer Lebensdauer von Bedeutung.

3 Bedingungen der Pigmentanreicherung

3.1 Lösungsverhalten der Begleitelemente des Aluminiums

Der Einfluß von Verunreinigungen auf die Phasenbildung und ihr Lösungsverhalten lassen sich aus binären Phasendiagrammen nur schwer erkennen. Sie zeigen aber die möglichen Reaktionen zur Mischphasenbildung bzw. Entmischung.

Bei eutektischer Zusammensetzung einer Legierung erstarrt die gesamte Schmelze ohne Schmelzintervall bei der eutektischen Temperatur. Die Legierungskomponenten sind dann wegen ihrer Unlöslichkeit im festen Zustand entmischt und meist sehr fein verteilt. Bei Vorliegen einer Mischungslücke findet bereits im flüssigen Zustand eine Entmischung statt.

Insgesamt spielt der Aktivitätskoeffizient der Legierungskomponenten eine Rolle. Ist er klein, ist mit der Bildung von Mischphasen und intermetallischen Phasen zu rechnen.

Kinetische Aspekte bleiben in Gleichgewichtsdiagrammen unberücksichtigt. Bei schneller Abkühlung verschiebt sich die Phasengrenze aufgrund unvollständigen Diffusionsausgleichs. Es entstehen Seigerungen, wobei sich die auszuscheidende Komponente mit fortschreitender Erstarrung in der Restschmelze anreichert. Insbesondere die Legierungen des Aluminiums mit Mn, Ti, Cr, Sb, Co und Fe mit ihren nur geringen Randlöslichkeiten lassen nahezu immer die Ausscheidung von intermetallischen Verbindungen erwarten.

Ausgehend davon, daß eine Schmelze in der Praxis nicht unter Gleichgewichtsbedingungen erstarrt, kann eine stärkere Anreicherung der Begleitmetalle im Aluminium entstehen, als es der Löslichkeit am Schmelzpunkt entspricht. Für eine Anreicherung ist ausschlaggebend, ob eine ausgeprägte Randlöslichkeit (Zn), die Neigung zur Verbindungsbildung (Ti) oder die Tendenz zur vollständigen Entmischung (Pb) vorliegt.

Neben den betrachteten Löslichkeiten der Legierungs- und Begleitelemente im flüssigen und festen Aluminium ist nun noch die Reduktion von Pigmentmetalloxiden durch Aluminium zu beachten.

3.2 Thermodynamische Bedingungen zur Pigmentanreicherung

Eine Anreicherung von Pigmentmetallen im Aluminium ist nur möglich, wenn die chemische Potentialdifferenz der Reduktionsreaktion positiv ist. Neben den Sauerstoffpotentialen der Elemente sind auch die Chlorpotentiale zu beachten, da beim Einschmelzen unter Abdecksalz flüssiges NaCl und KCl mit Aluminium in Kontakt tritt. Bei Zugabe von NaF oder CaF_2 als Flußmittel haben auch die Fluorpotentiale Einfluß auf die ablaufenden Reaktionen. Die Werte für die freie Bildungsenthalpie $\Delta G°$ ausgewählter Oxide, Chloride und Fluoride in bezug auf 1 mol O_2, Cl_2 bzw. F_2 bei einer Temperatur von 800°C zeigt Abbildung 1 [4].

Es ist ersichtlich, daß die Oxide von Cu bis Ti alle bei 800°C und 1 bar Gasdruck von Aluminium reduziert werden. Die freie Bildungsenthalpie $\Delta G°$ ist für diese Verbindungen negativ, die Differenz zu Aluminium positiv. Für die untersuchten Elemente ist eine nahezu vollständige Reduktion dieser Oxide aufgrund des Aluminiumüberschusses in der Schmelze zu erwarten. Ein etwas anderes Bild ergibt sich für die Chloride. Von den betrachteten Verbindungen können die Chloride von Cu bis Si durch Al reduziert werden. Bei den Fluorpotentialen sind die Werte für Ca, Li, Mg, Na und K niedriger als für Aluminium. Die anderen Metallfluoride lassen sich durch Aluminium vollständig reduzieren.

Diese Überlegungen gelten für 800°C und 1 bar Gasdruck sowie reine Stoffe, für die die Aktivität gleich eins ist. Für reale Schmelzen müssen die Aktivitäten bzw. die Aktivitätskoeffizienten γ_i für verdünnte Lösungen berücksichtigt werden. Bei geringer Konzentration und Gültigkeit des Henry`schen Gesetzes lassen sich die Aktivitätsverhältnisse als Geradenfunktion darstellen (Abbildung 2) [5]. Die Aktivität des Bleis ist wegen nahezu vollständiger Unlöslichkeit fast mit der Ordinate identisch. Im Unterschied dazu liegt die Aktivitätskurve für Eisen aufgrund der bevorzugten Verbindungsbildung nahe der Abszisse. Weitere Elemente mit hoher Neigung zur Verbindungsbildung sind Ti, Mn, Cr und Cu. Für Sb, Si, Mg und Zn sind die Abweichungen von der idealen Mischung geringer. Deshalb ist damit zu rechnen, daß mineralische Pigmente durch Aluminium reduziert und von ihm gelöst werden.

3.3 Wechselwirkungen zwischen Aluminium und Salzschlacke

Die Oberfläche des lackierten Schrottes ist stets mit einer Al_2O_3-Schicht belegt, die das Zusammenfließen der Aluminiumpartikel beim Einschmelzen behindert. Die Auf- oder Ablösung der Oxidhaut ist daher zur Erreichung hoher Metallausbeuten entscheidend.

Verunreinigungen im Aluminium haben einen großen Einfluß auf die Oberflächenspannung. Pb, Sb und Bi verringern diese schon bei geringen Zusätzen [3]. Ebenso verändern Verunreinigungen der Salzschmelze deren Oberflächenspannung. Ein Zusatz von Fluoriden zur Salzschmelze bewirkt eine Verringerung der Grenzflächenspannung zwischen Aluminium und Salzschmelze. Die Wirkung ist schon bei geringen Mengen sehr groß [6]. Die verminderten Grenzflächenspannungen erhöhen die Reaktionsfähigkeit des Metalls und der Salzschmelze.

Die Oxidschicht verhindert zwar eine weitere Oxidation des flüssigen Aluminiums, behindert aber auch dessen Zusammenfließen und die Trennung von der Oxidphase. Das Schmelzsalz soll die Al_2O_3-Schicht ablösen, diese sowie weitere Verunreinigungen aufnehmen und die Schmelze gleichzeitig weiter vor Oxidation schützen. Die Oxidation des flüssigen Aluminiums selbst ist temperaturabhängig. Oberhalb von ca. 770°C nimmt die Oxidationsgeschwindigkeit deutlich zu, da die Oxidschicht dann instabil und weiterer Stoffaustausch ermöglicht wird [7]. Eine Überhitzung des Aluminiums ist demnach zu vermeiden.

Herdschmelzöfen der Aluminiumindustrie arbeiten mit hoher Energiezufuhr. Eine örtliche Überhitzung wird durch Umpumpen des Metalls vermieden. Dabei werden Oxidhäute aufgerissen und das Metall kann leichter zusammenfließen. Die Metallausbeute wird dabei erhöht. Wird unter Salz umgeschmolzen, werden höhere Temperaturen von etwa 900°C eingestellt, um in den Bereich instabiler Oxidschichten zu gelangen. Bei dieser Temperatur ist auch der niedrigste Metallgehalt in der Krätze festgestellt worden [8].

Ein weiterer Aspekt zur Aluminiumoxidation ist das Verhalten der Legierungsmetalloxide. Hier ist für die Knetlegierungen insbesondere Magnesium relevant, welches zur Bildung von $MgO \cdot Al_2O_3$-Spinellen führt. Dadurch steigen Viskosität und Dichte der Salzschmelze an, was sich in abnehmender Metallausbeute durch vermindertes Absetzen der Metalltropfen äußert [8, 9]. Auf die Oxidhaut hat Mg ebenfalls großen Einfluß, da es die Bildung einer schützenden Schicht auf der Schmelzeoberfläche verhindert. Zusammen mit Si bzw. Zn setzt Mg die Oberflächenspannung und die Viskosität des Aluminiums herab, das dann in gebildeten Mikrokapillaren der Oxidschicht an die Oberfläche gelangt und dort oxidiert [10]. Diese Mechanismen sind sicher ebenso für die Reduktion der Pigmentmetalloxide durch flüssiges Aluminium verantwortlich.

Bei Anwesenheit von Schmelzsalz ist insbesondere bei Fluoridzusatz eine echte Aluminiumoxid-Löslichkeit in der Salzschmelze zu berücksichtigen. Bei der Fluoridzugabe zu chloridischen Salzschmelzen ist deshalb neben der Viskositätserniedrigung und dem damit verbundenen besseren Absetzverhalten der Metalltröpfchen die Steigerung der Salzlöslichkeit für Al_2O_3 wichtig. CaF_2 besitzt die größte Löslichkeit für Al_2O_3 von max. 25% bei 1300°C. Die besten Ergebnisse bei der Oxidhautablösung insbesondere für UBC-Schrott liefert jedoch Kryolith [11].

Eine Reaktion des flüssigen Aluminiums mit den Chloriden und Fluoriden des Schmelzsalzes nach $Al + 3(Na, K)(Cl, F) = Al(Cl, F)_3 + 3(Na, K)_{Al}$ findet nur in geringem Umfang statt, da die Gleichgewichtskonstanten für die Aluminiumchlorid- und -fluoridbildung aus NaCl und KCl sehr klein sind. Bei Magnesium ist jedoch eine entsprechende Reaktion zu erwarten [12] (siehe auch Abbildung 1).

Auf die Löslichkeit von Metallverbindungen in geschmolzenen Salzen hat die Zusammensetzung der Salzphase großen Einfluß. Die größte Löslichkeit zeigen die eigenen Salze z.B. durch erleichterte Bildung von Subverbindungen. Durch Zusatz von Salzen mit Kationen elektronegativerer Metalle verringert sich die Löslichkeit. Die geringste Löslichkeit besteht bei einem äquimolaren NaCl/KCl-Gemisch durch den geringen Dissoziationsgrad der Schmelze.

4 Versuchsdurchführung

Ausgangsmaterialien waren Aluminiumblech der Legierung AlMg0,5Mn1 (AA3005), handelsübliches Schmelzsalz, Lacke auf Polyethylen (PE) - und Polyvinylidenfluoridbasis

(PVDF) sowie Metalloxidpulver der entsprechenden Pigmente. Das verwendete Blech war außenseitig weiß lackiert und rückseitig mit einer Klarlackschicht versehen. Der Lackanteil beträgt 2.6%, das bedeutet einen Titaneintrag von 0,3% der eingesetzten Blechmenge. Neben den im weißen Lack vorhandenen, wurden der Schmelze weitere Pigmente entweder als zusätzliche Lackschicht oder synthetisch in Form von Oxidpulvern zugeführt.

Zum Umschmelzen der Blechproben wurden ein gasbeheizter Tiegelöfen und ein Vakuuminduktionsofen genutzt. Es wurden jeweils 400g Metall, dazu 0-160g Schmelzsalz in Graphittiegeln kalt eingesetzt und geschmolzen. Dabei wurden Art und Menge der Pigmente, Schmelzsalzmenge, Temperatur und Haltezeit variiert. Der Salzzusatz wurde entweder entsprechend den Arbeitsbedingungen im Salzbaddrehtrommelofen auf 20-40% des Metalleinsatzes eingestellt oder wie bei Mehrkammeröfen auf bis zu 2,5% reduziert bzw. vollständig weggelassen. Die Versuchsparameter zeigt Tabelle 4. Nach Beendigung der Versuche wurden die Metallphasen, die Schlacken bzw. Krätzen analysiert.

5 Versuchsergebnisse

5.1 Ermittlung von Anreicherungsfaktoren

Die Darstellung der Metall- und Schlackenanalysen in Abbildung 3 und 4 erfolgt als Funktion des Pigmentmetalleintrages in Prozent der eingesetzten Blechmenge. Stellvertretend sind hier nur die Ergebnisse für Titan und Blei dargestellt.

Die Titangehalte im Aluminium steigen zwar durch erhöhte Elementzugabe an, der Haupttitananteil reichert sich aber in der Schlacke bis zu 20% an. Im Unterschied zu Ti steigen die Pb-Gehalte im Aluminium auf 0,1-0,5%, bei hohen Zugaben bis 2%, und liegen damit deutlich über den oberen Grenzgehalten von 0,01 bzw. 0,05% (siehe Tabelle 3). Die aus den aufgetragenen Meßwerten berechnete Steigung der Ausgleichsgeraden wird als Anreicherungsfaktor des jeweiligen untersuchten Pigmentmetalls bezeichnet, der den Zuwachs im Aluminium in Abhängigkeit vom spezifischen Eintrag darstellt. Dieser variiert von 0,09 für Titan bis 65,3 für Antimon. Die Ergebnisse zeigt Tabelle 5. Die Faktoren ermöglichen einen direkten Vergleich der Anreicherung der einzelnen Pigmente in den verschiedenen Versuchsserien.

5.2 Einflußgrößen auf die Pigmentanreicherung

Die Auftragung der Anreicherungsfaktoren über den Aktivitätskoeffizienten der betrachteten Elemente in flüssigem Aluminium bei 927°C zeigt Abbildung 5. Hier entspricht das Ergebnis der Elemente Sb, Zn und Pb der Tendenz sinkender Anreicherung bei steigender Aktivität des

Pigmentmetalls im flüssigen Aluminium. Wichtig sind hier die Bedingungen beim Eintrag der Pigmente und die Wechselwirkungen mit der Schlacke.

In Abbildung 6 sind die Anreicherungsfaktoren als Funktion der Schmelztemperatur der Pigmentmetalle dargestellt. Nur Pb, Zn und Sb, die nach der Reduktion bei 800°C flüssig vorliegen, werden nennenswert im Aluminium angereichert. Sind die Reaktionsprodukte fest, oder bilden unlösliche Verbindungen, ist kaum eine Aufnahme im Aluminium feststellbar. Auch der teilweise hohe Dichteunterschied zwischen dem flüssigen NaCl/KCl-Salzgemisch und den Pigmentmetallen zeigt keinen Einfluß. Indirekten Einfluß hat die Aluminiumverschlackung, denn Aluminiumoxid setzt durch Spinellbildung die Aktivität des Pigments herab.

Auf die Anreicherung der Pigmentmetalle hat das Salz durch seine Löslichkeit für diese Elemente direkten Einfluß. Beispielsweise ist bei hohen Salzmengen die Aufnahmefähigkeit des Salzes für Bleiverbindungen hoch und die Bleikonzentration im Aluminium dadurch niedrig. Bei Verringerung der Salzmenge steigt die Bleikonzentration im Salz entsprechend an und Pb reichert sich vermehrt im Aluminium an. Bei weiterer Senkung der Salzmenge nimmt der Bleigehalt in der dann gebildeten Krätze zwar zu, fehlende Flüssigphasen und feste Oxidhäute führen aber dennoch zu einer verringerten Bleianreicherung im Aluminium.

5.3 Abgeleitete Reaktionsschritte bei der Anreicherung

Die Komplexität der Wechselwirkungen zwischen Metall- und Salzschmelze, führt zu einem sehr unterschiedlichen Verhalten der betrachteten Pigmentmetalle beim Umschmelzen der lackierten Schrotte. Trotzdem ist es möglich, allgemeine Reaktionsschritte der Anreicherung der Pigmentmetalle zu unterscheiden:

- Benetzung oder Lösung des Pigmentes durch Salzschlacke oder flüssiges Aluminium,
- ggf. Ablösung der gebildeten Aluminiumoxidschicht vom flüssigen Aluminium,
- vollständige bzw. stufenweise Reduktionsreaktion zwischen den bei hohen Temperaturen oxidischen Pigmentverbindungen und dem flüssigen Aluminium,
- teilweise Bildung intermetallischer Verbindungen wie Al_3Fe, Al_3Ti, Al_7Cr oder Al_9Co_2,
- Lösen oder Dispergieren der Metalltropfen / intermetallischen Verbindungen im flüssigen Aluminium.

Der in den Versuchen ermittelte Einfluß auf diese Reaktionsschritte wird im folgenden für die Pigmentmetalle Titan, Chrom und Blei zusammengefaßt:

Für Titanpigmente wurde eine geringe Benetzung durch Aluminium augenscheinlich festgestellt. Titandioxid hat von den betrachteten Metallen die geringste Reduktionspotentialdifferenz zu Aluminium. Titan weist vier Oxidationsstufen auf, so daß die Reduktion schrittweise abläuft. Die Suboxide weisen noch geringere Potentialdifferenzen zu Aluminium auf. Die sich um das Pigmentpartikel bildende Aluminiumoxidschicht verlangsamt offensichtlich den Reaktionsverlauf. Das erklärt die insgesamt sehr geringe Anreicherung des Titans.

Bei Chrom ist die Potentialdifferenz zwar größer als bei Titan, die Reaktionsprodukte liegen aber auch in fester Form vor. Die gebildete Aluminiumoxidschicht dürfte auch hier den Reaktionsfortschritt behindern. Obwohl die Löslichkeit von Chrom im Aluminium bei Erhöhung der Temperatur auf 1000°C bis auf 12% ansteigt, ist die Anreicherung ebenfalls gering.

Schon ein geringer Bleigehalt reduziert die Oberflächenspannung des Aluminiums. Die Reduktionspotentialdifferenz zwischen Aluminium und Blei ist gegenüber Ti und Cr wesentlich größer, und Blei hat bei 800°C eine Löslichkeit von 4,5%. Intermetallische Verbindungen treten nicht auf. Das führt zu einer weitgehenden Reduktion von Bleipigmenten und ihrer Lösung im Aluminium. Bis zu 80% des Bleieintrags wurden im Aluminium angereichert.

6. Zusammenfassung

Es wurden die Auswirkungen beim Eintrag von mineralischen Pigmenten während des Aluminiumrecyclings untersucht. Dabei wurden die Einflußgrößen Pigmentart und -menge, Temperatur und Salzzusatz variiert. Für die einzelnen Pigmentmetalle ergeben sich sehr unterschiedliche Anreicherungen. Für vergleichende Aussagen wurden Anreicherungsfaktoren bestimmt. Dabei zeigt sich, daß nur die Elemente Blei, Zink und Antimon, die nach der Reduktion flüssig vorliegen, sich leicht über die zulässigen Grenzgehalte anreichern. Sind diese Metalle im Aluminium gelöst, oder werden beim Umschmelzen eingetragen, können sie nicht durch eine Salzbehandlung entfernt werden. Die Anreicherung der Elemente Titan, Chrom, Eisen und Kobalt kann bereits durch Einschmelzen ohne oder mit nur geringen Salzmengen bei tiefer Temperatur effektiv vermindert werden. Noch wirksamer ist ein Abschwelen und anschließendes Absieben der Schwelrückstände vor dem Einschmelzen.

In Herdöfen kann der Pigmenteintrag auch beim Einschmelzen lackierter Schrotte durch vorsichtiges Chargieren auf das Schmelzbad ohne starke Vermischung mit dem flüssigem Aluminium vermindert werden. Wird ganz ohne Schmelzsalz gearbeitet, kann davon ausgegangen werden, daß die Pigmentreste überwiegend mit der Krätze entfernt werden. Bei Einsatz von Salz stellen Salzmenge und -zusammensetzung einen Kompromiß zwischen der möglichen Anreicherung von Verunreinigungen und dem Erreichen hoher Metallausbeuten dar.

Insgesamt sind weniger die thermodynamischen Potentialdifferenzen, als vielmehr die Arbeitsbedingungen während des Umschmelzens (Temperatur, Salzzusatz, Rührung) reaktionsbestimmend. Hier sind vor allem die Oxidschichten zu nennen, deren Stabilität und Menge über mögliche Reaktionen entscheiden.

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Tabelle 1: Zusammensetzung verschiedener Knetlegierungen [1]

	Typ	Cu in %	Zn in %	Si in %	Mn in %	Mg in %	Fe in %
Knet-legierungen	AA3004	0,25	0,25	0,3	1,0-1,5	0,8-1,3	0,7
	AA 5182	0,15	0,25	0,2	0,2-0,5	4,0-5,0	0,35
	AA 6061	0,15-0,4	0,25	0,4-0,8	0,15	0,8-1,2	0,7
	AA 7277	0,8-1,7	3,7-4,3	0,5	-	1,7-2,3	0,7

Tabelle 2: Anorganische Pigmente in Lacken [2]

Element Farbe	Ti	Zn	Fe	Cr	Pb	Cd	Co	Cu	Sb
weiß	TiO_2	ZnO,ZnS +$BaSO_4$			$2PbCO_3$ *$Pb(OH)_2$			+	+
schwarz			Fe_3O_4 $Cu(Fe,Cr)_2$	O_4-Spinell			+	+	+
rot			Fe_2O_3	$7PbCrO_4$·	Pb_3O_4 $PbSO_4$ ·$PbMoO_4$	$Cd(S,Se)$			
orange			$FeOOH$	$PbCrO_4$*PbO					+
gelb		$(Zn,Cd)S$	$FeOOH$	$Pb(Cr,S)O_4$ $Pb(SbO_3)_2$		CdS			+
braun		$ZnFe_2O_4$ (Spinell)	$(Fe,Cr)_2O_3$, $ZnFe_2O_4$	+	$PbCrO_4$				
blau			Me(I)Fe(II) Fe(III)$(CN)_6$· H_2O*	$CoAlCr_2O_4$ (Spinell)			CoO*MeO (Al,Ti,Zn,Cr)	+	
grün	$(CoNiZn)_2$ TiO_4 (Spi-nell)	+		Cr_2O_3			+		

* = 4 - 8 % Eisenblau im Automobillack

Tabelle 3: Grenzgehalte von Verunreinigungen in AlMn1Mg0,5-Legierungen und deren Auswirkungen auf die Werkstoffeigenschaften [1, 3]

Element	Oberer Grenzgehalt	Auswirkung auf die Werkstoffeigenschaften
Ti	0,05 %	Grobkornbildung, höhere Kaltverformung
Cr	0,05 %	Höhere Festigkeit, Abfall der Dehnung
Pb	0,05 %	Anlagerung an Korngrenzen, Versprödung, sinkende Warmumformbarkeit

Sb	0,05 %	Grobkornbildung
Zn	0,25 %	Geringes Umformvermögen
Fe	0,5 %	Versprödung

Tabelle 4: Versuchsparameter und Metallausbeuten der Lack- und Pigmentversuche

Lack, Pigment	Pigment-zugabe [%]	relative Salz-menge [%]	Temperatur [°C]	Haltezeit [min]	Metallausbeute [%]
Übersichtsversuche					
grundiert		20, 30, 40	800	12, 15, 13	99,6/ 103,2/ 102,5
gelb		20, 30, 40	800	9, 13, 10	97,0/ 97,4/ 97,8
orange		20, 30, 40	800	12, 10, 12	95,7/ 94,6/ 91,9
braun		30, 40, 30, 30	800, 900(23)	14, 11, 3, 13	90,5/ 92,7/ 93,4/ 93,7
weiß		30, 40	800	14, 10	90,7/ 88,6
rot		30, 40	800	13, 12	89,2/ 88,4
blau		30, 40	800	12, 10	97,0/ 96,3
Einzelelementversuche					
Titan	0,5 /1 /1,5 /2	38	800	30	95,4 /93,4 /92,9 /92,9
	1	25, 13, 10, 5, 3	800	30, 30, 25, 15, 30	93,9/ 95,8/ 97,3/ 91,7/ 92,7
	1/ 1,3/ 0,4/ 0,5/ 0,5	0	800, 800, 750, 1000, 1000	30, 20, 30, 15, 45	93,2/ 89,4/ 96,5/ 91,9/ 96,8
Blei	0,5/ 1/ 1/ 0,5	25, 25, 19, 19	800	30, 30, 20, 30	95,8/ 94,4/ 99,3/ 98,5
	1	10, 5, 0	800	30	97,3/ 96,3/ 92,9
Chrom	0,25/ 0,5/ 1	19	800	30	96,8/ 96,8/ 96,3
	1/ 1/ 1/ 2/ 1	10, 5, 3, 3, 3	800	30, 20, 20, 30, 30	92,2/ 89,2/ 93,2/ 87,5/ 91,9
	1/ 1,4/ 0,4/ 0,4/ 0,4	0	800, 800, 1000, 1000, 1000	30, 20, 25, 6, 20	93,9/ 101/ 97,2/ 95,8/ 96,3
orange	20/ 16	5	880, 1080	20, 25	88,1/ 86,9
weiß	11,5	5	870	20	87,2

Tabelle 5: Anreicherungsfaktoren der verschiedenen Pigmentmetalle im Aluminium

Element	Ti	Pb	Cr	Sb	Fe	Zn
Übersichtsversuche	0,09	16,2	0,66	62,5	2,70	48,7
alle Versuche	0,62	22,0	0,73	65,3	n.u.	n.u.

n.u.= nicht untersucht

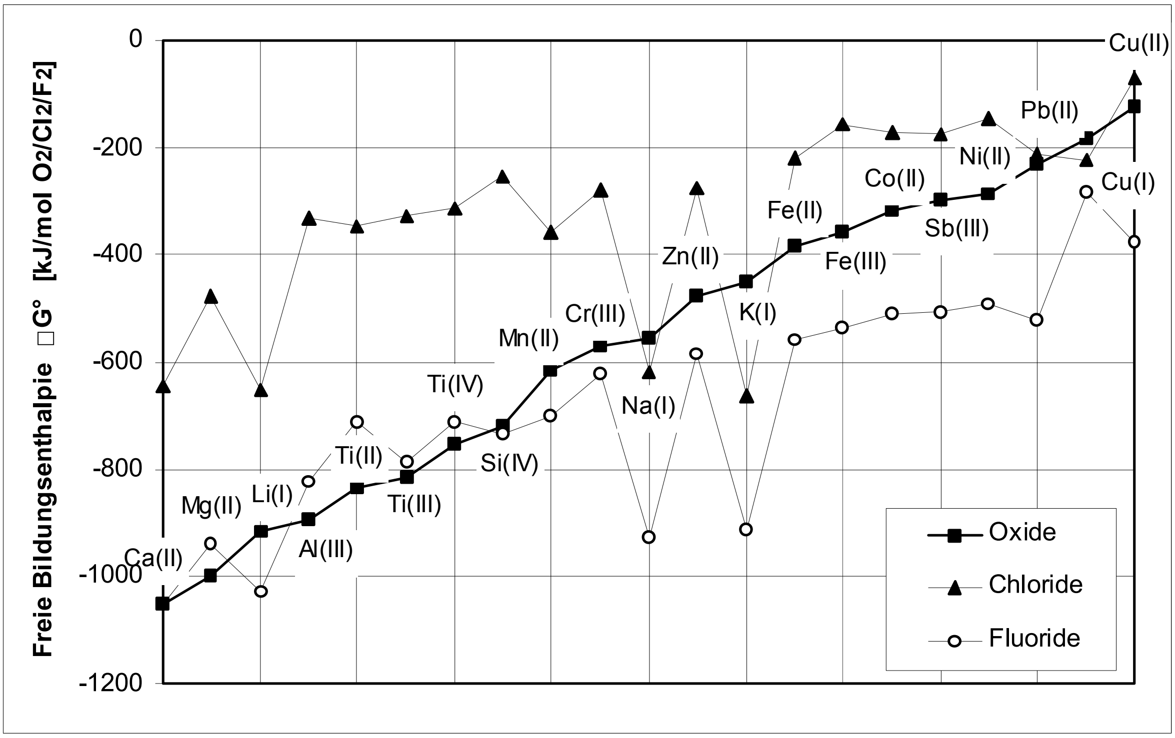

Abbildung 1: Freie Bildungsenthalpien einiger Metalle für ihre Oxide, Chloride und Fluoride bei 800°C und 1 bar Gasdruck. Daten: [4]

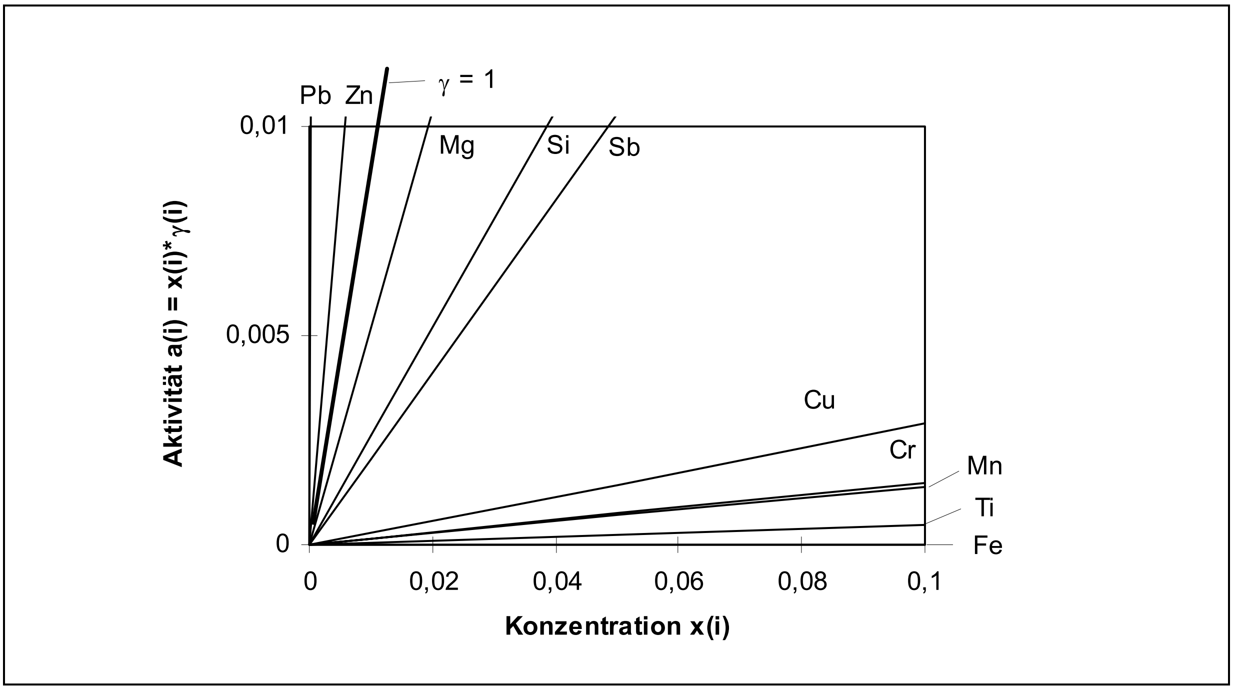

Abbildung 2: Aktivitätsverlauf in flüssigen binären Aluminiumlegierungen bei 1200K, nach Sommer u.a. [5]

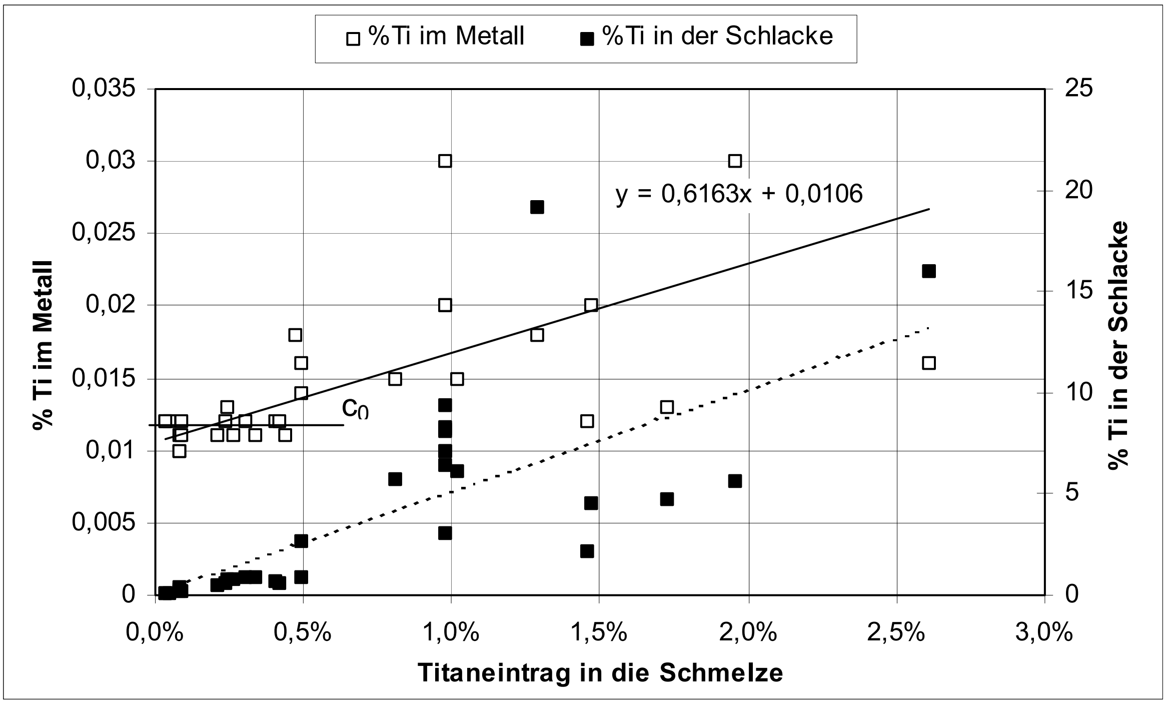

Abbildung 3: Titangehalte in Metall und Schlacke in Abhängigkeit vom Titaneintrag in die Schmelze

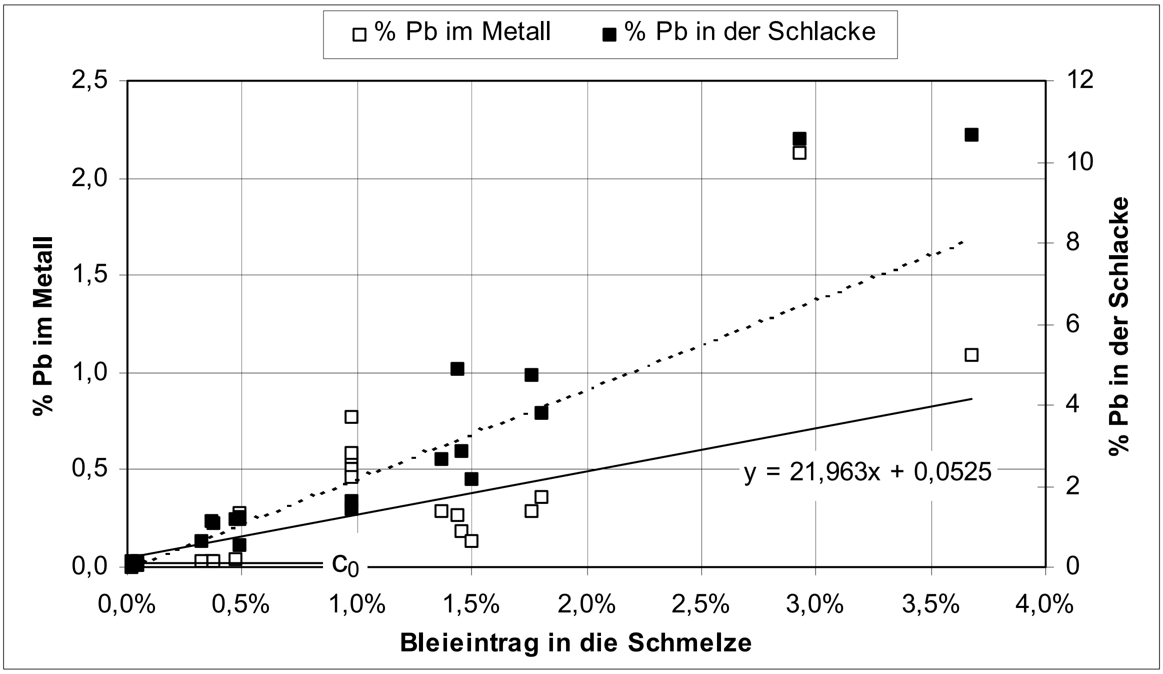

Abbildung 4: Bleigehalte in Metall und Schlacke in Abhängigkeit vom Bleieintrag in die Schmelze

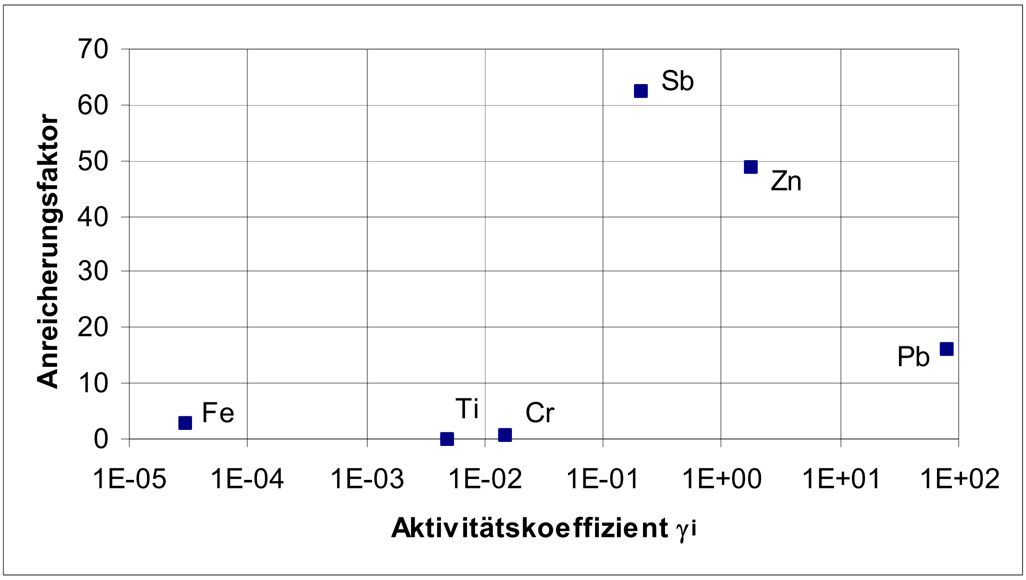

Abbildung 5: Abhängigkeit der Pigmentanreicherung vom Aktivitätskoeffizienten in flüssigem Aluminium bei 927°C

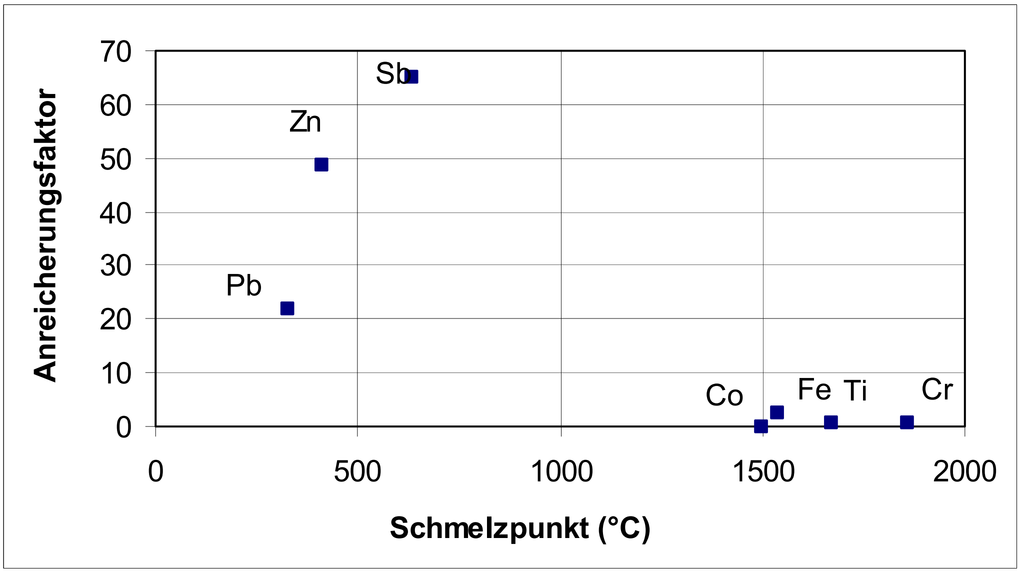

Abbildung 6: Abhängigkeit der Pigmentanreicherung vom Schmelzpunkt der Pigmentmetalle

IMPROVED ALUMINIUM RECOVERY AT RECYCLING PLANTS BY INTEGRATED SLAG REFINING*

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ABSTRACT

Extensive experiments show that a reduced oxide content in KCl-NaCl-CaF2-slags lead to an increased aluminium recovery in recycling processes. A centrifuge-based equipment was developed to continuously remove oxide from such melts. This can be process integrated in conventional rotary drum furnace plants in order to recover aluminium from slag and recycling salt directly in the plant. A mass balance is presented for such a concept. A bundle of economic advantages can be achieved.

On the other hand also for re-melting plants the process integration of the centrifuge should be feasible. Hot dross from hearth furnaces can be treated immediately and the incorporated aluminium is recovered. Using an optimized Al2O3 level in the dross-treatment-vessel the maximum metal yield can be achieved.

In both cases a salt-oxide mixture (50 : 50) is produced, much lower in volume (and recycling costs) compared to the state of the art process.

KEYWORDS
Aluminium, raw materials, recycling, metallic form, oxides, salt, scraps, turnings, dross, and slag, refining plant, oxide collector, furnace operation, melting process, refiners plant, aluminium yield

* Source: Proceedings of the European Metallurgical Conference EMC 2001; Vol. 3, Light Metals-Process Control-Analytics and Modelling-Education and Training-Precious and Rare Metals - 2001; pp 121-139

1 Introduction

Raw materials dedicated to the recycling of aluminium have to contain the aluminium in a not oxidized but metallic form. The transformation of such oxides into metal is technically and economically not feasible. The major recycling target is to recover the metallic aluminium content of scraps and residues with the highest possible yield combined with the lowest effort.

During processing and use of aluminium-products a broad range of scraps, intermediates and residues occur. A special interest is given to turnings and drosses which build approximately 45 % of the raw materials mix of a refining plant [1]. In a close context the by-product “slag” has to be seen, as these materials have to be molten using salt as oxide collector and atmosphere barrier. Figure 1 shows the raw materials mix in 1997 of Germany’s refining operations. Table 1 summerizes the estimated amount of turnings, drosses and slags.

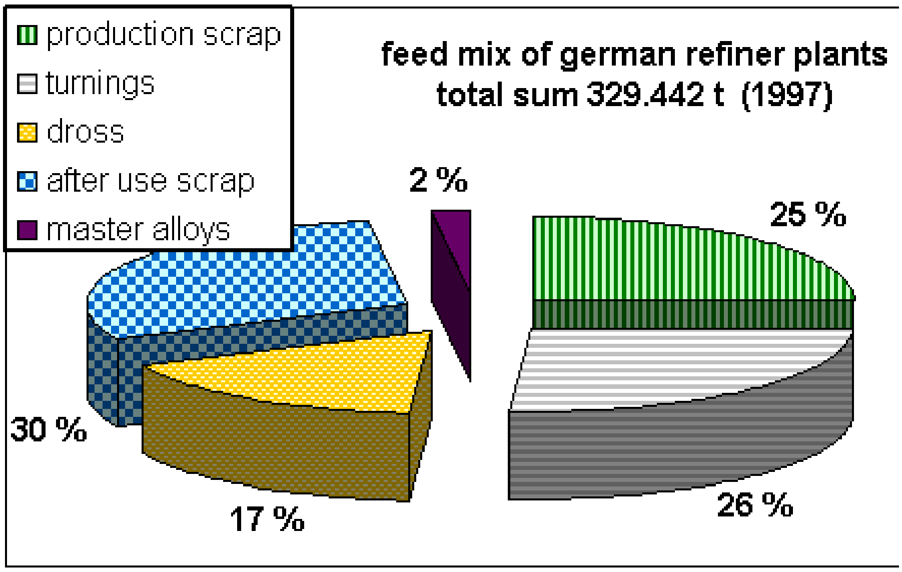


Figure 1: Raw materials mix in 1997 in Germany (Al refiners operation)

One target of this investigation is to optimize the salt composition in order to obtain higher aluminium yields in the furnace operation. As a second target a concept will be developped to integrate the slag treatment with the melting process in order to recover the lost aluminium content already at the refiners plant. A third target is the reduction of salt purchased from external sources.

Table 1: Total amount (* estimations) of turnings, dross and slag in Germany 1997

wrought alloy turnings	27 000 t/a
cast alloy turnings	50-60 000 t/a
turnings from semis	130-170 000 t/a
turnings from final processing	50-100 000 t/a
turnings (total)	**ca. 260-360 000 t/a***
primary dross	15 000 t/a
remelters dross	30 000 t/a
dross from foundries	35 000 t/a
refiners dross (converter)	20 000 t/a
refiners dross (hearth furnace)	ca. 10 000 t/a
dross (total)	**ca. 110 000 t/a***
slag from tilt type rotary furnaces	20-30 000 t/a *
slag from rotary drum furnaces	ca. 200 000 t/a
slag (total)	**ca. 230 000 t/a**

2 Established recycling processes for aluminium turnings, drosses and slags

2.1 Conditioning of aluminium turnings

During mechanical processing of aluminium turnings from cast and forged parts are produced and collected typically classified by alloy composition. Quite often an emulsion of oil and water is used and contaminates this type of aluminium scrap.

A wet conditioning process is based on a counter current flow washing step, using centrifuges. The water/oil content is reduced to each 2 %, the removed emulsion is separated using demulgators. The final drying takes place in rotary drum coolers, followed by an iron separation using magnetic fields. By seiving the turnings are split into a > 1 mm coarse fraction and a < 1 mm fine fraction. The latter has to be compacted prior to the melting process [2, 3].

A thermal conditioning process is conducted in indirect heated discontinuously operated rotary drums with a well controlled oxygen deficit in the oven atmosphere. The de-oiled and dry turnings are magnetically split and seived as mentioned above. The off-gases are subsequently burned at temperatures > 800 °C and quenched to 250 °C with water to avoid PCDF-formation [4, 5].

2.2 Conditioning of aluminium dross

Dross is a by-product of all aluminium melting processes. Depending on scrap-type, alloy-treatment and melting equipment the amount, metal content and properties of dross vary in a wide range. Dross is a mixture of aluminium, aluminium-oxide and oxides of alloying elements, additionally halogenide-, carbide- or nitride-compounds of these metals are regulary found. Typically dross contains a large amount of metallic aluminium. This is mechanically fixed in a cellular structure of aluminium-oxide, which has a tension strength strong enough to keep aluminium 20 times of its own weight bonded. As dross contains also fine dispered gas bubbles (foam structure), it easily separates from the aluminium melt due to the reduced density [6, 7].

The following process parameters have a strong influence on volume, morphology and metal content of dross:

- surface/volume-ratio of the scrap
- type (organic, inorganic) and amount of impurities
- melting conditions and melting equipment
- melt composition (especially Mg-, Na-, Li-, Ca-content [8])
- refining procedure
- way of dross removal (temperature, tools)
- cooling parameters of the removed dross

A direct comparison and evaluation of the various dross conditioning processes [9, 10] is difficult, as the raw material source is diffrent. Generally modern processes are based on a fast quenching step in order to avoid an oxidation of the incorporated aluminium metal droplets. It is followed by a mechanical benefication step which removes as much oxide as possible. Alternatively a direct melting of the > 1 mm fraction is state of the art [11]. The by-product dross-dust has to be dumped or processed separately in a slag treatment plant, the < 1 mm fraction (dross residue) can be sold to the steel industry for desoxidation purposes.

Table 2 summerizes size, aluminium content and proportion for the four products of the mechanical treatment process. It can be seen that all values varies widely depending on the history, especially the < 1 mm dross-residue (table 2).

Table 2: Products of the „cold“ consolidation of dross [12]
(*estimations)

	particle size	origin	Al-content	proportion	next step
lump fraction	lumps	hand sorting	70-90 % Al	up to 20 %	melting
coarse fraction	<100 mm	seive	50-70 % Al	30-80 %	salt melting
dross residue	< 1 mm	seive	20-50 % Al	10-40 %*	desox. in steel, landfill
dross dust	< 1 mm	filter	5-20 % Al	5-20 %*	land fill, slag recycler

2.3 Rotary drum furnace process

Still up to now the rotary drum furnace is the most common unit to melt high impurity scraps. It consists of a cylindrical steel shell, which is horizontally mounted on wheels and lined with ceramic bricks. The ceramic lining is typically interrupted by mixing paddles in order to maintain an improved mixing and furnace operation [13].

A liquid salt consisting of sodium- and potassium-chloride is used to collect oxides and to avoid oxidation by the atmosphere. CaF_2 is added to improve the coagulation of aluminium droplets. The lining is continuously cleaned by the slag due to the rotating movement of the kiln. The productivity depends on the raw material mix, salt quality/quantity and the operation mode. Using oxygen-burners, optimized furnace sealing and an automatic control of the atmosphere the thermal yield can be moved up to 66 % [2]. A thermal energy balancing results in a calculated oxidation loss for aluminium of about 2 – 3 % of the charged metallic aluminium.

A "salt factor" is introduced to characterize/calculate the necessary amount of salt:

SF = (salt amount)/(weight of raw material mix – trial determined aluminium recovery)

The use of salt is especially necessary if raw materials with high specific surfaces or high oxide contents are to be recycled. Depending on the technical and economic conditions a limit for the total oxide content exists (productivity, energy and salt consumption, slag treatment costs). Figure 2 shows exemplary the specific energy consumption of an aluminium rotary drum furnace as a function of the charged oxide volume. As it can be seen the energy consumption can be reduced by choosing smaller salt factors.

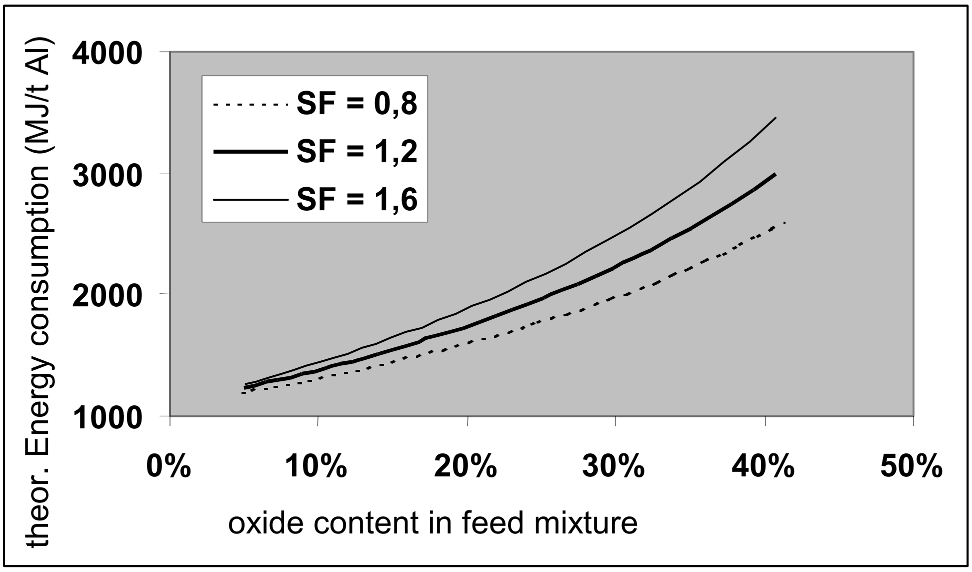


Figure 2: Theoretical energy consumption of a rotary drum furnace with rising oxide contents in the Aluminium-scrap (MJ/t Al)

2.4 Smelting in a tilt type rotary furnace

A more recent melting process is based on a tiltable furnace and also operated with salt addition. But compared to the conventional rotating drum furnace the salt volume is significantly reduced (salt factor 0,4 up to 0,8). This results in a non liquid but pasty slag, impossible to tap or cast. The oven has to be tilt entirely to be emptied through the charging hole. This type of furnace is especially designed for heavy oxidized materials, eg. dross. Oxygen burners mounted close to the off-gas opening forces the flame to turn back. This leads to a high thermal efficiency and less specific energy consumption [14, 15, 16].

Table 3 [17] compares the two salt-smelting-techniques. The conventional rotary drum furnace (RDF) recovers at least 90 % of the aluminium content if charged with a standard raw materials mix. A hypothetical salt factor reduction form 1.8 to 1.0 would reduce the specific energy consumption to about 90 % of the reference operation, a further reduction is technically not possible (tapping problems). A further optimization can be realized with the tilt type rotary furnace (TTRF), which allows even a 100 % dross charge.

Table 3: Comparison of conventional rotary drum furnace (RDF) and tilt type rotary furnace (TTRF) operation

	rotary drum furnace		**tilttype rotary furnace**	
	excess salt addition	optimized salt addition	scrap mix (normal)	only dross
gas burner	cold air		oxygen	
salt factor	1,8	1,0	0,5	
scrap input	11,8 t	13,0 t	6,97 t	6,0 t
salt input	3,2 t	2,0 t	0,52 t	1,5 t
total input	15 t		7,5 t	
Al output	9,9 t	11,0 t	5,92 t	3,3 t
Al yield (kg metal/scrap input)	85 %		85 %	55 %
slag output	5,0 t	4,0 t	1,57 t	4,2 t
oxide content in slag	36 %	49 %	67 %	
energy consumption (per total input)	2600 MJ/t	2600 MJ/t	1700 MJ/t	1700 MJ/t
energy consumption (per scrap input)	3300 MJ/t Al	3000 MJ/t Al	1830 MJ/t Al	2100 MJ/t Al
energy consumption (per Al output)	3900 MJ/t Al	3550 MJ/t Al	2150 MJ/t Al	3800 MJ/t Al
tap to tap time	ca. 6 h	4-8 h	ca. 3 h	2-3 h

2.5 Slag treatment/salt recovery

Closely linked to the consolidation and metallurgical processes for aluminium scraps and residues is the treatment of the “by-product” slag. In the past years the specific slag volume could be reduced from 400 – 700 kg/t to 300 – 500 kg/t [17]. The oxide input as well as oxidized aluminium from the melting procedure is collected by the salt forming a physical salt-oxide-mixture. Unavoidable are small aluminium droplets, being too small to coagulate. That reduces the melting yield. Table 4 summerizes the proportion of these three phases in RDF and TTRF processes.

Table 4: Composition of slags from RDF- and TRF-furnace operations (*estimations)

	rotary drum furnace (liquid salt melt)		**tilt type rotary furnace** (pasty salt cake)
	typical	min/max	min/max
Aluminium metal	8 %	5/20 %	5/15 %*
oxides, CaF_2	37 %	20/40 %	50/60 %*
NaCl, KCl	55 %	45/75 %	25/45 %*

Due to the water soluble chloride-phase land filling of the slag is ecologically no solution looking on the risk of ground water contamination and gas-formation (H_2, CH_4, NH_3, PH_3, H_2S). Besides this also the recovery of the melting salt is economically feasible. The salt, typically a NaCl-KCl-mixture shows a minimum melting temperature of 664 °C at 44 % NaCl/56 % KCl (equimolarity) [18, 19].

Typically some percent of CaF_2 are added to improve coagulation of aluminium droplets. The salt due to its low surface tension creeps between the oxide film and the molten metal using cracks formed by thermal expansion or Na-gas-formation. As the solubility is almost zero the oxides form a liquid-solid-suspension with the salt, the viscosity rises. The viscosity itself is strongly depending on volume size and type of oxides dispersed in the salt. Figure 3 shows the thixotropic behaviour forced by flat and thin γ-Al_2O_3 dispersoids.

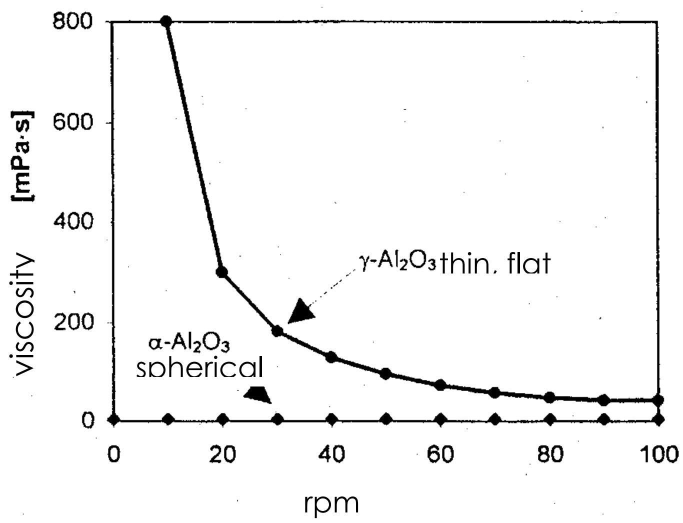


Figure 3: Rheologic behaviour of a oxide-salt mixture with oxide-morphology in a mechanical stirred crucible [20]

3 Experimental results of salt melting tests with high oxidized raw materials

3.1 Equipment

An electrically heated crucible was charged with NaCl/KCl-salt as the temperature exceeded 100 °C. After melting a thermo-couple was placed 3 cm below the surface, a mechanical stirrer was mounted in a depth of 4 – 5 cm to keep the turbulence in the upper crucible section. Figure 4 shows a scheme of the experimental arrangement.

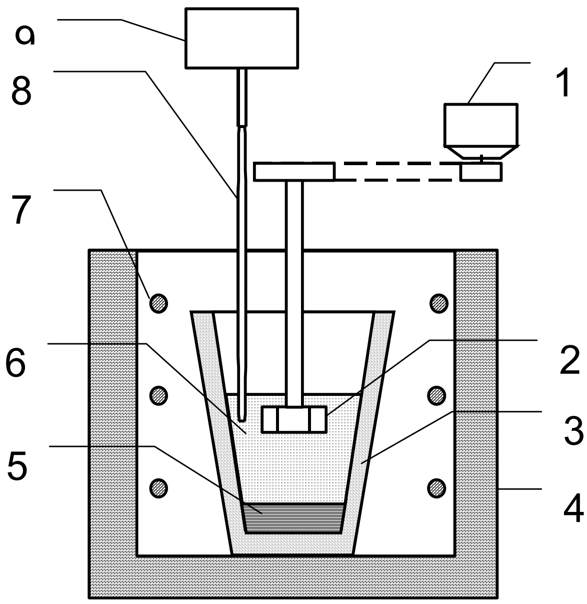


Figure 4: Scheme of the experimental equipment
1– motor; 2– stirrer; 3– crucible; 4– lining; 5– aluminium; 6– salt
7– heater;8– Al_2O_3-protection tube with thermocouple;
9– temperature measurement

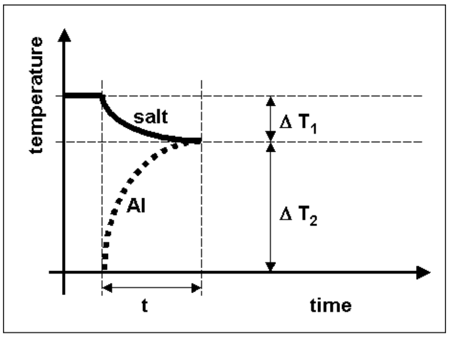
3.2 Melting behaviour of fine aluminium turnings

The very fine turnings-fraction shows a tapped density of 0,78 g/cm^2, a particle size distribution as presented in table 5 and a mean oxygen content of approximately 1,45 %.

Table 5: Particle size distribution of a turnings-fraction (< 2 mm)

fraction (mm)	>4	>2-4	>0,8-2	0,25-0,8	< 0,25
proportion (%)	0,05	0,07	45,6	45,5	8,8

Based on these data a specific surface area of about 1 m^2/kg can be assumed (calculation as a 0,8 mm aluminium foil).
The dry and at 400 °C preheated turnings scrap charge was inserted close to the stirrer shaft into the vortex and immediatly immersed by the melt. A heat exchange coefficient α between melt and scrap can be defined using the temperature drop after charging.



$$\alpha = \frac{m \cdot c_p \cdot \Delta T_1}{F \cdot t \cdot \Delta T_2}$$

m	mass of scrap added (kg)
F	specific surface area (m^2/kg)
c_p	thermal capacity salt (J/kg · K)
ΔT_1	salt temperature drop at charging (K)
ΔT_2	Al temperature increase (K)
t	time to reach minimum of salt temperature (s)

Figure 5 presents the heat transfer depending on the turbulance conditions and on the amount of scrap added. It shows that the rotating speed of the stirrer = mixing condition has a significant effect on the time between charging and melting. The local turbulance is strongly depending on the viscosity of the melt, which is again a function of oxide content and stirring condition (thixotropy).

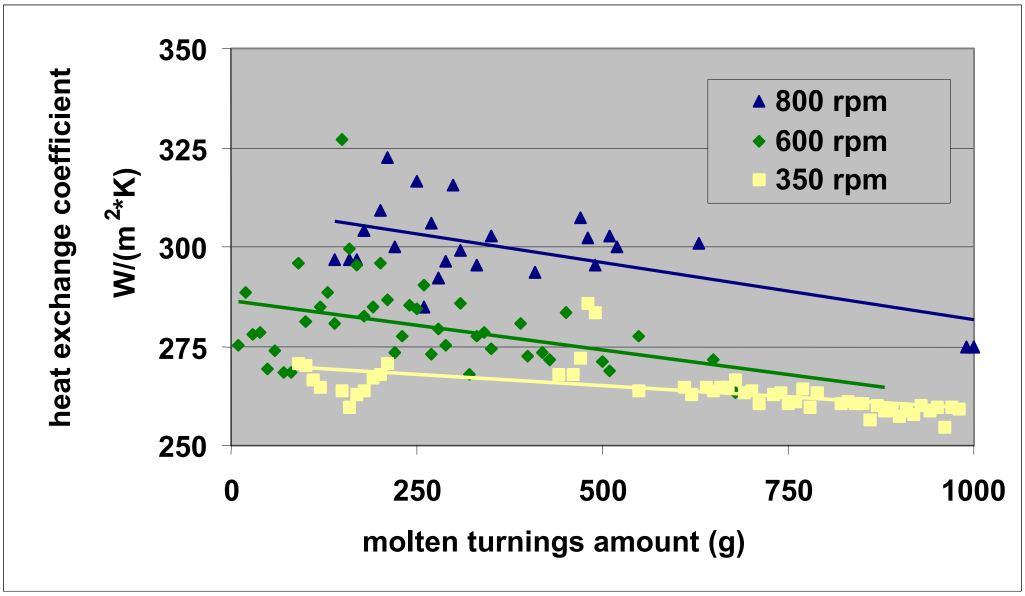


Figure 5: Heat exchange coefficient in stirred salt melts depending on rotating speed of the stirrer (portion: 10 g per charging step)

3.3 Melting behaviour of aluminium dross

Aluminium dross was split by seiving into a powder and a coarse fraction. Both fractions again were each split into 6 sub-fractions. The particle size distribution of the coarse fraction shows figure 6, the volume > 40 mm was additionally separated by hand into high and low metallic contents.

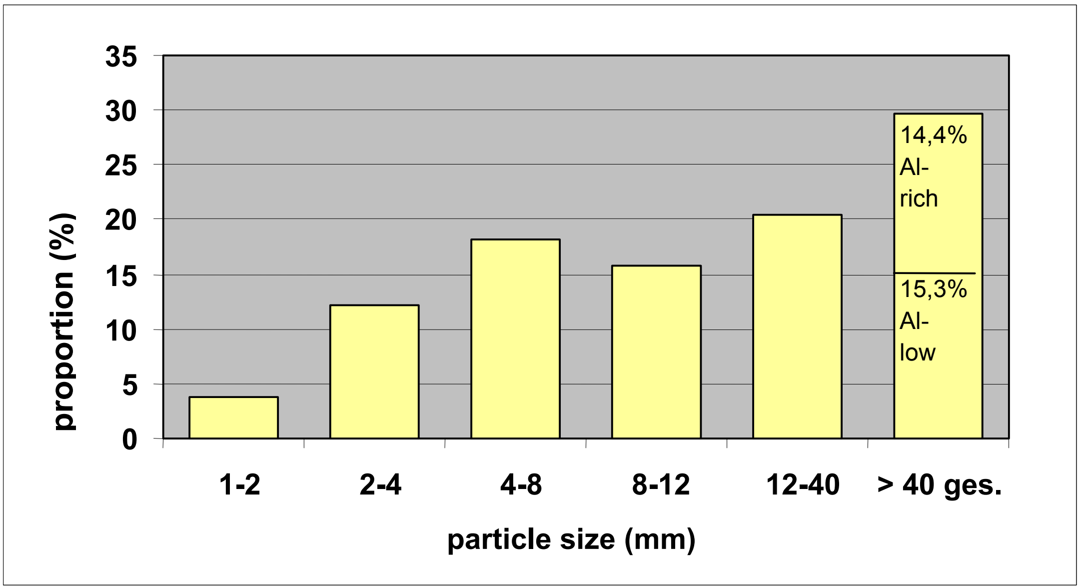


Figure 6: Particle size distribution of aluminium dross

From figure 7 a strong dependence between particle size and metal yield can be seen. Particles less than 75 – 125 µm (log d_p < 1) from the bottom line of any metal recovery.

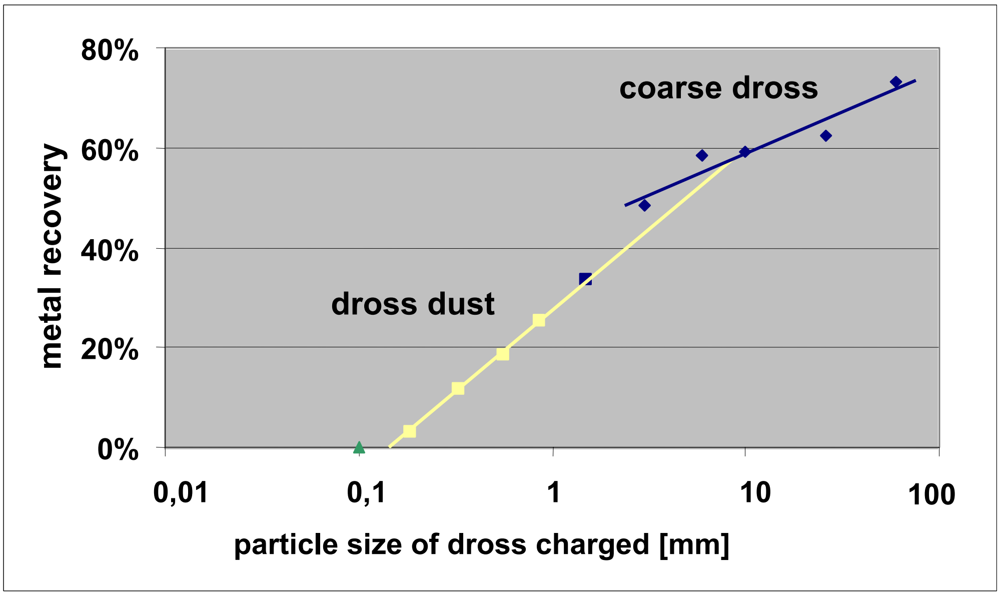


Figure 7: Metal recovery from coarse dross and dross powder with rising particle size

It has to be stated that even with an addition of 2 % CaF_2 the metal yield of dross dust is always unsufficiently low. Additional trials were conducted with the fine fraction of the aluminium dross in order to further investigate the interrelation between particle size and CaF_2-addition on the metal yield.

As figure 8 indicates a further increase of CaF_2 to 3 % did not influence significantly the metal yield and the processing of dross powder < 1 mm is most likely uneconomical.

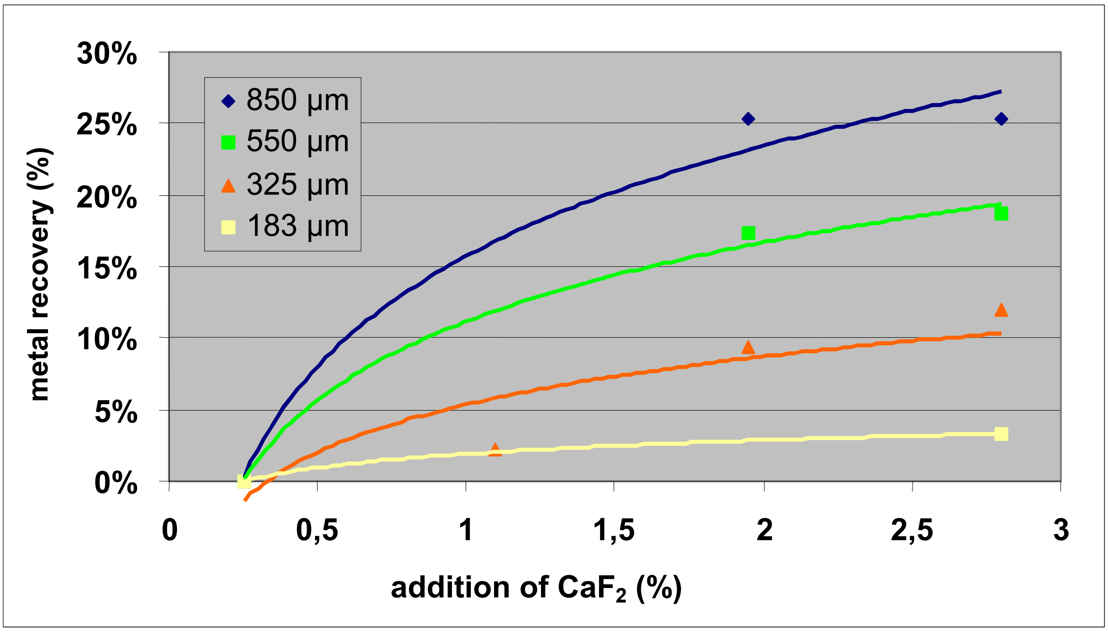


Figure 8: Metal recovery from dross-powder with increasing addition of CaF_2

3.4 Effect of the oxide-content in slag on metal recovery

Industrial supplied slag from RDF-operation was analysed in respect of the major component-contents. Table 6 shows the results of the chemical analysis of recycled salt and slag after scrap/dross treatment. The values indicate a untypical high salt factor.

Table 6: Composition of salt and slag from industrial RDF-operation

	Al met. (%)	Al_2O_3 (%)	CaF_2 (%)	NaCl (%)	KCl (%)
recycling salt	-	0,43	0,13	69,3	27,4
slag	7,5	28,0	1,6	62,9	

This slag was used to investigate the effect of the oxide content on the metal recovery yield. The slag was diluted with recycling salt 2, 2,5 and 3 times of the slag weight. The slag-salt-mixture was molten and stirred for 1 hour in order to allow the dispersed aluminium droplets to coagulate. From figure 9 it can be seen that an increasing oxide content in the slag up to 15 % helps coagulation of the droplets into larger diameters which allows settling from the slag.

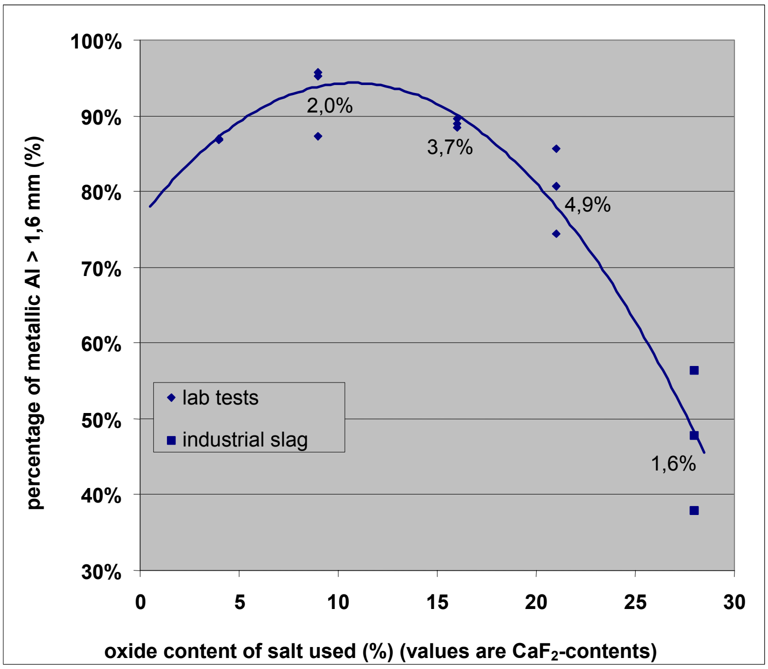


Figure 9: Coagulated Al (> 1,6 mm droplets) as function of oxide-content in the salt

Above 15 % the increasing viscosity hinders coagulation and further settling. Industrial values with a slag of 28 % Al_2O_3 fit quite good in the drawn relationship.

3.5 Salt refining in molten condition

From the above described lab scale tests it could be seen that the maximum metal yields can be achieved at oxide contents of 10 – 15 % in the salt. This is due to a counter current effect of increasing friction between the suspended oxides and the oxide film and increasing viscosity. Conventional rotary drum furnaces are operating with 25 – 30 % oxides in the tapped slag. In order to develop an integrated smelting-slag refining concept extended tests were conducted to remove oxides immediately from the molten process slag.

First trials on filtration of oxide-containing NaCl/KCl slags showed quickly strong difficulties in holding back the fine oxides as they are part of a quite wide particle size distribution from < 1 to << 1 000 µm. Using cake filtration techniques soon a very dense oxide layer is formed on top of the felt and due to the small density difference the liquid salt can not penetrate it sufficiently.

A second series investigated a simple gravity segregation process. Only a small portion of cleaned salt was obtained and the oxide-salt-bottom-phase showed a much to high salt content.

In a third test series an IME-optimized centrifugal rotor was immersed in the slag. After two minutes at a rotating speed of 400 rpm the rotor was pulled up and accelerated to a higher rotating speed. The liquid salt slag was centrifugal extracted in order to receive a dry filter cake. The cake was removed and the rotor immersed again. Figure 10 presents the main part of this experimental equipment – the rotor head.

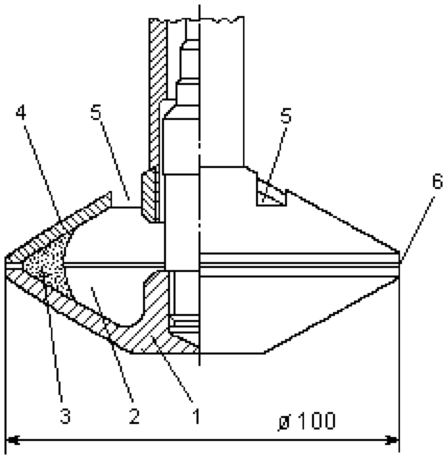


Figure 10: Scheme of the centrifugal rotor head
1. rotor bottom, 2. area of suspension, 3. segregated oxide, 4. rotor top, 5. suspension inlet, 6. salt outlet

The separation results are shown in figures 11 – 13. Up to CaF_2-content of 4 % a constant oxide content of nearly 45 % and a CaF_2-content of < 3 % in the cake could be obtained. The CaF_2-content depends more or less on the salt matrix. It was interesting to see and counter-dictionary to the common understanding (10 % solubility in the ternary diagram NaCl-KCl-CaF_2 at 800 °C) that at a very low level of 3,8 % CaF_2 can't be dissolved. It is separated solid from the slag and found in the oxide phase of the rotor. A systematic investigation of the NaCl-KCl,CaF_2-System is necessary and part of a current investigation at IME.

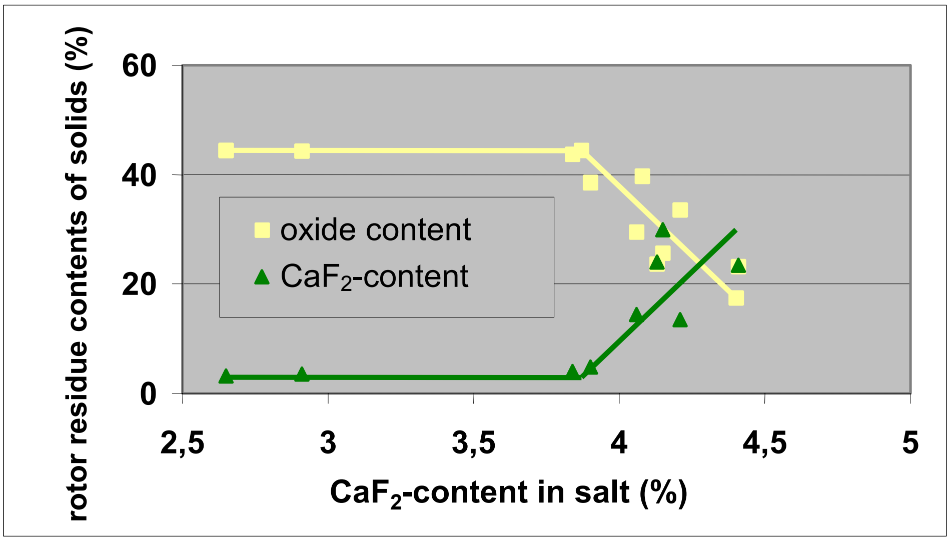


Figure 11: CaF_2- and oxide contents in the solid residue of the centrifugal rotor head with increasing CaF_2-additions to the salt

With increasing rotating speed the centrifugal acceleration is improved, a separation factor $q = \omega^2 r/g$ can be used to classify the fluid flow system. The positive effect is shown in figure 12, as the oxide content can even exceed the 50 % level, the salt matrix is recovered with higher yields.

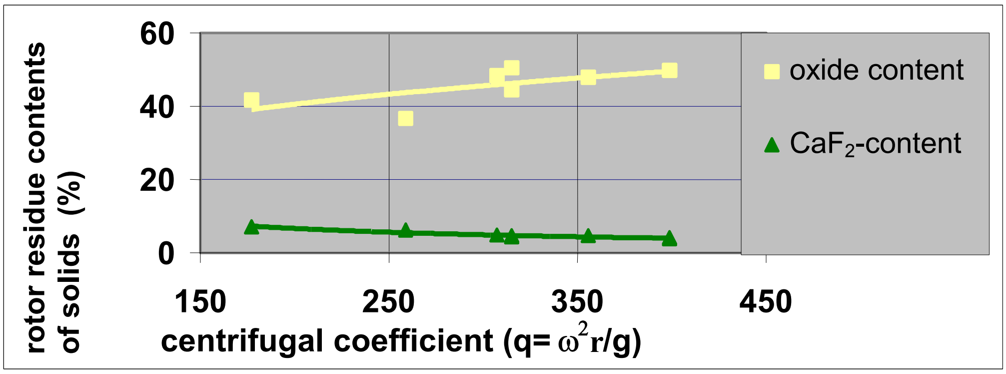


Figure 12: CaF_2- and oxide content in the solid residue of the centrifugal rotor head with increasing rotating speed

Probably the most exciting result is shown in figure 13. If 2 % CaF_2 is added to the salt, the metallic aluminium content in the solid residue of the rotor, which would be the product delivered to external slag refiners, can be reduced from > 5 % to much less than 0,5 %.

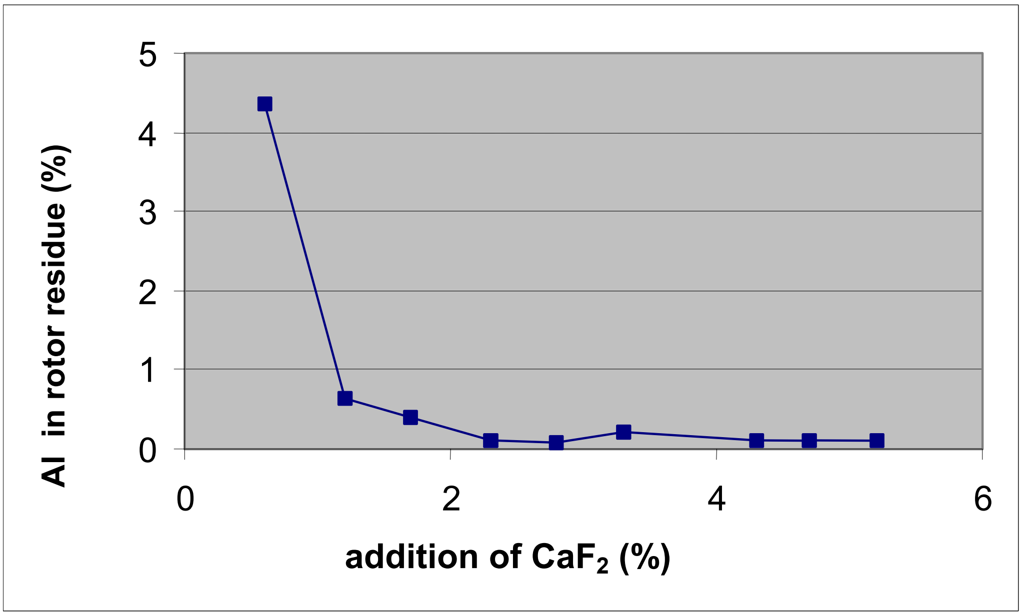


Figure 13: Aluminium losses in the solid residue of the centrifugal rotor head with increasing CaF_2-additions to the salt

4 Process integrated separation of oxides

4.1 Concept for rotary drum furnaces

Rotary drum furnaces are especially useful if scraps and residues with increased oxide and/or impurity levels are recycled. The presented results about the melting behaviour of fine turnings, dross powder, dross dust and above the influence of oxide contents forces to develop an applied concept for "high oxide" processes. In respect to metal recovery yield it is recommended to control the oxide level in the salt to 10 – 15 % and avoid significant higher values. But presently rotating drum furnace operations can't run economically with such low oxide levels (= high salt/scrap ratio) due to the high slag volume, external slag treatment cost, increased energy consumption as more salt has to be molten and a reduced productivity. The idea is to implement an inline slag-cleaning/oxide removal process step in order to recover molten recycling salt and the dispersed aluminium metal already at the recycling plant. It is recommended to use a separate heated ladle with a centrifugal rotor head to treat the tapped slag immediately after scrap melting. A high concentrated oxide/salt mix with very low aluminium inclusions will be the product given to salt recyclers, liquid salt can be separated and returned to the next drum melting sequence and segregated aluminium can be added to the main stream. A certain amount of salt will be kept in the ladle to dilute the next slag tapping to the optimum level of 15 % oxides.

Figure 14 shows a very simplified mass flow balance of a standard dross treatment process (black numbers) and an improved process (cursive numbers).

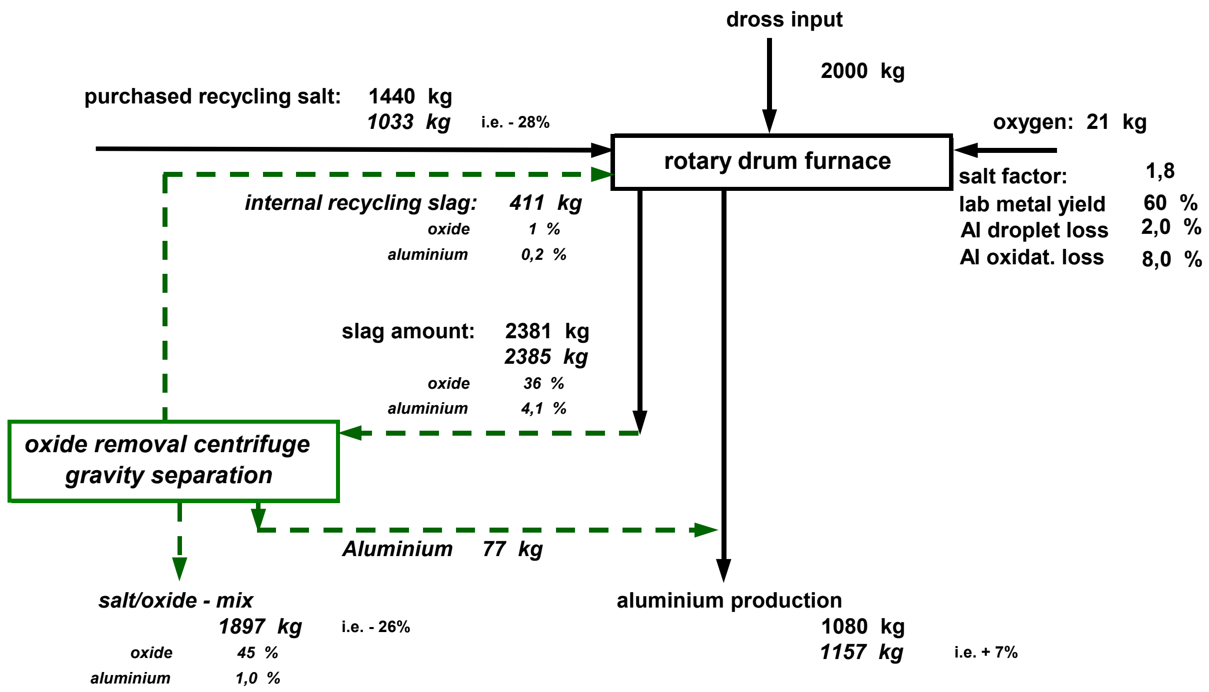


Figure 14: Integrated centrifugal salt cleaning into the standard rotary drum furnace operation

Assumed that only 2 000 kg dross will be charged to a drum furnace and a previous melting test shows a maximum melting recovery of 60 %, a salt factor of 1,8 is practicable. This leads to a demand of 1 440 kg salt, typically bought from a recycling plant. As always aluminium is lost in slag by oxidation and as droplets only 1 080 kg (e. g. 90 % yield related to a laboratory test) will be recovered as a metal bullion. Approx. 2 400 kg of slag will be tapped with about 36 % oxide and 4,1 % aluminium metal despersed. Even the latter is given away today for external recovery with resp. cost. The new separation equipment would recover approx. 80 kg molten Al and 410 kg molten recycling salt. 1 900 kg salt/oxide mix (= 75 % of present volume) have to be treated externally.

The advantages are

- increased aluminium yield (+ 7 %)
- reduced slag treatment costs (- 25 %)
- reduced salt purchased (- 30 %)
- reduced melting energy consumption (- 8 – 10 %)

Additional costs will be thermal energy needed to keep the slag liquid, capital- and personnel costs for the new process step and costs for consumption materials (lining, etc.).

4.2 Concept for hearth furnace dross

At remelter-plants dross is continuously produced in melting- or warming-up-hearth-furnaces. Today the dross is cooled, collected and given to external refining operations (see 2.2, 4.1). A concept to recover the metallic aluminium straight from the hot dross is presented below.

The high aluminium containing dross is hot charged to a salt melt with optimized oxide content much lower than in RDF-furnaces (see 3.4). Excess oxide is continuously removed by a centrifugal system (separate chamber), the CaF_2-content is controlled and adjusted. The liquid aluminium is forced to separate from the oxide-network, coagulates and segregates due to the higher density. Much higher Al-recovery-yields can be expected. The centrifuge-vessel can be build quite compact and serves with high throughput and flexibility. The energy input may be arranged by indirect gas/oil-burners or even electrically by submerged electrodes [21]. Figure 15 presents a conceptional flow chart of the above mentioned process (inline treatment of hot dross). A special care has to be taken regarding the salt addition, if Al-billets for a subsequent rolling/forging processing are produced (wrought alloy).

A preliminary comparison between the actual and a process integrated dross treatment is summerized in Table 7, based on the input of 1 000 kg dross.

Advantages are expected in

- heat energy use of the hot dross
- reduction of aluminium oxidation compared to a cooling/mechanical treatment-/warming-up-process
- reduced aluminium losses
- reduced by-product volume (slag and dross residue)

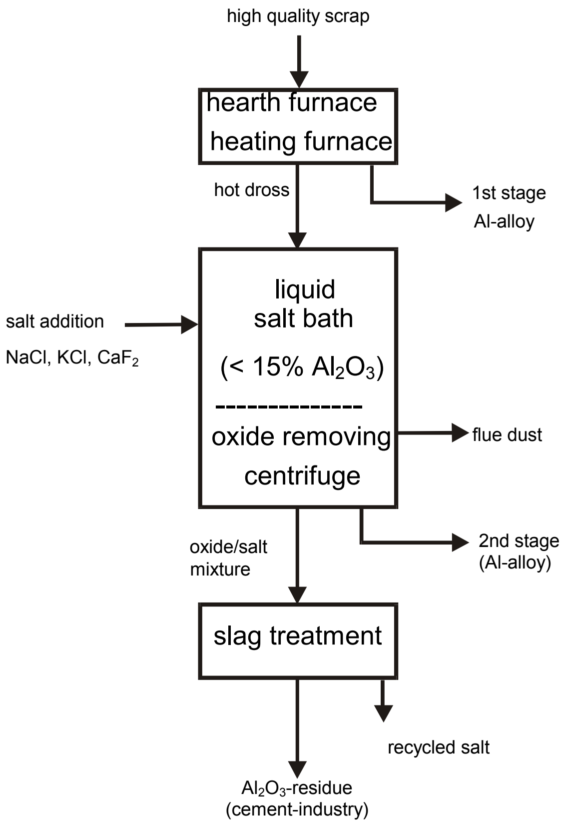


Figure 15: Integrated centrifugal dross treatment in molten salt with a continuous oxide removal and increased metal yields

Table 7: Process data and expected product volumes for dross treatment processes (conventional and proposed integrated salt melting)

	conventional dross treatment process (related to 1 t hot dross)	**hot charging/centrifugal salt melting process (related to 1 t hot dross)**
aluminium recovered	approx. 480 kg	approx. 670 kg
aluminium yield (related to hot dross content)	69 %	96 %
salt addition	approx. 170 kg	approx. 300 kg
dross residue (losses)	approx. 410 kg	none
slag (to recycling plant)	approx. 350 kg	approx. 650 kg
energy consumption	5 000 MJ/t	1 000 MJ/t

5 Summary

Extensive experiments show that a reduced oxide content in KCl-NaCl-CaF_2-slags lead to an increased aluminium recovery in recycling processes. A centrifuge-based equipment was developed to continuously remove oxide from such melts. This can be process integrated in conventional rotary drum furnace plants in order to recover aluminium from slag and recycling salt directly in the plant. A mass balance is presented for such a concept. A bundle of economic advantages can be achieved.

On the other hand also for remelting plants the process integration of the centrifuge should be feasible. Hot dross from hearth furnaces can be treated immediately and the incorporated aluminium is recovered. Using an optimized Al_2O_3 level in the dross-treatment-vessel the maximum metal yield can be achieved.

In both cases a salt-oxide mixture (50 : 50) is produced, much lower in volume (and recycling costs) compared to the state of the art process.

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STUDY OF THE APPLICATION OF MELTING SALT AT THE PROCESSING OF SPECIAL ALUMINIUM SCRAPS AND DROSS*

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ABSTRACT[1]

The excellent recycling properties for make aluminium a sustainable material in modern economy. The German recycling activity is about 2,3 Mio ton/y including in-house scrap. High yield in Al-recycling can be achieved from new and old scrap. But for fines and high oxide containing scrap the metal yield in the known recycling processes is rather low. New special processes are developed to perform economical treating of various fines with high yield. Furthermore the loss of aluminium in slag has to be reduced. The aim of this work is to increase the metal yield for the mentioned types of scrap and to reduce the amount of salt-slag.

The extensive experiments show that a reduced oxide content in NaCl-KCl-CaF_2-slags leads to an increased aluminium recovery in the recycling processes. A centrifuge-based equipment was developed to remove continuously oxides from liquid salt melts. By the integration of a salt-hearth-furnace with a conventional rotary kiln-process the aluminium of the salt slag could be directly recovered at the refiners and the liquid salt could be brought back to the melting operation. On the other hand also for re-melting plants the process integration of a centrifuge should be feasible. Hot dross from hearth furnaces can be treated immediately and the contained aluminium could be recovered. An oxide-level of about 15 % in the dross-treatment-vessel leads to the maximum metal yield can be achieved.

In both cases a lower amount of salt-oxide mixture is produced as in conventional rotary kiln processes. The mixture consists of roughly 50 % oxides and salt. Because of the lower gas development during the leaching it can be recycled with less effort.

KEYWORDS

Aluminium, sustainable material, recycling, recycling process, in-house scrap, new and old scrap, metal yield, rotary kiln, salt slag, oxide content, NaCl-KCl-CaF_2-slags, oxides, refiner, re-melter

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[1] Summary of Ph.D. thesis

PROCESSING OF SALT SLAG FROM THE SECONDARY ALUMINIUM PRODUCTION*

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ABSTRACT

The importance of aluminium recycling is evident not only because of the increasing public awareness of questions of sustainability but also due to its much lower energy consumption compared to primary production and its advantage of being recyclable without quality loss. Moreover the amount of solid waste connected with the production of secondary aluminium amounts to only 5% of that of primary production. A residue produced by melting aluminium scrap in a rotary furnace is salt slag. Salt slag consists of salt, oxides and metallic aluminium and is processed in order to separate these components so that their reuse is possible. Two processes applied for the processing of salt slag are described in the following.

KEYWORDS
Secondary aluminium production, rotary furnace, salt slag processing

* Source: Proceedings of CETEM-SEGEMAR, Aachen, 1998

Introduction

Aluminium is today the second most important metal. Only iron is being used more than aluminium. The amount of aluminium used in Germany in 1995 was 1.9 million tons [1].

Primary aluminium is produced from bauxite. Bauxite is being processed into alumina by the Bayer-process which is then reduced to aluminium by electrolysis. The high energy demand of this process is one of the reasons for the great importance of aluminium recycling: Secondary aluminium production consumes only 5% of the energy needed for primary production if salt slag processing is neglected. Including salt slag treatment the energy consumption of secondary production amounts to 12 % of that of primary production. Other advantages of the secondary aluminium production are the fact that aluminium is recyclable without quality loss and the much lower amount of solid waste connected with the secondary production of only 5 % compared to that of primary production. Nevertheless the primary production plays an important role as the aluminium demand cannot be satisfied by secondary production alone. In Germany today the share of secondary production of the total aluminium production is higher than 40% [1].

Although a variety of melting furnaces for aluminium scrap exist the most commonly used furnace type in Germany is the rotary furnace where scrap is melted under a salt layer and salt slag is produced as a residue. The melting process in a rotary furnace will be described in the following.

Scrap melting in a rotary furnace

The most commonly used furnace in the secondary aluminium industry in Germany is the rotary furnace where aluminium scrap is melted under a layer of salt which consists of a mixture of approximately 30% KCl (potash) and 70% NaCl (rock salt) which may also contain small amounts of CaF_2 (fluorspar). This salt layer fulfils a variety of tasks: It enhances the heat transfer to the metal, it prevents the oxidation of the metal and takes up contaminants, such as oxides, carbides and others contained in the scrap or produced by reactions during the melting process.

The amount of salt used for the melting process depends on the scrap characteristics and varies in a range of 300 - 400 kg/t aluminium scrap [2]. First, the salt is melted down in the rotary furnace. Next the scrap is charged into the salt bath. After the metal is molten it is tapped and the salt slag is cast into steel moulds where it cools down.

The advantage of the rotary furnace is that even highly contaminated scrap can be handled. The disadvantages are the high energy demand because in addition to the metal the salt has to be melted and the costs for the processing of the salt slag. Depending on the scrap mix the amount of salt slag produced per ton of secondary aluminium ranges from 400 to 700 kg [3]. It contains contaminants like oxides, carbides and sulphides as well as metallic aluminium which is entrapped in the slag and traces of PCDD/F [4].

Salt slag processing in Germany

As the salt slag produced during the secondary aluminium production may no longer be dumped in Germany because of the danger that toxic substances are leached and gases are emitted it has to be treated. The aim is to win the metallic aluminium and separate the salt from the contamination in order to be able to reuse the components. Several salt slag treatment plants are in operation in Germany. The processes employed there are basically very similar as they all consist of a wet and a dry processing stage. Two different processes will be described in the following.

The first process used at HANSE near Hannover manages to completely reuse the slag so that no waste is produced [5]. The separation of aluminium from the material flow is realised by selective crushing and screening in the dry stage.

The material is fed onto the dry stage by a bucket wheeler. Here the first separation takes place which is the hand-picking of plates and large chunks of metallic aluminium.

Pre-crushing is done by a specially designed impact crusher. On the following conveyer belt large aluminium pieces are hand-picked. After that the material is crushed again in an impact crusher. The material is screened and the fraction > 50 mm is returned to the impact crusher. Further comminution is done in a rod mill which is followed by a 4 mm screen where aluminium particles > 4 mm are separated from the material flow. The < 4 mm fraction is ground in a roller mill stage consisting of nine different mills. The material is ground in 3 stages with the screens behind the mills being 3,25 mm, 2,5 mm and 0,71 mm. The aluminium fractions >3,25 mm, 3,25 - 2,5 mm and 2,5 - 0,71 mm are mixed and make up the fine aluminium product.

The different metal fractions which contain approximately 80% of metallic aluminium are sold to the secondary smelters who produce cast alloys from them. The metal yield of this material is approximately 70% [4].

The residue which consists of salt and oxides is then processed in the wet stage of the plant. Here the salt is at first dissolved at 80 °C for 2-3 hours. 12 - 14 m^3 of water are used per ton of feed in order to bring the salt into solution. About 10 m^3 of hydrogen (H_2), ammonia (NH_4), phosphine (PH_3), hydrogen sulphide (H_2S) and methane (CH_4) are produced per ton of feed material. In order to keep the methane and hydrogen concentrations in the off-gas lower than 4 vol.-% 5000 m^3/hour of air are exhausted.

Ammonia is scrubbed from the off-gas with sulphuric acid. 0,3 m^3 of sulphuric acid are needed per ton of leached material. The ammonium sulphate solution can be sold to the chip-board industry or transformed into crystalline ammonium sulphate which can be used as a fertiliser by vacuum crystallisation. Activated carbon filters absorb the toxic phosphane and the hydrogen sulphide from the remaining off-gas.

After the leaching process the material is fed onto a thickener for four stage thickening. The first stage product is a clear, saturated salt solution overflow. The underflow however is cleaned from salt solution in the three remaining stages. The water fed onto the last thickener stage is the wash water from the following band filters. Flocculants are added into the thickener in order to accelerate the settling velocity.

The underflow of the last stage of the thickener, i.e. the oxide residue, is fed onto the belt filter. It is washed with fresh water twice in order to achieve the required chloride content of 0,2%. The water usage is 6-9 m^3 per hour. The moisture content of the oxide residue is 34-38% behind the belt filters. It is then air dried and sold to cement producers.

The clear, salt saturated overflow solution from the thickener is put into a five stage vaporiser. The first stage vaporises the water at 100 mbar and 125°C. Every following stage is 15° C colder than the preceding, so that the fifth stage only has a temperature of 65 °C. The process is heated by steam. In the last three stages crystals are added which enhance crystallisation.

After the fifth vaporisation stage the salt crystals are dewatered in basket centrifuges. The liquid is again fed to the thickener. The salt product with a moisture content of 3 wt.-% consists of 30% KCl and 70% NaCl and can be reused as fluxing salt for the melting process.

The water-circuit is a completely closed circuit. As the products still contain some moisture and some of the water is lost by vaporisation a certain amount of fresh, decarbonated water has to be added.

The second process employed by Kali + Salz AG is slightly different from the aforementioned one [3]. The differences can mainly be found in the wet processing stage and the products. The main reason for the differences is the fact that this plant is situated next to a potash mine and the residue can be dumped on the potash mine dump.

The salt slag of < 600 mm is being crushed in a four-stage system. Each crushing stage is followed by a screen where aluminium which is reused for secondary aluminium production is separated from the material flow. The material < 0,6 mm consists of salt and oxides and is further processed in the wet processing stage where the potash is at first dissolved at a temperature of 100 °C. The gases produced during the leaching process are cleaned and transformed into ammonium sulphate ($(NH_4)_2SO_2$), sodium phosphate and sodium sulphate. The salt solution resulting from these processes is used for the production of fertilisers in the plant where also the potash from the mine is processed. The cleaned gas consists mainly of methane and hydrogen and is used for steam and electricity production.

The hot potash solution is pumped into the crystallisation plant where the potash is re-crystallised by cooling in a vacuum atmosphere. The dissolved sodium chloride remains in solution and is returned to the leaching stage. The crystallised potash is dried and sold as a fertiliser.

The insoluble oxide and rock salt residue is dewatered by filtration under pressure. This material is used for recultivation purposes of the potash mine dump where the rock salt from the mining operation is dumped. A water-resistant clay layer prevents the heavy metals present in the material from reaching the ground water.

Comparison of the HANSE and the Kali + Salz salt slag treatment process

Both processes are similar in the dry processing stage which consists of selective crushing and screening stages. The product of the dry stage of both processes is aluminium which can be used for secondary production. The main difference can be seen in the leaching process: Whilst the HANSE process brings both rock salt and potash into solution so that the residue consists of oxides only the process employed by Kali + Salz focuses on dissolving and re-crystallising potash so that a residue containing oxides as well as rock salt is produced.

The salt mixture produced by the HANSE process can be reused for melting aluminium scrap in the rotary furnace whilst the oxide product is used in the cement industry. The off-gases are transformed into ammonium sulphate for the chipboard or fertiliser production. The remaining gas is cleaned. The Kali + Salz alternative has the advantage that not only ammonium sulphate is produced from the gases but that moreover hydrogen and methane are used for the production of electricity. The products of this process are potash which is sold as a fertiliser and a mixture of rock salt and oxides which is dumped on the potash mine dump. The reason why, in contrast to the first process, not the complete salt is dissolved and re-crystallised can mainly be seen in the energy demand of the process (480 kWh/t thermal energy and 50 kWh/t electric energy) which is a lot higher than that of the primary production of fluxing salt (10 kWh/t electric energy) [3]. Moreover the fact that the oxide-rock salt residue can be put onto the potash mine dump also plays an important role. The Kali + Salz process is cheaper than the one employed by HANSE which leads to an advantage of Kali + Salz on the market, especially against the background of existing overcapacities for salt slag treatment in Germany.

The Kali + Salz process is very well suited for the combination with a potash mine. For any other circumstance the HANSE process has the advantage that the solids of the salt slag are completely reusable and no dumping is necessary after the treatment whereas a great amount of solids, the oxide and rock salt residue, is dumped in the Kali + Salz process. Therefore most other salt slag treatment plants in Germany operate similar to the HANSE process [4].

The use of the combustible gases for electricity and steam production as realised at Kali + Salz, however, is a very good alternative to ordinary off-gas cleaning.

Summary

Since 1993 the dumping of salt slag which is produced when secondary aluminium alloys are melted in a rotary furnace under a salt layer is no longer possible in Germany. Two salt slag treatment processes are presented. Both manage to separate the components of the salt slag from each other in slightly different ways and with a different focus regarding the reuse of solids and off-gas treatment.

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GRENZEN DES METALLRECYCLINGS*

(LIMITS OF METAL RECYCLING)

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ABSTRACT

This article presents a means of analysis for establishing the feasibility of aluminium recycling and its requirements. Scrap availability is the focal point of the view, since it exerts an influence on all recycling activities and is equally important for all metals. From this, the recycling content of the used metal quantity, which varies regionally and temporally and is product-specific, can be determined. The recycling quota is, by comparison, a more accurate measure for gauging the success of recycling activities. As defined here, it takes into consideration the collection of secondary materials. For both recycled content and recycling quota, the quality of raw materials, i.e. their condition, alloy composition, and recycling technique used can be evaluated. Eventually, the costs for processing secondary raw materials terminate the recycling, again influenced by the metal price, content and quality.

KEYWORDS

Recycling, scrap availability, recycling quota

* Source: Contribution to the course „Nachhaltige Metallwirtschaft“ at Fachhochschule Hamburg, 2000

Einleitung

Die Bedeutung des Recyclings als Bestandteil der Metallversorgung ist unumstritten. Neben den ökonomischen und ökologischen Vorteilen des Einsatzes sekundärer Rohstoffe gibt es eine Reihe von Faktoren, die Aufwand und Nutzen des Recyclings begrenzen. Dies sind unter anderem die Metallgehalte der Vorstoffe, die Entstehung von Sekundärabfällen, die Vielzahl der Legierungstypen, eine steigende Anzahl von Verbundwerkstoffen und die Auswirkungen anwendungsspezifischer Werkstoffbehandlungen auf die erreichbare Metallqualität.

Für die vorgestellten NE-Metalle Aluminium, Kupfer und Zink ist das Recycling sehr unterschiedlich zu bewerten, da in Bezug auf Einsatzbereiche, anfallende Mengen und Verfahrenstechnik erhebliche Unterschiede bestehen. Keines dieser Metalle allein könnte beispielsweise repräsentative Ergebnisse für eine optimale Recyclingquote für Metalle liefern.

Der Beitrag beschäftigt sich mit heutigen und zukünftigen Recyclingpotentialen, gleichermaßen werden die Grenzen des Recyclings diskutiert. Hier sind vor allem die Verfügbarkeit und Qualität sekundärer Rohstoffe sowie technologische Entwicklung bei Aufbereitung und Umschmelzen und ökonomische Faktoren mit ihren vielfältigen Wirkzusammenhängen zu berücksichtigen. Die Bewertung von Recyclingkonzepten wird zusätzlich durch den oft mißverständlichen Gebrauch der beschreibenden Größen erschwert.

Die Verfügbarkeit sekundärer Rohstoffe

Die Versorgung der Metallproduktion mit sekundären Rohstoffen unterliegt vielfältiger Einflüsse, die zunächst am Beispiel Aluminium erläutert werden. Insbesondere Zeit- und Qualitätsaspekte begrenzen die Verfügbarkeit von Sekundärmaterial. Bei einer Analyse der existierenden Metallströme stellt man fest, daß ein weiteres Problem des Recyclings in der Definition von Recyclingquoten und –anteilen und somit in der Beschreibung und Beurteilung von Recyclingaktivitäten liegt. Dieser Beitrag stellt hierzu technisch-metallurgisch basierte Lösungen vor.

Die Differenz zwischen der in Deutschland eingesetzten und produzierten Aluminiummenge ist erheblich, und es stellt sich die Frage, wie der hohe Metallbedarf der verarbeitenden Industrie gedeckt wird und welche Rolle dabei das Recycling spielt. Laut Metallstatistik (Abbildung 1) würde der Recyclinganteil an der Produktion nur 18 % betragen, wobei der gesamten im Halbzeug- und Gußbereich eingesetzten Metallmenge aber nur die Sekundäraluminiumproduktion auf Gußlegierungsbasis gegenübergestellt wird [1]. Dies führt unbestritten zu falschen Schlußfolgerungen.

Zur korrekten Definition der Begriffe des Recyclings ist zunächst eine qualitative und quantitative Beschreibung der Schrottströme aus den Anwendungsgebieten in die bestehenden Recyclingpfade wichtig. Zu beachten ist dabei die Aufteilung der Aluminiumwerkstoffe in zwei Legierungsgruppen. Bei den Gußlegierungen ist der Gehalt an Legierungselementen, vor allem Silizium und Kupfer, hoch, Knetlegierungen sind dagegen niedriger legiert, meist mit Magnesium und Mangan und sollten deshalb möglichst sortenrein in den Recyclingkreislauf gelangen.

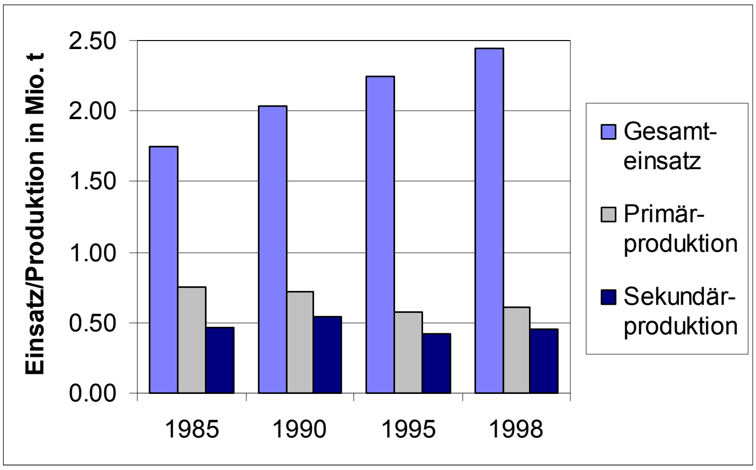


Abbildung 1: Entwicklung von Gesamteinsatz, Primär- und Sekundärproduktion von Aluminium in Deutschland [1]

Der stofflichen Trennung sind aber durch Anwendung und Erfassung Grenzen gesetzt. Abbildung 2 zeigt den deutschen Einsatz von Guß- und Knetlegierungen, der eindeutig vom Verkehrssektor dominiert wird [2]. In jedem dieser Anwendungsbereiche, mit Ausnahme des Verpackungsbereichs, fallen nach der Nutzung Guß- und Knetlegierungen an, die oftmals vermischt sind.

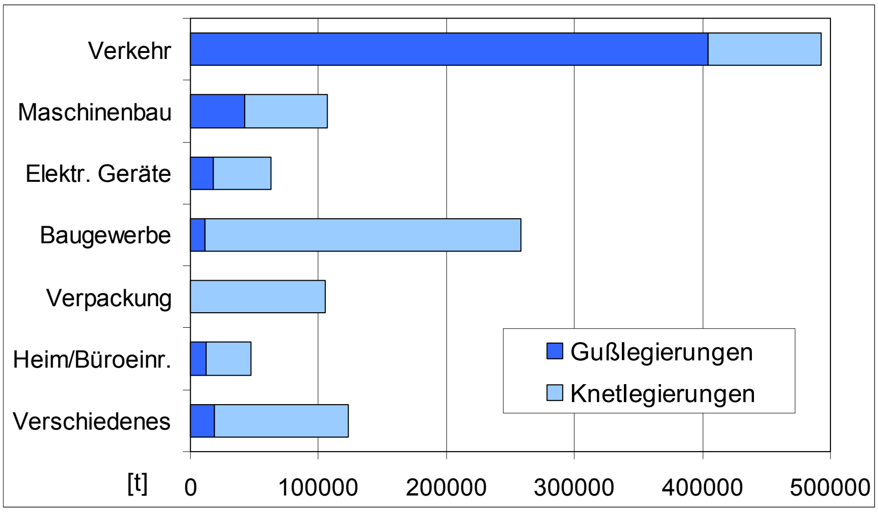


Abbildung 2: Verwendung von Aluminiumguß- und -knetlegierungen 1997 [2]

Bei der Betrachtung einzelner Anwendungsbereiche müssen weiterhin geschlossene und offene Recyclingkreisläufe werden: Closed-loop-recycling existiert, wenn Schrotte einem vergleichbaren Wiedereinsatz zugeführt werden. Open-loop-recycling liegt vor, wenn sekundäre Rohstoffe nach der Verhüttung einer anderen Nutzung meist auch in Form anderer Legierungen zugeführt werden. Hierbei sind insbesondere die Schmelzhütten (Refiner) zu nennen, die beispielsweise aus einem Gemisch unterschiedlichster Alt- und Neuschrotte Gußlegierungen für die Automobilindustrie herstellen.

Neben diesen „idealisierten“ Zuständen existiert ein stofflicher und räumlicher Übergangsbereich. Stofflich, da Knetlegierungen zu Gußlegierungen verarbeitet werden und damit eine werkstofftechnische Veränderung erfahren. Räumlich, da Produktionsschrotte nicht nur firmenintern, sondern auch extern aufgearbeitet werden und somit nicht in einem geschlossenen Kreislauf verbleiben. Sortenreine Knetlegierungsschrotte werden dabei gezielt von den Umschmelzhütten (Remelter) zu Walz- und Preßbarren verarbeitet, die in geschlossene und offene Recyclingkreisläufe gelangen. Vermischte und verunreinigte Schrotte werden ausschließlich durch die Schmelzwerke (Refiner) zu Gußlegierungen verarbeitet und gelangen somit in offene Recyclingkreisläufe [3].

Während der Nutzung sind Metalls in Depots gebunden. Die Depotmenge für Aluminium wird weltweit auf 700 Mio. t geschätzt. Die Verteilung ist dabei räumlich, stofflich und zeitlich ausgeprägt. Die Depoteigenschaften des Aluminiums können anhand ausgewählter Produktgruppen, Produkte, Produktteile oder Nutzungsarten beschrieben werden (Tab. 1). Für Verpackungen liegt beispielsweise eine hohe räumliche Verteilung bei kleiner Produktgröße und großer Ausbreitung vor. Die stoffliche Reinheit kann dabei hoch (Menüschale, Getränkedose), mittel (Verschlußkappen, lackierte Folien) oder gering (bedampfte Chipstüten, Tetrapack) sein. Die Verweilzeit ist mit einer mittleren Lebensdauer von einem halben Jahr gering [4].

Depoteigenschaften		**Verpackung**	**Verkehr** Zug/Flugzeug	Auto	**Bau**	**Masch.-bau**	**Elektrotechnik**
räumlich	Größe	gering	hoch	mittel	hoch	mittel	mittel
	Ausbreitung	hoch	gering	hoch	mittel	mittel	hoch
stofflich	Reinheit	variiert	hoch	gering	hoch	mittel	variiert
zeitlich	Verweilzeit	gering	hoch	mittel	hoch	hoch	variiert

Tabelle 1: Depoteigenschaften von Aluminium in ausgewählten Nutzungsbereichen [4]

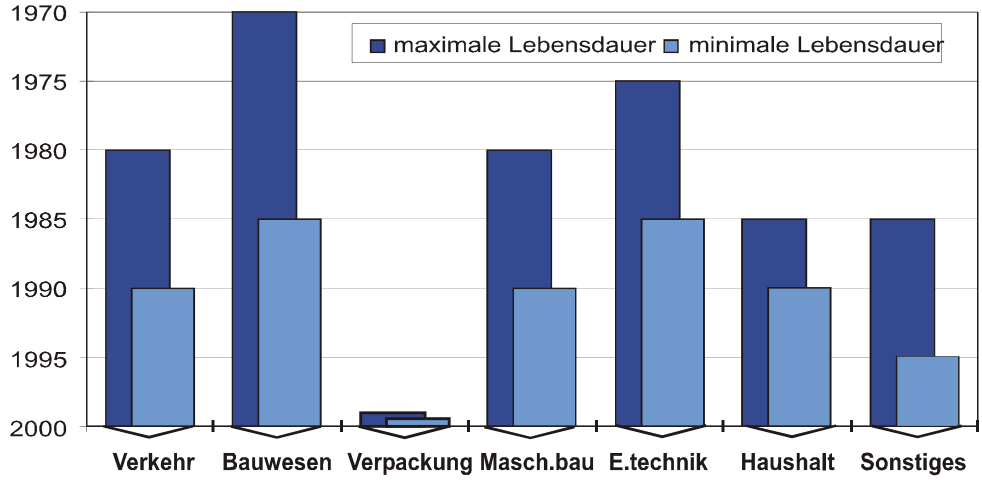
Den zeitlichen Aspekt verdeutlicht die Darstellung von Lebensdauer, Recyclingquoten, Rücklaufmengen und resultierender Differenz zum derzeitigen Bedarf in den verschiedenen Anwendungen in Abbildung 3. Demnach fallen heute z.B. Schrotte aus dem Maschinenbau an, die zwischen 1980 und 1990 produziert wurden. Lediglich die erwähnten Verpackungsmaterialien gelangen im gleichen Bilanzzeitraum in den Sekundärkreislauf zurück. Die Differenz zwischen anfallender Schrottmenge und benötigtem Metall vergrößert sich auch aufgrund der hohen Zuwachsraten im Aluminiumeinsatz.

Die Ermittlung des Schrottaufkommens basiert auf den Depotmengen für einzelne Anwendungen und deren Recyclingquoten. Der aus dieser Abschätzung resultierende Recyclinganteil würde für eine vollständige Erfassung der Schrotte 60% betragen. Ursache für den Unterschied zu dem zuvor genannten Wert von 18% ist allein die Bestimmung der Recyclingquote. Hierzu einige Definitionen [5, 6]:

Für das Metallrecycling setzt sich die Recyclingquote aus der Erfassungsquote und der technischen Recyclingquote zusammen. Diese Trennung verdeutlicht die unterschiedlichen Ebenen des Recyclings und läßt eine ressourcenorientierte Betrachtung zu.

Die Erfassungsquote EQ ist dabei die Menge an verfügbarem Sekundärmaterial, welches über Sammelsysteme erfasst wird, bezogen auf die produzierte Menge.

$$EQ = \frac{\text{gesammelte Menge}}{\text{produzierte Menge}} \cdot 100\%$$



	Verkehr	Bauwesen	Verpackung	Masch.bau	E.technik	Haushalt	Sonstiges
Recyclingquote	85%	90%	65%	85%	85%	80%	50%
Rücklaufmenge nach mittlerer Lebensdauer	337.500 t	158.400 t	71.500 t	67.200 t	61.200 t	50.400 t	70.000 t
Differenz zum heutigen Einsatz	235.000 t	120.000 t	35.000 t	58.000 t	2.000 t	40.000 t	60.000 t

Abbildung 3: Recyclingquoten und Rücklaufmengen aus verschiedenen Anwendungen bei vollständiger Erfassung

Technische Recyclingquote RQt bestimmt die Menge an Material, welches nach der Sammlung tatsächlich als Recyclingmetall zur Verwertung gelangt, d.h. es handelt sich um das Ausbringen des technischen Gesamtprozesses.

$$RQ_t = \frac{\text{produzierte Menge an Sekundärmaterial}}{\text{der Verwertung zugeführte Menge}} \cdot 100\%$$

Die technische Recyclingquote setzt sich aus zwei Teilen zusammen, der Aufbereitungsquote, die angibt wie viel erfasstes Aluminium für das Schmelzen bereitgestellt wird, und der Schmelzausbeute, die angibt, wie viel Aluminium daraus als Flüssigmetall gewonnen wird, d.h. hierin sind die endgültigen Verluste in der anfallenden Salzschlacke oder Krätze berücksichtigt. Zusammen ergeben die Quoten aus Erfassung, Aufbereitung und Schmelzen die ressourcenorientierte Recyclingquote (Abbildung 4).

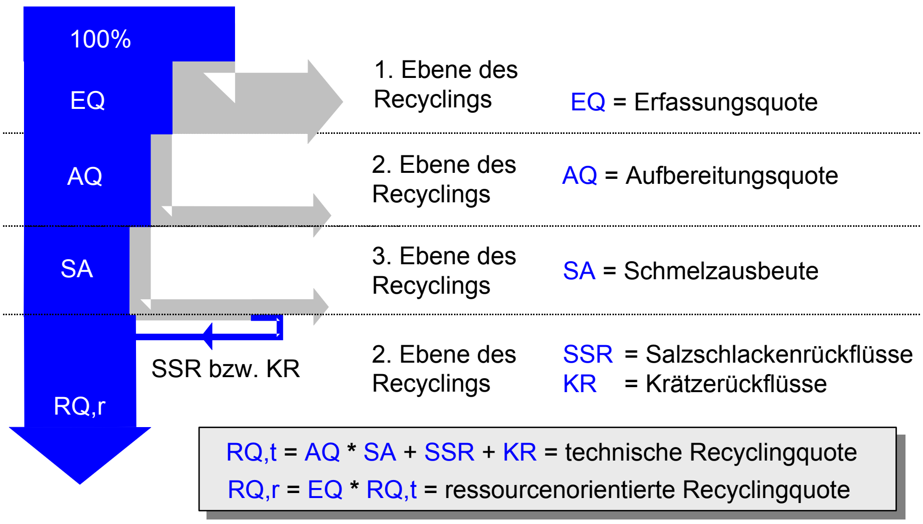


Abbildung 4: Definition der Recyclingquoten für Erfassung, Aufbereitung und Schmelzen [5]

Am Beispiel des deutschen Verpackungsrecyclings lassen sich die verschiedenen Ebenen des Recyclings veranschaulichen. 1997 betrug der Verbrauch an Leichtverpackungen (LVP) 1.778.198 t [6]. Von den gebrauchten Verpackungen wurden 1.582.596 t erfaßt, was einer Erfassungsquote von 89 % entspricht. In den Sortieranlagen werden Kunststoffe, Weißblech und Verbunde aussortiert und eine Al-Fraktion (LVP Al40) zur weiteren Verwertung in mechanischer Aufbereitung, Verbundstoffaufbereitung oder Pyrolyse bereitgestellt. Die Sortierquote beträgt 80,6 % und die Aufbereitungsquote für die Al-Fraktion 91,1 %. Der Metallrückfluss aus Salzschlacken- (SSR) und Krätzeaufbereitung (KR) beträgt 1,7 %. Die technische Recyclingquote liegt somit bei 68,4 % und die ressourcenorientierte Recyclingquote bei 61,7 %.

Für die Nutzungsbereiche von Aluminium sind die ermittelten Quoten sehr unterschiedlich [4]. Dabei reicht die Spanne der Erfassung von ca. 25% für den Aluminiuminhalt des Siedlungsabfalls bis nahezu 100% der Menge aus dem Bausektor und wird so zu der entscheidenden Größe für eine möglichst effiziente Ausnutzung sekundärer Rohstoffe (Abb. 5).

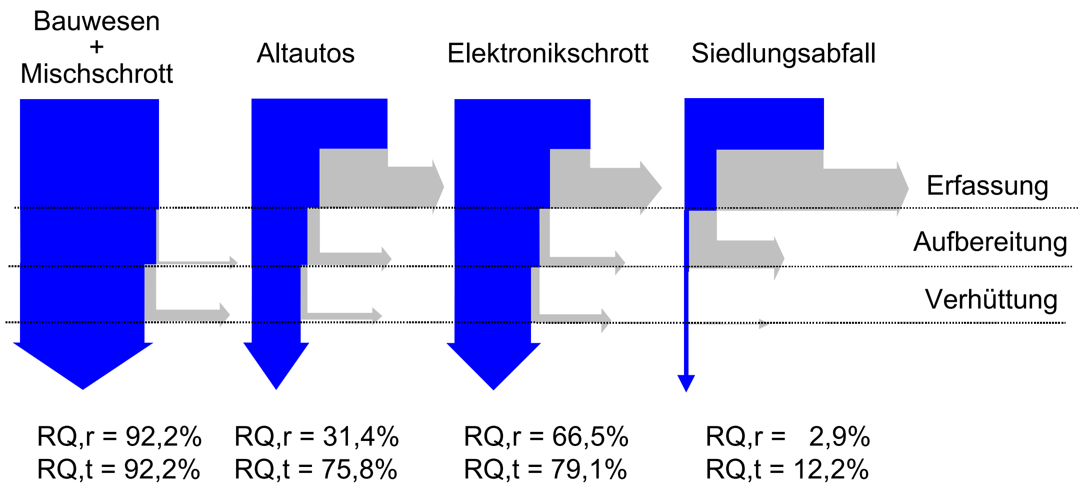


Abbildung 5: Auswahl technischer und ressourcenorientierter Recyclingquoten für Aluminiumprodukte [6]

Die Recyclingquote definiert den wiedergewinnbaren Metallanteil der eingesetzten Werkstoffe bzw. Bauteile. Im Unterschied dazu ist der Recyclinganteil der zur Verarbeitung eingesetzte Anteil an Sekundärmetall. Wird die Erfassungsquote zur Ermittlung des Recyclinganteils im Gesamtsystem Aluminium berücksichtigt, sinkt dieser von 60 auf 46 % (vergl. Abbildung 3). Der Recyclinganteil liegt immer dann deutlich unter der Recyclingquote, wenn bei steigendem Metalleinsatz mehr Primärmetall erzeugt werden muss, als es den Verlusten während der Nutzung entspricht. Der Recyclinganteil ist jedoch als Maß für den Recyclingerfolg ungeeignet, da er eine regionale Größe darstellt, die vom existierenden offenen Schrottmarkt und dem steigenden Metallbedarf in der Anwendung stark verfälscht wird.

Qualitätseinfluß sekundärer Rohstoffe auf das Recycling

Neben der Verfügbarkeit ist auch die Qualität der Vorstoffe, d.h. ihre Beschaffenheit und vor allem ihr Legierungszustand für das Recycling von entscheidender Bedeutung.

Aluminium: Eine Raffination des unedlen Aluminiums ist nur eingeschränkt möglich und Begleitmetalle wie Eisen, Mangan, Silizium, Magnesium, Kupfer und Zink bleiben überwiegend in der Metallphase gelöst. Aus diesem Grund wird bei der Primärerzeugung die Raffination vor der Reduktion durchgeführt, beim Recycling bedeutet dies eine Trennung der Schrotte nach Legierungsart und Reinheit bereits vor dem Schmelzen. Danach bleibt nur das Verdünnen mit Hüttenmetall oder das Verschneiden unterschiedlicher Schmelzen als Möglichkeit der Legierungseinstellung.

Als Folge des verstärkten Recyclings von Knetlegierungen bei den Umschmelzbetrieben lässt die Schrottversorgung der deutschen Aluminiumschmelzwerke (Abb. 6) in den Jahren 1975-1999 abnehmende Anteile an Neuschrott erkennen, deren Anteil sich auf 30 % verringerte, während der Anteil an Altschrott sich gegenläufig entwickelte [7].

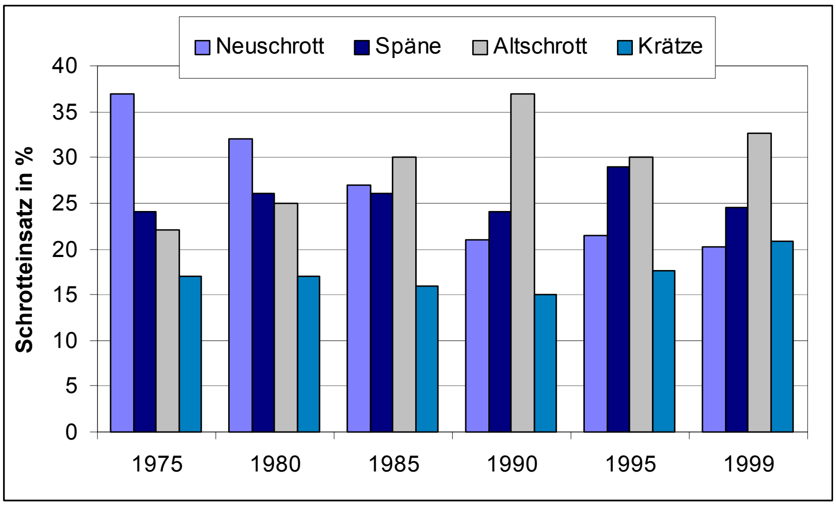


Abbildung 6: Entwicklung der Schrottversorgung der deutschen Aluminiumschmelzwerke von 1975 bis 1999 [7]

Für das Beispiel Aluminium verdeutlicht die Schrottbilanz 1997 in Abbildung 7 die Aspekte der Schrottverfügbarkeit und der Qualität. Zunächst ist ein geringer Exportüberschuß zu erkennen, der sich aus Altschrotten, Bearbeitungsabfällen und Spänen zusammensetzt. Für die Sekundäraluminiumproduktion wurden ca. 400.000 t Schrott (Al-Gehalt) eingesetzt, wovon etwa 70.000 t Knetlegierungen sortenrein umgeschmolzen wurden. Weitere Knetlegierungen wurden in den Gießereien der Primärhütten (174.900 t) und der Halbzeugwerke (190.000 t) umgeschmolzen [8, 9]. Der Produktionsschrottanfall von ca. 920.000 t wird in der Halbzeugfertigung als Kreislaufmaterial direkt wieder eingesetzt und somit statistisch nicht erfaßt.

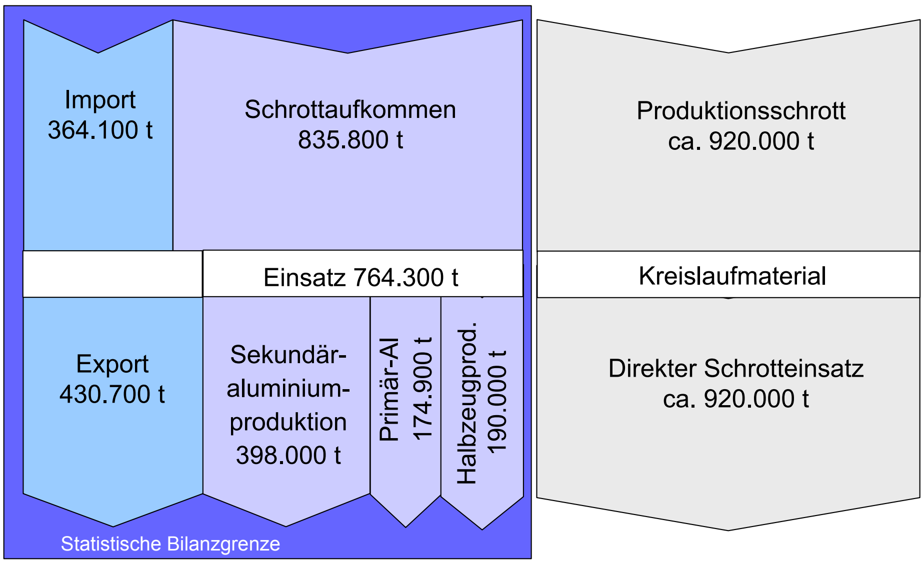


Abbildung 7: Schrottbilanz 1997 [8, 9]

Der gezeigte Schrotteinsatz zuzüglich einer importierten Menge von 168.000 t Sekundäraluminium und dem Schrottanteil des ausländischen Primärmetalls ergibt schließlich einen realen

Recyclinganteil an der deutschen Gesamtproduktion von 37 %. Dieser ist ein mengenbezogener Mittelwert der einzelnen Anwendungsgebiete. Die Wechselwirkung zwischen den Produktbereichen läßt sich durch die existierenden Schrottströme quantifizieren (Abb. 8). Es ergibt sich eine Legierungskaskade, wobei unlegiertes Aluminium den Ausgangspunkt bildet. Es hat demnach den geringsten Recyclinganteil. Ein Absenken des Legierungszustandes, d.h. eine Umkehr der üblichen Versorgungsrichtung in Abbildung 9 ist nur mit einem der Primärerzeugung vergleichbaren Aufwand möglich.

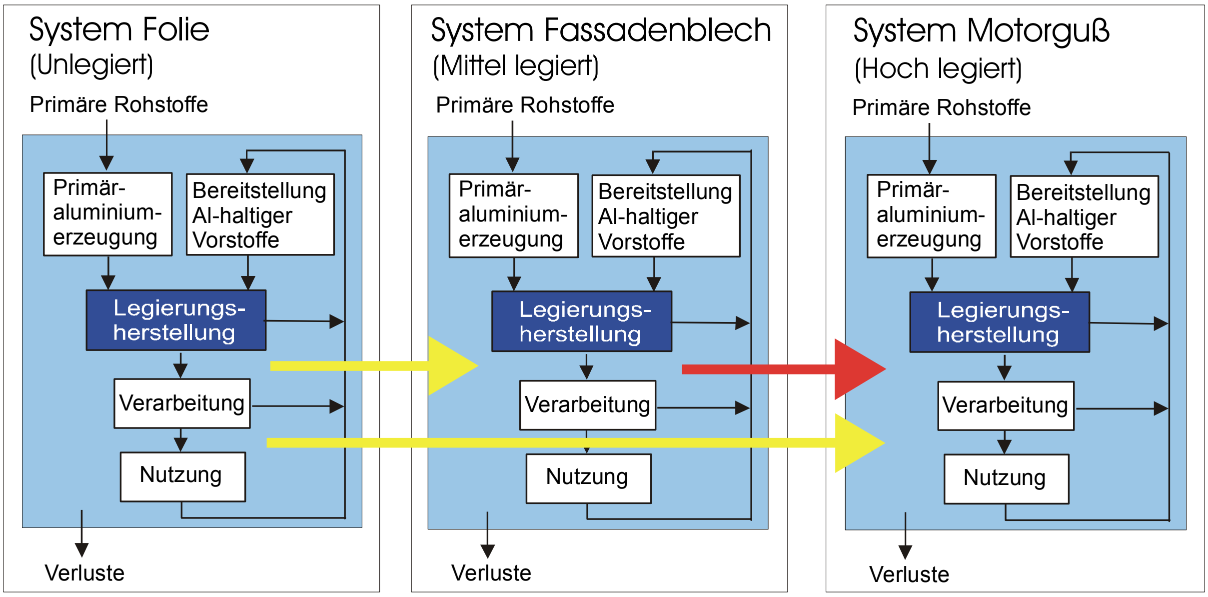


Abbildung 8: Wechselwirkung zwischen den Recyclingsystemen

Letztlich kann also der Erfolg von Recyclingaktivitäten nur an der wiedergewonnenen Metallmenge und somit an der Einsparung von Primärmetall im Gesamtsystem Aluminium gemessen werden. Darüber hinaus wirken die sortenreine Erfassung und Aufbereitung einer Anreicherung von Legierungselementen im Recyclingkreislauf entgegen und erhalten somit die größtmögliche Einsetzbarkeit der durch die Verknappung ohnehin teuren Sekundärrohstoffe.

Kupfer: Für die Metallversorgung der kupferverarbeitenden Industrie in Deutschland von 1,14 Mio. t 1998 ergibt sich eine ähnliche Importabhängigkeit wie für Aluminium, hier lag jedoch die Sekundärproduktion mit 370.000 t bereits über der Primärproduktion (320.000 t), die ebenfalls große Mengen sekundärer Rohstoffe einsetzt [1]. Der Recyclinganteil an der deutschen Gesamtproduktion liegt bei 51 %

Das Recycling von Kupfer kann sowohl in reinen Sekundärhütten als auch in Primärhütten stattfinden, die Aggregate und Zwischenprodukte der Sekundär- und Primärhütten sind dabei ähnlich oder gleich. Es wird zwischen metallischen Kupfer- und -legierungsschrotten sowie Vorstoffen mit nichtmetallischen Kupfergehalten unterschieden. Zu den metallischen Sekundärrohstoffen zählen reine und hochkupferhaltige Schrotte sowie kupfer/eisenhaltige Verbunde. Schlacken, Aschen und kupferhaltige Schlämme der Galvanikindustrie (mit Kupfergehalten unter 30 %) sind nichtmetallische Rohstoffe. Je nach ihrem Kupfergehalt und der chemischer Zusammensetzung werden diese Vorstoffe in unterschiedliche Prozeßebenen eingesetzt (Abb. 9). Nur etwa 28 % der Vorstoffe sind nichtmetallischer, oxidischer Art und müssen unter hohem Kokseinsatz zunächst reduziert werden.

Durch die anschließende elektrolytische Raffination ist die Qualität des Kupfers identisch, so daß eine direkte Substitution der primären Rohstoffe erreicht wird. Dies ist insbesondere zu beachten da der Energieeinsatz für Primär- und Sekundärproduktion (für einen repräsentativen Vorstoffmix) mit 21,8 bzw. 20,5 GJ/t Kathodenkupfer nahezu gleich hoch ist, der Kupferbergbau aufgrund der niedrigen Erzgehalte jedoch zusätzlich 35 MJ/t Kupferinhalt im Konzentrat benötigt [10].

Kupfer besitzt demnach einfachere Voraussetzungen für hohe Recyclingquoten, da es hauptsächlich in rein metallischer Form eingesetzt wird, wie z.B. in Drähten und Rohren. Ebenso können die wichtigsten Legierungen Messing und Bronze in reiner Form umgeschmolzen werden. Der elektrochemisch edle Charakter des Kupfers und die damit verbundenen exzellenten Raffinationseigenschaften lassen darüber hinaus eine Rück-gewinnung auch aus sehr niedrig kupferhaltigen Vorstoffen mit hoher Metallausbeute zu.

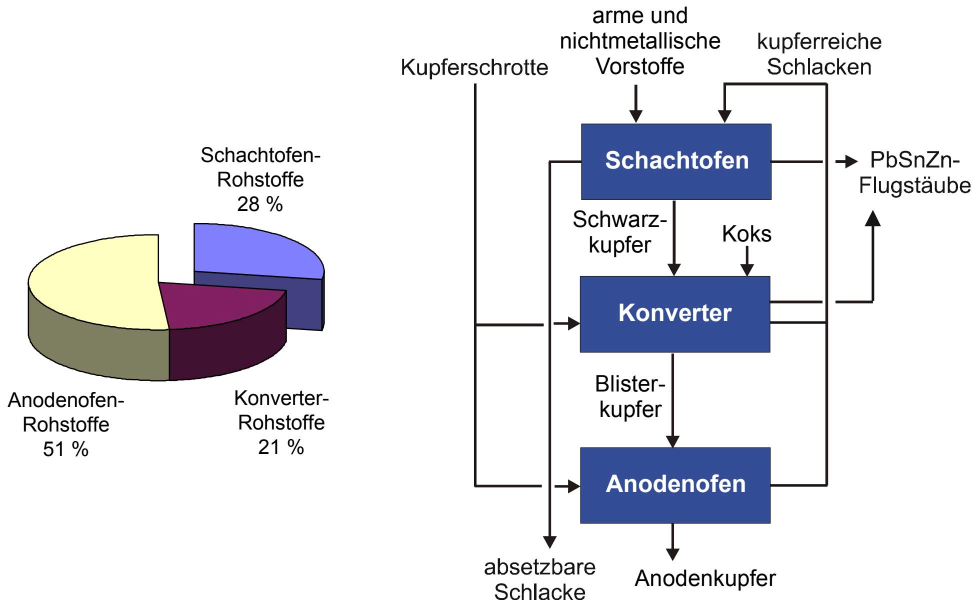


Abbildung 9: Verteilung der Vorstoffe auf die Prozeßstufen der Sekundärkupfererzeugung

Zink gelangt meist nur auf Umwegen in der Recyclingkreislauf, da es überwiegend als Legierungselement (Messing) oder als Beschichtung auf Stahlbauteilen eingesetzt wird. Nur ca. 22 % der Zinkproduktion werden zu Halbzeugen oder Gußstücken verarbeitet (Tab.2) [11]. Darüber hinaus wird Zink als aktiver Korrosionsschutz oder Chemikalie verbraucht und steht somit aus diesen Anwendungen dem Recycling nicht mehr zur Verfügung.

Anwendung	Anteil
Verzinkung	47 %
Messing	19 %
Zinklegierungen	14 %
Halbzeuge	8 %
Chemikalien	9 %

Tabelle 2: Anwendungsgebiete für Zink [11]

Insgesamt liegt der Recyclinganteil an der weltweiten Gesamtproduktion aufgrund der gezeigten Anwendungen nur bei 18 %. In Deutschland liegt der Anteil an Sekundärmaterial mit 49 % deutlich höher, allein 21 % der Primärzinkerzeugung stammen aus sekundären Rohstoffen. Dies wird größtenteils durch die Einschleusung von Wälzoxid aus der Aufbereitung zinkhaltiger Stahlwerksfilterstäube in die hydrometallurgische Primärerzeugung erreicht (Abb. 10).

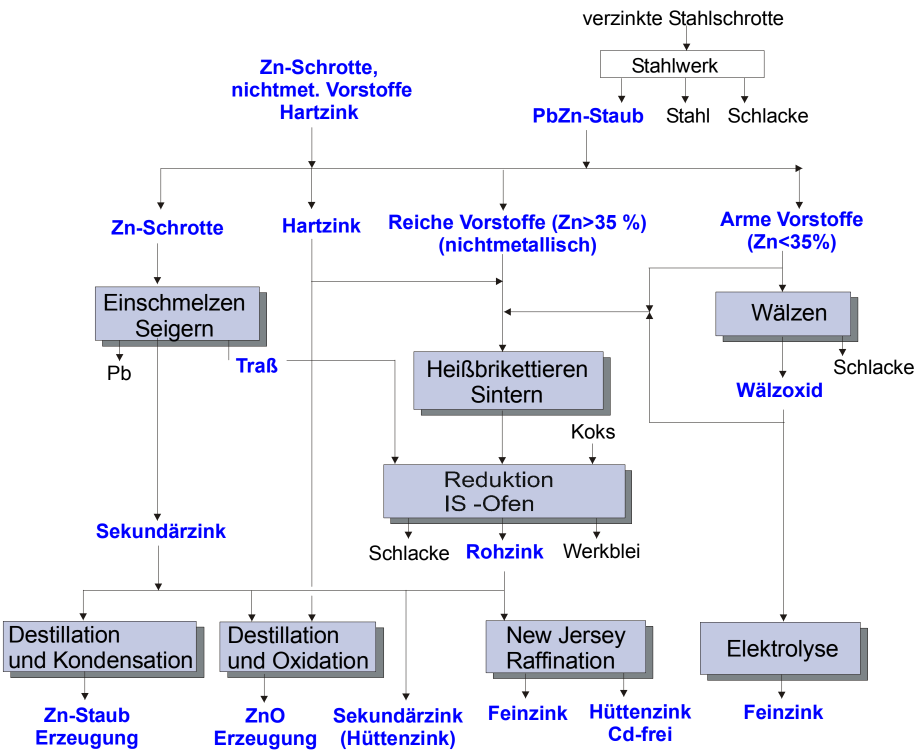


Abbildung 10: Verfahrensschema der Sekundärzinkerzeugung

Technologische Entwicklung

Am Beispiel der Aluminiumverpackungen lassen sich die aus technologischer Entwicklung resultierenden Potentiale verdeutlichen. Die Al-Fraktion aus den Sortieranlagen, mit 40 % Aluminiumgehalt und überwiegend organischem Rest ist schmelzmetallurgisch nicht zu verarbeiten. Durch die Kombination mechanischer und thermischer Aufbereitungsverfahren gelingt es jedoch, eine hochwertige Fraktion mit ca. 99 % Al herzustellen, die mit einer Schmelzausbeute von über 90 % verarbeitet werden kann. Die Aufbereitungsquote liegt jedoch mit insgesamt 73,4 % relativ niedrig. Durch den Einsatz einer vollautomatischen Sortierung könnte allein das Ausbringen dieser Stufe von 80,6 auf 94 % gesteigert werden. Prozessspezifisch steigt dann zwar der Energieverbrauch, bezogen auf die größere Produktmenge kehrt sich dies jedoch zu einem Vorteil um.

Szenariorechnungen zeigen, daß sich bei entsprechender Schmelztechnik für die zukünftigen Recyclingkonzepte NT (ausschließlich neueste Technologie) und deren mögliche Umsetzung im Jahr 2010 Einsparpotentiale von 2000 bzw. 1370 MJ/t erzeugter Legierung ergeben, bei einer Erhöhung der Aluminiummenge um 20 bzw. 4 % (Abb. 11) [12, 13].

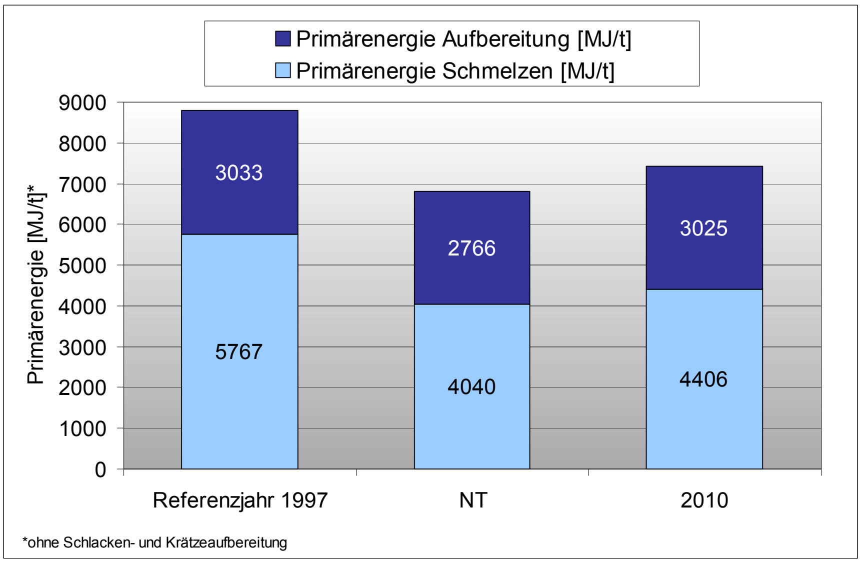


Abbildung 11: Vergleich des Primärenergieaufwands heutiger und zukünftig möglicher Konzepte zum Verpackungsrecycling [12, 13]

Der Energieaufwand begrenzt jedoch eine weitere Steigerung der Aufbereitungsquote ab ca. 90 % (Abb. 12), da dann neben technischen Verbesserungen zusätzliche Aufbereitungsschritte für Sortierreste und Aufbereitungsabgänge erforderlich werden.

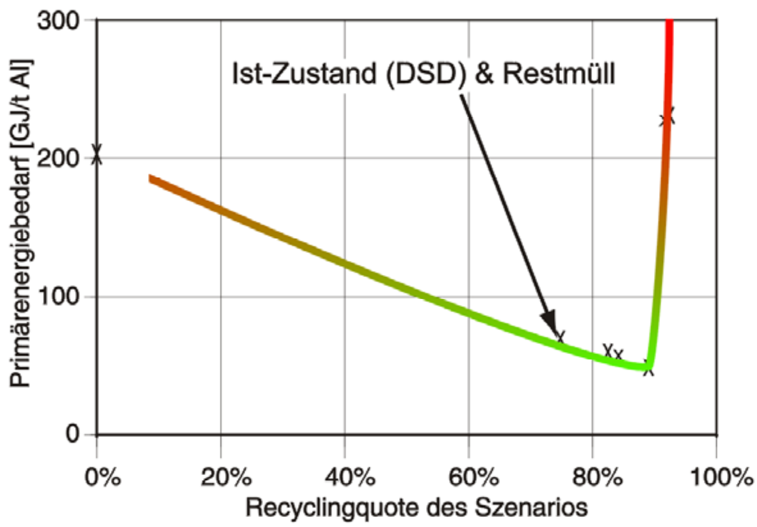


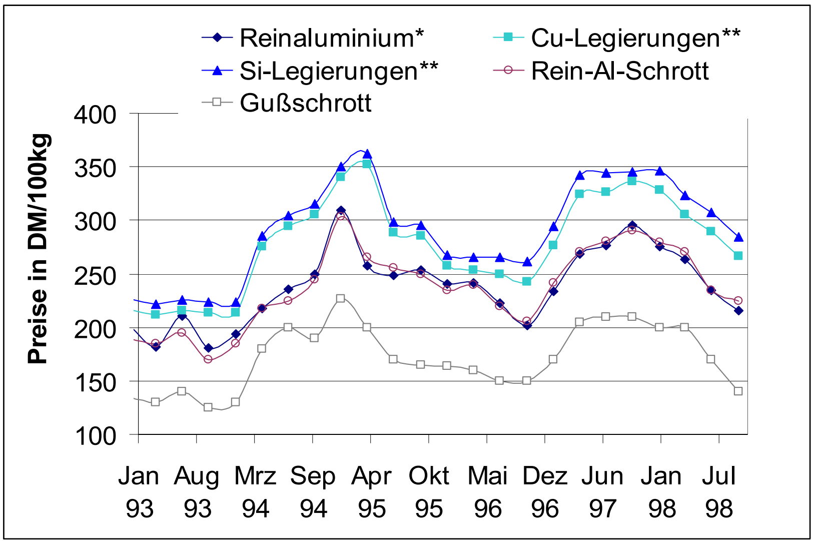
Abbildung 12: Primärenergiebedarf in Abhängigkeit von der Recyclingquote am Beispiel von Aluminium in Leichtverpackungen [12]

Hieran schließen sich auch für andere Metalle weitere Fragen nach den Grenzen des Recyclings an. Stehen der hohe Aufwand für die Behandlung bestimmter Materialien auch bezüglich entstehender Emissionen und Abfälle im richtigen Verhältnis zum erzielten Ergebnis? Ist es sinnvoll Stoffkreisläufe um jeden Preis zu schließen? Solche Fragen lassen sich ebenfalls nicht pauschal beantworten und verdeutlichen die gezeigte Notwendigkeit einer differenzierten Betrachtung der jeweiligen Produktionslinien.

Grenzen wirtschaftlicher Einsetzbarkeit

Die Wirtschaftlichkeit des Metallrecyclings ist durch die Differenz zwischen Schrottpreis und erzielbarem Verkaufspreise der verschiedenen Umschmelzlegierungen bestimmt. Der Preis für Umschmelzlegierungen ist speziellen Einflüssen unterworfen, z. B. der Verfügbarkeit bestimmter Schrottsorten auf der Produktionsseite und insbesondere der Konkurrenzsituation auf der Verbraucherseite. Die Preisfindung für Schrotte geht momentan noch von der Basis genormter Gußlegierungen, d.h., von den Produkteigenschaften aus, wobei dann bestimmte Abschläge je nach Metallgehalt, Legierung und Verunreinigungsgrad des Schrottes verrechnet werden. Bei der großen Anzahl der gehandelten Gußlegierungen und der firmenspezifischen Anforderungen kann der angegebene Preis für die Gußlegierungen allenfalls als Anhaltswert betrachtet werden [14].

Die Preisentwicklung im Zeitraum von 1993-1996 für Reinaluminium- und Gußschrott auf der einen und Reinaluminium, siliziumhaltige und kupferhaltige Umschmelzlegierungen (Abb. 13) zeigt den gemeinsamen Trend, d.h. die relativ konstante Differenz der Preise für Gußschrott und kupfer- und siliziumhaltigen Legierungen.



(*LME-Kassanotierung für unverzollte Ware **Kleinmengen bis 3 t

Abbildung 13: Preisvergleich zwischen Reinaluminium, Si- und Cu-haltigen Legierungen sowie Schrott aus Reinaluminium und Guß von 1993 bis 1998 [16]

Wenn sich auch die Preise für Reinaluminium (Al 99,7) und Reinaluminiumschrott ähnlich verhalten, sind sie doch stärkeren Schwankungen unterworfen.

Da die Kosten für das Recycling weitgehend unabhängig vom Metallpreis sind, steuern sie den Ertrag. Dieser hängt zusätzlich von der Qualität der Sekundärrohstoffe ab (Abb. 14). Ist sie hoch, ist zwar auch der Schrottkaufpreis hoch, der Erlös kann jedoch durch die geringen Aufbereitungs- und Schmelzkosten gegenüber minderwertigeren Vorstoffen erhöht werden.

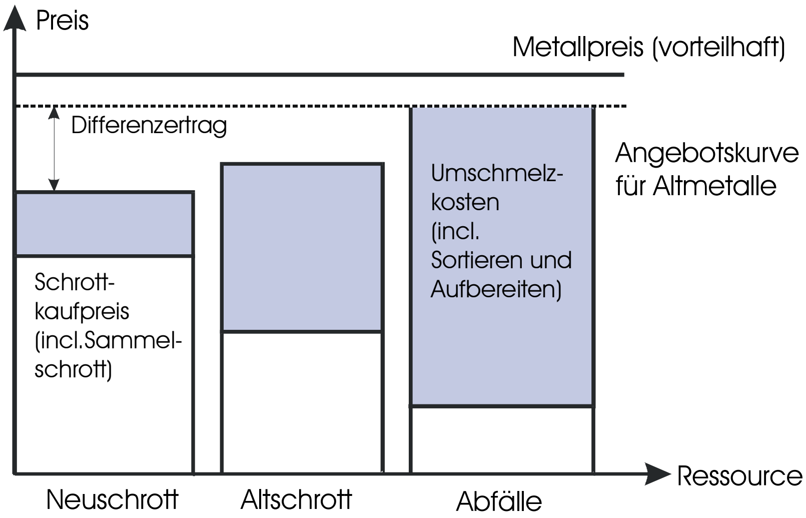


Abbildung 14: Zusammenhang zwischen Schrottpreis, Umschmelzkosten und Differenzertrag für verschiedene Schrotte [17]

Für das Umschmelzwerk wird der Grenzpreis des Metallschrotts durch dessen Gebrauchswert im metallurgischen Prozeß bestimmt. Dieser hängt neben dem Metallpreis von der Beschaffenheit der Vorstoffe, der Auslastung des Werks und den technischen Parametern der Anlage ab. Sinkende Metallpreise führen schließlich bei Erreichen des Grenzpreises wieder zu größeren Inventaren.

Der Umschmelzer ist daran interessiert, so präzise Informationen wie möglich über die Zusammensetzung der Schrotte zu bekommen, um die Risiken der Preiskalkulation zu begrenzen. Andererseits verkauft der Altmetallhändler sein Produkt an die Sekundärhütte, für die es den höchsten Gebrauchswert besitzt. Er muß dann die Qualität des Vorstoffes garantieren, woraus sich die Notwendigkeit einer stärkeren Differenzierung bei der Erfassung der Schrotte ergibt oder die Investition in Zerkleinerungs- und Sortieranlagen.

Ungeachtet der erzielten und möglichen Produktivitätssteigerungen bei Erfassung und Aufbereitung gibt es einen Punkt, ab dem der Gebrauchswert sekundärer Rohstoffe zu niedrig ist, um diese Kosten zu decken. Bei einigen Rückständen und minderwertigen Abfällen, wie z.B. Stahlwerksfilterstäube, ist dieser Punkt bereits erreicht. Hier stellt sich dann die Frage, wie die Kosten für ein solches subventioniertes Recyclingkonzept getragen werden [17].

Aus dieser Betrachtung lassen sich für die diskutierten Metalle Grenzgehalte in den sekundären Rohstoffen ableiten, Tabelle 3. In Anlehnung an die Kaufformeln für Konzentrate wird den Berechnungen der Wert des gewinnbaren Metallinhalts zu Grunde gelegt. Darüber hinaus werden Zuzahlungen für die Entsorgung minderwertiger metallhaltiger Abfälle berücksichtigt, die einen Einsatz solcher Vorstoffe erst ermöglichen.

Al	50 % Al (ohne Aufbereitung) Metallinhalt nach Abzug des Schmelzverlust: 40 % Metallwert: 900 DM/t Material Schmelzkosten: 700-1400 DM/t Material
Cu	1. 2% Metallwert: 75 DM/t Material + 200 DM/t Zuzahlung 2. 3 % Cu, (10 ppm Au, 50 ppm Ag) Metallwert (verlustfrei): 110+160+15 = 285 DM/t Material 3. 7,5% Cu Metallwert: 285 DM/t Material Schmelzkosten: 250 DM/t Material Raffinierkosten: (250 DM/t Kupfer) 10 bzw. 20 DM/t Material gesamt 260 bzw. 270 DM/t Material
Zn	Oxidische Vorstoffe: 23% Zn (+ Pb) Metallwert nach Abzug des Schmelzverlust: 260 DM/t Material + 100 DM/t Zuzahlung (anteilig) = 300 DM/t Material Wälzkosten: 250 DM/t Material Raffinierkosten: (500 DM/t Metall) 60 DM/t Material gesamt 310 DM/t Material

Tabelle 3: Grenzgehalte wirtschaftlicher Einsetzbarkeit für aluminium-, kupfer- und zinkhaltige Sekundärrohstoffe (Metallpreise 5/2000)

Zusammenfassung

Der Beitrag zeigt verschiedene Grenzen des Metallrecyclings für Aluminium, Kupfer und Zink auf. Im Mittelpunkt steht die Schrottverfügbarkeit, das sie einen für alle Metalle gleichermaßen wichtigen Einfluß auf die Recyclingaktivitäten ausübt. So lässt sich der Recyclinganteil an der verarbeiteten Metallmenge ermitteln, der regional, zeitlich, produkt- und metallspezifisch variiert. Die Recyclingquote ist dagegen ein überwiegend technikspezifisches Maß für den Erfolg von Recyclings, bei dem auch die Erfassung sekundärer Vorstoffe berücksichtigt werden muß. Die Technik selbst kann eindeutig über Metallausbringen und Energieeinsatz beschrieben werden. Für Recyclinganteil und -quote ist die Qualität der Vorstoffe, d.h. die Beschaffenheit, der Legierungszustand und der Metallgehalt von Bedeutung. Schließlich begrenzen die Verarbeitungskosten sekundärer Rohstoffe das Recycling, die wiederum von Metallpreis, Metallinhalt und Qualität beeinflußt werden.

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RECYCLING OF ALUMINIUM FROM OBSOLETE CARS: ECONOMIC, TECHNICAL AND ECOLOGICAL ASPECTS*

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ABSTRACT

In Germany the recovery of aluminium from obsolete cars follows two different paths.
Aluminium is dismantled by companies specialised on the recycling of cars. This occurs for large and valuable parts containing aluminium such as engine blocks and tires.
The remaining aluminium is recovered by a two-stage process: first, the obsolete car is shredded and the aluminium goes to the non-ferrous metal fraction of the shredding process. Secondly, the non-ferrous metal fraction is processed in sink-float plants where aluminium and heavy non-ferrous metals are recovered. Afterwards the aluminium is sold to secondary aluminium smelters.
The technical recycling quota for the aluminium recovery is 81.5 % for the shredding process and 99.0 % for the swim-sink process. This amounts to an overall technical recycling quota of 80 .1 %.

KEYWORDS

Recycling, cars, dismantling, shredder, swim-sink process, recycling quota

* Source: Proceedings of CETEM-Aachen workshop on Mineral Processing and Environmental Issues, Rio de Janeiro, 1997

1.) Introduction

On January, the 29th in the year 1886 Carl Benz obtained the German patent with the number 37435 for his motor car with three wheels and 0.9 hp. This was the birth of the automobile, a development that has since brought individual mobility to many people - in Germany statistically almost every second inhabitant owns a car. This amounts to over 40 million cars in 1996 compared to 4.5 million cars in 1960 - an almost tenfold increase in a period of 36 years.

With the growing amount of cars in use the amount of obsolete cars grows, too, as can be seen from figure 1 where the declining numbers from 1990 to 1992 characterise the period directly after the reunification of Germany when old cars could be sold to the former GDR for high prices.

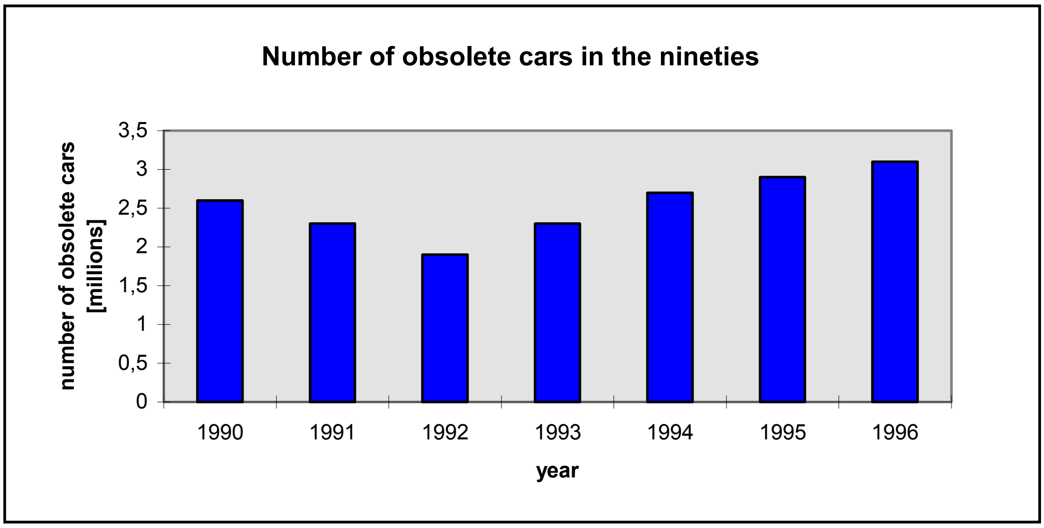

Figure 1: Number of obsolete cars in Germany in the nineties **/1/**

This large number of obsolete cars of about 3 million a year in Germany represents a considerable potential for recycling of valuable materials, mainly metals.

2.) Composition of obsolete cars

A car is a very complex industrial good thus consisting of many different materials. The composition of modern cars has significantly changed in the last 20 years. Figure 2 shows that in 1975 steel and iron made for almost three quarters of the weight of a car. In 1995 their share was only 63 %. The decrease in the amount of steel and iron was mainly due to the growing usage of plastics in cars. Their share more than doubled from 6 % in 1975 to 13 % in 1995. Also, especially during the last 10 to 15 years, the amount of aluminium used in cars grew to about 6 to 7 % today.

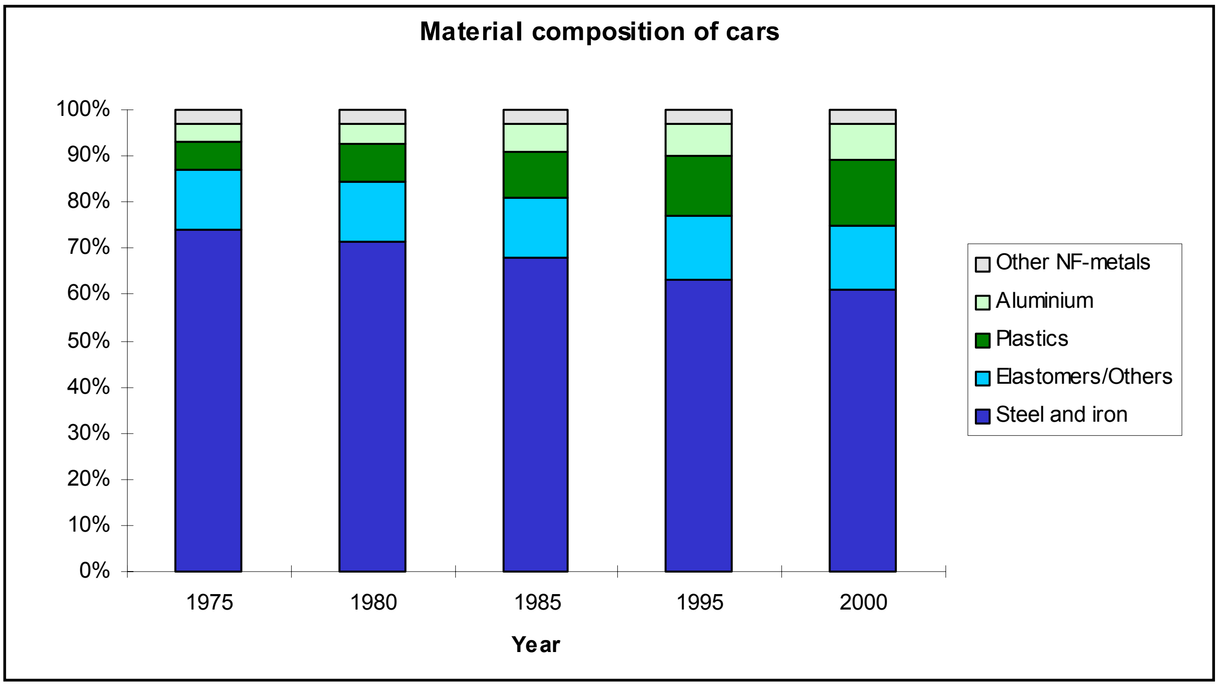

Figure 2: Changes in the material composition of cars **[2]**

The share of ferrous and non-ferrous metals in the material blend of an obsolete car is about 72 % at the moment. The recycling of cars aims therefore at the recovery of the metals, especially the steel and iron fraction.

3.) The usage of aluminium in cars

Aluminium is used in cars for different purposes. Table 1 shows the distribution of aluminium in cars within the different car components. Also, the share of cast and wrought aluminium alloys used for the different applications is given, which is important with regard to recycling: only pure wrought aluminium scrap can be recycled into wrought alloys again, mixed scrap of cast and wrought alloys can only be recycled into cast aluminium that is alloyed to a higher extent. As can be seen from table 1 the engine block makes up for half of the aluminium used in cars. The chassis counts for another 30 %. For both applications mainly cast alloys are used. For the body of a car aluminium is not yet used to a great extent but is believed to gain a bigger share in the future. For the body mainly wrought aluminium alloys are used.

Table 1: Share of aluminium in cars for different applications and share of cast and wrought alloys **[3]**

	share of total aluminium used in car	share of cast Al-alloys	share of wrought Al-alloys
engine parts	50 %	90 %	10 %
chassis	30 %	90 %	10 %
body	15 %	20 %	80 %
interior fittings	5 %	40 %	60 %
whole car	100 %	85 %	15 %

4.) Recycling of obsolete cars - Technical, economic and ecological aspects with special regard to aluminium

4.1 Collection and dismantling

Obsolete cars can reach the recycling path in Germany following three different ways: about 80 % of the cars are brought to companies specialised on the recycling of cars. Another 15 % go to scrap dealers and about 5 % are brought directly to the shredder.

Those cars that do not reach the shredder directly (about 95 %) are dismantled which means that useful spare parts are taken off. This is the main business for the companies that collect old cars. Also it is necessary to take the remaining fuel and oil from the car before it can be sold to a shredder plant.

Concerning the aluminium used in cars the dismantling of the engine block as a spare part accounts for almost 50 % of the aluminium. About 45 % of the engine blocks are removed at the moment **[4]**. If an obsolete car possesses aluminium tires they are normally dismantled as they are quite valuable special outfitting parts. Therefore, the aluminium share of obsolete cars is already reduced before the real recycling starts. Still, the remaining aluminium forms an important raw material for the secondary aluminium smelters in Germany after it has been recovered by the processes described below.

4.2 The shredder plant

After the obsolete car has undergone dismantling it is sold to a shredder plant. These plants are specialised in the recovery of metals from complex technical goods by separating the different materials using a shredding and several sorting stages.
The first stage of a shredder plant is the shredder itself. The principle of this machine is shown in figure 3.

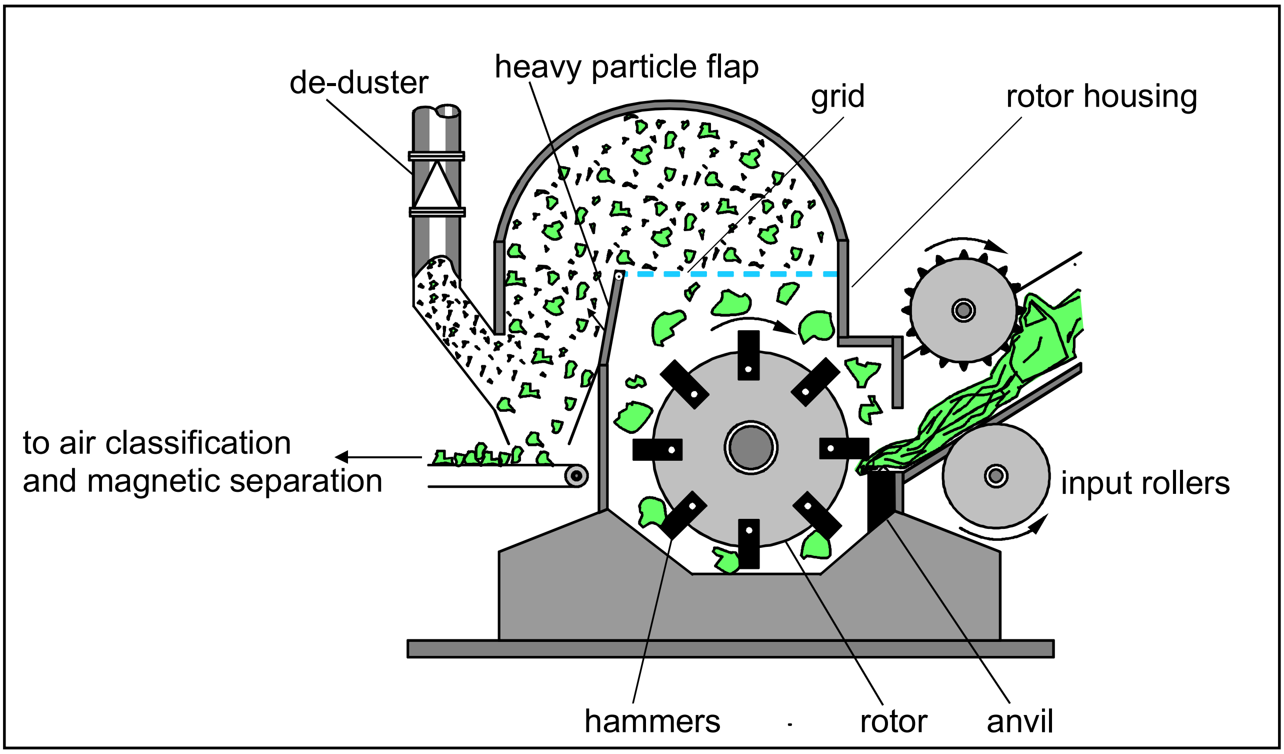

Figure 3: Principle of a shredder

The input rollers flatten the car body and feed it into the rotor housing. At the anvil edge the hammers that are connected flexibly to the rotor tear the car to pieces. When the scrap pieces are small enough they can leave the rotor housing through the top grid. Particles that cannot be comminuted leave the shredder through the heavy particle flap. The de-duster separates the dust from the remaining material which is now fed to the sorting stages of the shredder plant.
The first sorting stage consists of an air classifier. This classifier separates the heavy metallic particles from the light materials such as plastics, fibres, foam rubber etc. as well as the fine rust and paintwork particles. These materials form the so-called shredder residue that amounts to an average of 22 % of the input material. The

heavy fraction of the air classifying stage is now fed to a magnetic drum separator. This second sorting stage produces the steel and iron fraction that accounts for an average of 72 % of the input material. The remaining non-magnetic fraction (about 6 % of the input material) contains the non-ferrous metals as well as rubber and other non-metallic heavy materials.

Figure 4 shows in which fractions the aluminium remains after the shredding process.

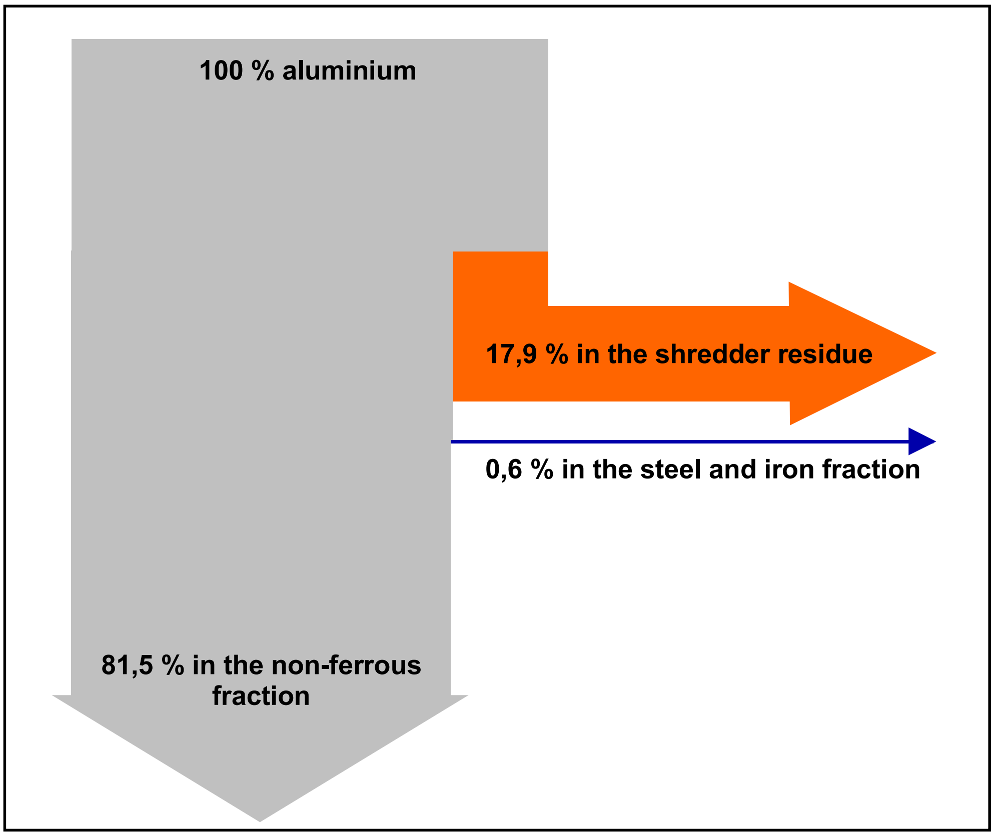

Figure 4: Distribution of aluminium contained in obsolete cars after the shredding process

As can be seen from figure 4 the technical recycling quota for aluminium is 81,5 % as the aluminium contained in the shredder residue and in the steel and iron fraction is lost for recycling.

4.3 Technical, economic and ecological data for German shredder plants

The data presented in table 2 was collected during several visits to different shredding plants in Germany. The data gives mean values which can differ significantly from plant to plant. The numbers in brackets give the ranges for the data.

Table 2: Technical, economic and ecological data of the shredding process

Economic data	
investment cost	about 34.5 million US$ for a modern plant
operating cost	52 US$/t of obsolete cars(37 US$/t up to 69 US$/t)
price paid for an obsolete car	28 US$ (0-57 US$)
cost for disposal of 1 t of shredder residue	129 US$ (72-172 US$)
amount of iron and steel fraction	720 kg/t (600-800 kg/t)
amount of non-ferrous fraction	60 kg/t (10-100 kg/t)
revenues for iron and steel fraction	100 US$/t (83-115 US$/t)
revenues for non-ferrous fraction	172 US$/t (103-287 US$/t)
Technical and ecological data	
energy demand for shredding	31 kWh/t (21-39 kWh/t (depending on the degree of dismantling))
energy demand for air classification etc.	13 kWh/t (8-18 kWh/t (depending on the degree of dismantling))
amount of solid waste arising	220 kg/t (140-300 kg/t) (shredder residue)
area covered (sealed)	about 45.000 m² including storage area
noise emission at plant limits	46 dB(A) (modern plant)
dust emission	15 mg/m³ (modern plant)
sewage water	depending on rainfall
wear of hammers	1 set for 10.000 t throughput (1000-3000 kg)
wear of grids	1 set for 35.000-40.000 t throughput (6000-7000 kg)
throughput	e.g. 65-70 t/h (about 80 cars/h) with a 1.480 kW shredder unit
Other data	
number of employees	9 (3 to 16)
position of shredding plants	typically industrial areas

The calculation of the profits/losses gives the following numbers:

cost:	100 US$/obsolete car (48-153 US$/obsolete car)
revenues:	74 US$/obsolete car (60-90 US$/obsolete car)
profits/losses:	-26 US$/obsolete car (-63 up to 42 US$/obsolete car)

As can be seen, the shredding of obsolete cars is economically feasible in Germany only under favourable conditions, i.e. when the disposal costs for the shredder residue and the operating costs are low.

The technical data shows that the overall energy demand for the treatment of obsolete cars is on average 44 kWh/t. The wear of hammers and grids is relatively high but can be neglected if seen on a per ton basis: 0,3 kg/t hammers and 0,18 kg/t grids.

The ecological data shows the main problem for all shredding plants: per ton of shredded cars 220 kg of shredder residue arise which have to be disposed of on household waste dumps. This causes not only high disposal costs but is also a potential for damage to the environment if the waste dump is not operated in an environmentally sound manner. Dust emissions from a shredding plant are very low due to effective dust control systems. The rainfall water is collected and used for the dedusting system. Surplus water is fed to the sewerage after passing an oil separator.

4.4 Recovery of aluminium from the non-ferrous fraction of the shredding process

The aluminium contained in obsolete cars reports mainly to the non-ferrous fraction of the shredding process. The non-ferrous fraction is a mixture of about 45 % metals and 55 % non-metals. It therefore has to be processed further in order to recover the aluminium and other valuable metals. For this purpose in Germany so-called sink-float plants are operated.

The sink-float plants buy the non-ferrous metals fraction from the shredder plants and use different sorting stages for the recovery of the metals. The process described below is an example for one of the German sink-float plants. The processes used in other plants differ but the core elements are the same.

First, the material is screened into three fractions: >80 mm, 80-16 mm and <16 mm. The coarse fraction is handpicked aiming at aluminium (cast and wrought alloys), stainless steel, iron and combinations of iron with aluminium, the latter going back to the shredding plant. The fine fraction is exported to Southeast Asia as handpicking in Germany is not economically feasible.

The fraction 80-16 mm is processed in the core element of the sink-float plant, a two-stage heavy media separation. First, a magnetic separator separates combinations of iron with other materials. This material flow goes back to the shredder plant.

In the following washing stage the material is cleaned from dust that would cause problems in the heavy media separation. Also, material lighter than water is separated as a fluff fraction by feeding the water overflow from the washing stage to a screen. The water is treated and fed back to the circuit.

After the washing stage the material is fed to the first heavy media stage where a density of about 2.0 g/cm³ (a suspension of magnetite and water) is used to float magnesium, rubber and other non-metals. After draining and rinsing off the heavy media from the material, the floated fraction is fed to an eddy-current separator where the magnesium is separated from the non-metallic materials.

The heavy particles from the first stage are fed to the second sink-float stage where a density of about 3.0 g/cm³ (a suspension of ferrosilica and water) is used to float aluminium and stones. After separation the material is drained and rinsed of the heavy media.

The heavy fraction from the second heavy media separation stage is sold for further processing. It contains all heavy non-ferrous metals such as copper, zinc and lead as well as stainless steel. The floated aluminium and stone fraction is fed to an eddy-current separator in order the produce a clean aluminium fraction that is the main product of the sink-float-plant. The stone fraction still contains insulated copper wires which makes it a saleable material.

Figure 5 gives an overview of the sink-float plant and the material flows for a non-ferrous metal fraction with a metal content of 45 %.

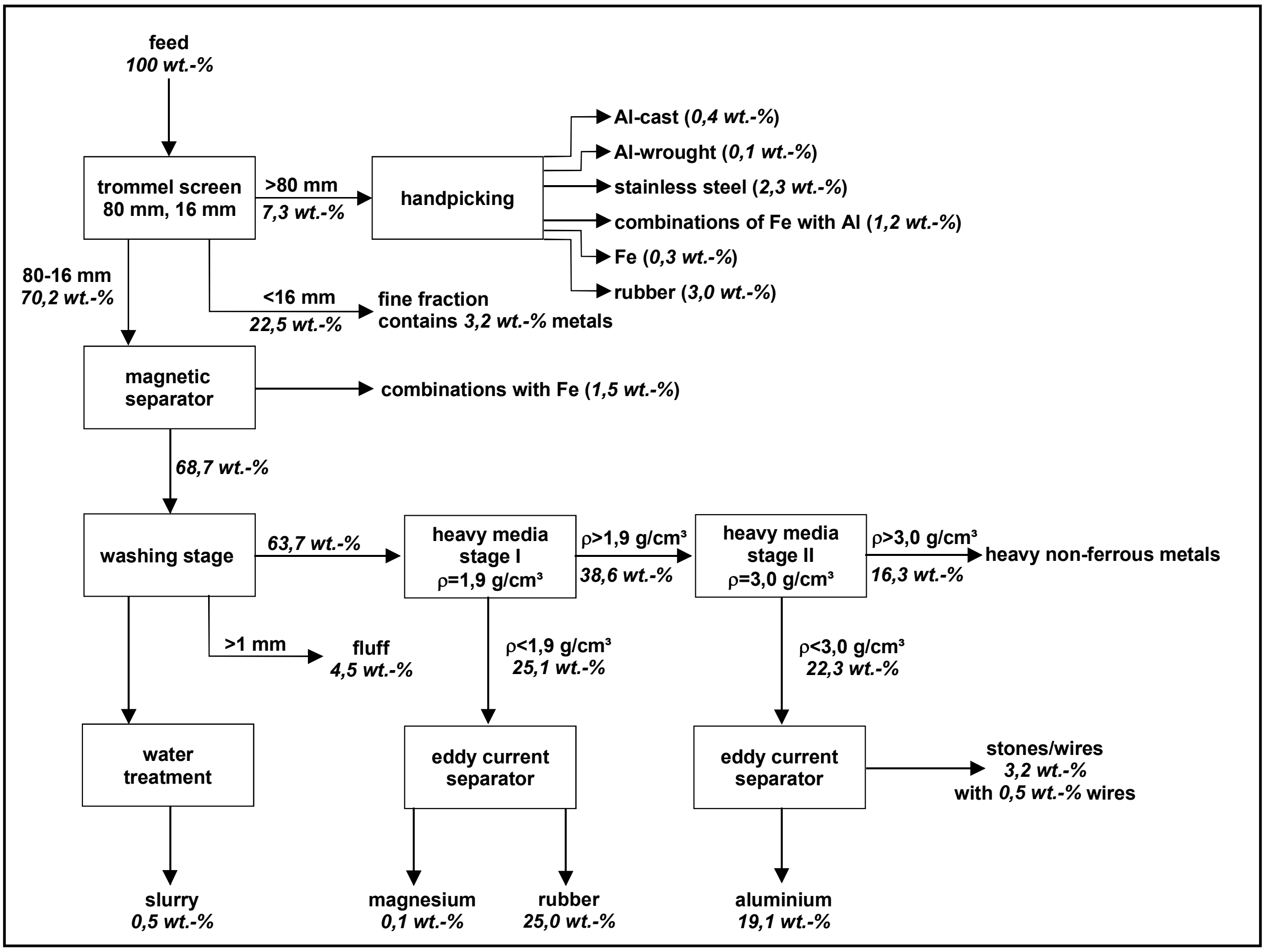

Figure 5: Flow-sheet of a sink-float plant for the processing of non-ferrous metal fractions from shredder plants

Figure 6 shows where the aluminium contained in the non-ferrous metal fraction ends up after the processing in the sink-float plant.

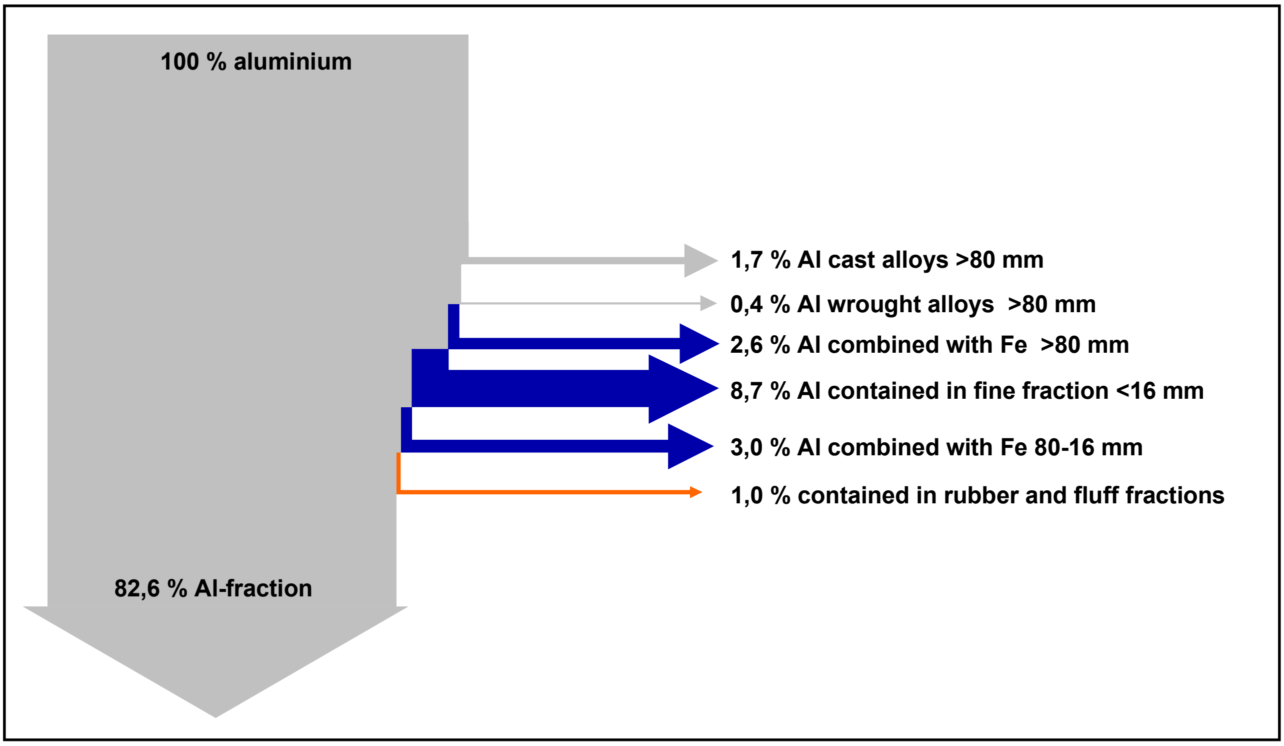

Figure 6: Distribution of aluminium contained in the non-ferrous metals fraction after processing in the sink-float plant

As can be seen from figure 6 the sink-float process achieves an overall recovery of 99.0 % of the aluminium contained in the non-ferrous metal fraction.

4.5 Data of the sink-float process

The data presented in table 3 are specific for the plant described above.

The calculation of profits is based on assumptions concerning the prices for the products and a non-ferrous metal fraction containing 45 % of metals. The price for such a highly enriched fraction would be at the upper end of the scale which has been taken into account when calculating the profits:

cost:	207 US$/t (138-322 US$/t)
revenue:	390 US$/t
profits:	68 US$/t

Table 3: Technical, economic and ecological data of the sink-float process

Economic data	
investment cost	about 1.4 to 1.7 million US$
operating cost	92-103 US$/t
price for non-ferrous metal fraction	172 US$/t (103-287 US$/t)
cost for disposal of waste at household waste dump	92 US$/t
revenues	about 1.15 US$ per kg of aluminium about 0.85 US$ per kg of other non ferrous metals
amount of aluminium recovered	196 kg/t
amount of other non-ferrous metals recovered	191 kg/t
Technical and ecological data	
energy demand	15-18 kWh/t
amount of solid waste arising	325 kg/t to household waste dump (rubber, fluff, etc.) 5 kg/t to hazardous waste dump (slurry from water treatment)
area covered (sealed)	about 24.000 m² including storage area
fresh water used	0,085 m³/t
sewage water	depending on rainfall
consumption of magnetite	2-2,5 kg/t
consumption of ferrosilica	2-2,5 kg/t
Other data	
number of employees	25
position of plant	industrial area

Because the price for the non-ferrous metal fraction is based on the metal content, the sink-float processing is a kind of wage-processing. It is therefore economically feasible as long as the framework, especially the possibilities for the deposition of the occuring waste material, is reasonable.

The technical data show that the energy demand is about 15-18 kWh/t. The consumption of heavy media amounts to 2-2.5 kg/t magnetite and ferrosilica respectively. Due to the closed water cycle the demand for fresh water is low at about 0.085 m³/t.

The main ecological problem is the same as at the shredder plants: per ton of material processed an average of 325 kg of solid waste material arises. This figure is even higher for non-ferrous metal fractions containing less than 45 % of metals.

The rainfall water is collected and used for the water cycle. Surplus water is fed to the sewerage after passing an oil separator.

5.) Conclusions

In Germany the recovery of aluminium from obsolete cars follows two different paths. Aluminium is dismantled by companies specialised on the recycling of cars. This occurs for large and valuable parts containing aluminium such as engine blocks and tires.

The remaining aluminium is recovered by a two-stage process: first, the obsolete car is shredded and the aluminium goes to the non-ferrous metal fraction of the shredding process. Secondly, the non-ferrous metal fraction is processed in sink-float plants where aluminium and heavy non-ferrous metals are recovered. Afterwards the aluminium is sold to secondary aluminium smelters.
The technical recycling quota for the aluminium recovery is 81.5 % for the shredding process and 99.0 % for the swim-sink process. This amounts to an overall technical recycling quota of 80 .1 %.

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A RESOURCE - ORIENTATED VIEW ON THE DISPOSAL OF WASTE GENERATED DURING PRIMARY ALUMINIUM PRODUCTION*

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ABSTRACT

The use of bauxite for the production of aluminium is linked to the initiation of a complex network of raw material flows. The disposal of waste material arising at the production of alumina and aluminium is a major problem, both from an ecological and an economical point of view. The specific amount of waste generated in the course of the aluminium production process, such as Red mud, Spent Potlining and Filter Residues vary greatly, depending on the grade and the quality of the bauxite used on the technical performance of the Bayer-Process and the aluminium smelters and on the disposal or processing technology. This paper provides an overview of the Red Mud disposal technology, the alumina and the aluminium production process and of the Spent Potlining processing. The parameters which influence the amount of waste generated during the process steps are described, followed by a quantification of these parameters showing the optimisation potential of the quantities of waste material that are generated.

The present study provides a framework for integration of a waste material assessment into the design of a resource management system. Finally, conclusions are drawn and options are suggested for the processing, recycling and eliminating the aluminium-related waste materials in a way which is environmentally sound, and which is in accordance with the concept of "sustainable development" in the minerals and metals industry.

KEYWORDS
Aluminium production, waste disposal, red mud, sustainable development

* Source: M.A. Sánchez, F. Vergara and S.H. Astro, Eds.: Waste Treatment and Environmental Impact in the Mining Industry. University of Concepción.

INTRODUCTION

The Collaborative Research Center 525 entitled “Resource – Orientated Analysis of Metallic Raw Material Flows” was established in 1997 at the Aachen University of Technology (RWTH Aachen) with funding from the *Deutsche Forschungsgemeinschaft* (DFG). The aim of this project is to investigate and analyse the flow of raw materials against the background of the necessary supply of the society with mineral resources as well as with processed and manufactured goods. In this context, the demand arises for a holistic assessment of raw material flows. Therefore, nine Institutes of the Aachen University of Technology are collaborating with the Jülich Research Center as part of this project. The initial phase focuses on the aluminium flow analyses, extending from bauxite deposits through mining to alumina and aluminium processing and also includes secondary production processes and tailings disposal. The material flow analysis is carried out taking into account economical, ecological and social factors.

The Institute of Mining Engineering I (Sub-Program 2) is analysing, modelling and balancing the demand for resources at bauxite mining. Furthermore, Sub-program 2 conducts research on waste disposal technologies related to the aluminium production process.

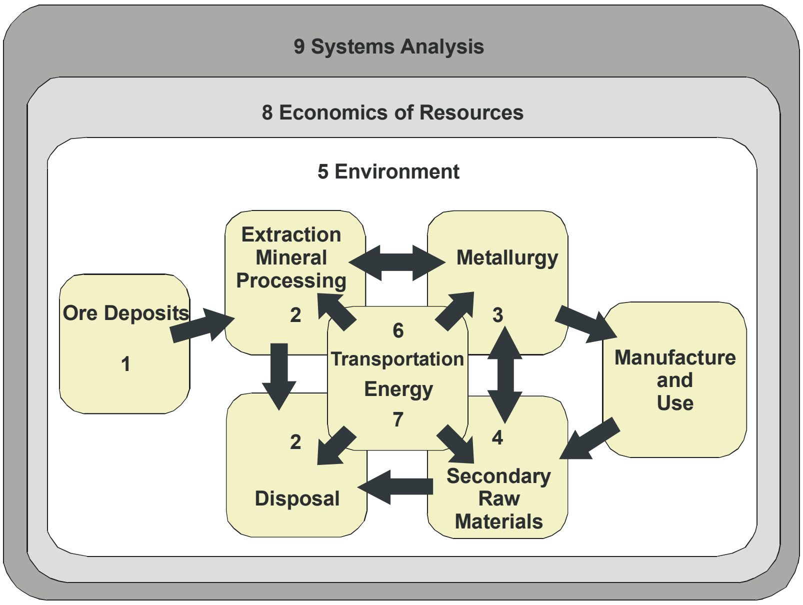

Figure 1: Linkage and structure of the CRC525

ALUMINIUM PRODUCTION PROCESS

Bauxite Extraction

In 1998, 125 mio. tons of bauxite were produced worldwide; most bauxite is extracted from shallow, thin-layered ore deposits. Bauxite is mined throughout the world at more than 70 sites in 25 countries. Mines in equatorial regions and in the southern hemisphere account for an increasingly large share of bauxite production. Major producers are Australia, Guinea, Brazil and Jamaica. Figure 2 shows the distribution of operating bauxite mines worldwide.

Alumina Production

The most common digestion process for the aluminium oxide production is based on the wet- chemical extraction of the alumina, the so-called „Bayer Process“. In this process, the ore is leached with caustic soda and other process materials (CaO, flocculants). 90-98% of the Al_2O_3 content is dissolved. The remaining insoluble contents of the ore, silicate bound Al_2O_3 as well as the process materials and the caustic soda which has not been recovered form the so-called “Red Mud”. Before disposal, the Red Mud is separated from the digestion liquor and washed, in order to minimise the loss of caustic soda. Red Mud represents the largest amount of waste generated during alumina production.

Figure 2: Bauxite extracting countries and sites. The size of the bullets corresponds to the annual production of the region. [Martens et al. 2000]

Aluminium Production

The aluminium production process is named after two scientists, Hall and Héroult (Hall and Héroult process) who discovered the reduction process in 1886. In this process, alumina is dissolved into molten cryolite (Na_3AlF_6) in electrolytic cells, or pots, where the alumina is electrolytically reduced to aluminium metal. A large number of pots are arranged in series to form a potline; an aluminium production plant generally consists of several potlines. The pots operate at approximately 930°C to 960°C.

The lining of the reduction cell is composed of carbon, which is baked by insulation and contained within a steel container, called a potshell. The carbon portion of the lining serves as the cathode. Over the life time of the cathode, the material has to be changed as impregnation of the carbon results in an increase of thermal conductivity. Once the material is removed from the shell it is referred to as Spent Potlining (SPL). The life cycle of a cathode ranges from three to ten years.

WASTE GENERATION DURING ALUMINA AND ALUMINIUM PRODUCTION

During the alumina and primary aluminium production processes, waste material is produced in some process stages. Figure 3 shows the simplified process chain and gives an overview of the waste materials generated. In the following, the analysis will focus on selected waste materials related to the primary aluminium production process.

Overburden

Most of the bauxite deposits are very shallow and mined in an open pit. There are also a few underground mines which account for only a small share of global bauxite production. The overburden usually consists of loose soil and uncemented or minor consolidated rock. It is removed by scrapers, front-end loaders, hydraulic excavators or draglines. Usually the topsoil is seperated from the overburden and used for reclamation. The overburden – to - bauxite ratio varies between 0.02:1 and 9:1, averaging at 0.75:1. The material is commonly stored in the open-pit after once the mining process has ceased.

Red Mud

After separation from the pregnant solution, the Red Mud that was generated is commonly stored in tailings ponds or waste dumps, as there are currently no ways to utilize it economically. At some locations however, the Red Mud is not stored at controlled disposal sites but is released into the countryside or even, dumped into the sea.

Looking at the disposal technology, the industry basically relies on five different methods of Red Mud disposal. Three of them are based on wet transport conditions for the waste material, and two on dry conditions. Other technical variations include the presence or absence of drainage and sealing devices, and the geometry of the disposal site. Figure 4 illustrates the disposal techniques used worldwide (with calculated figures for the resources water, land use and energy).

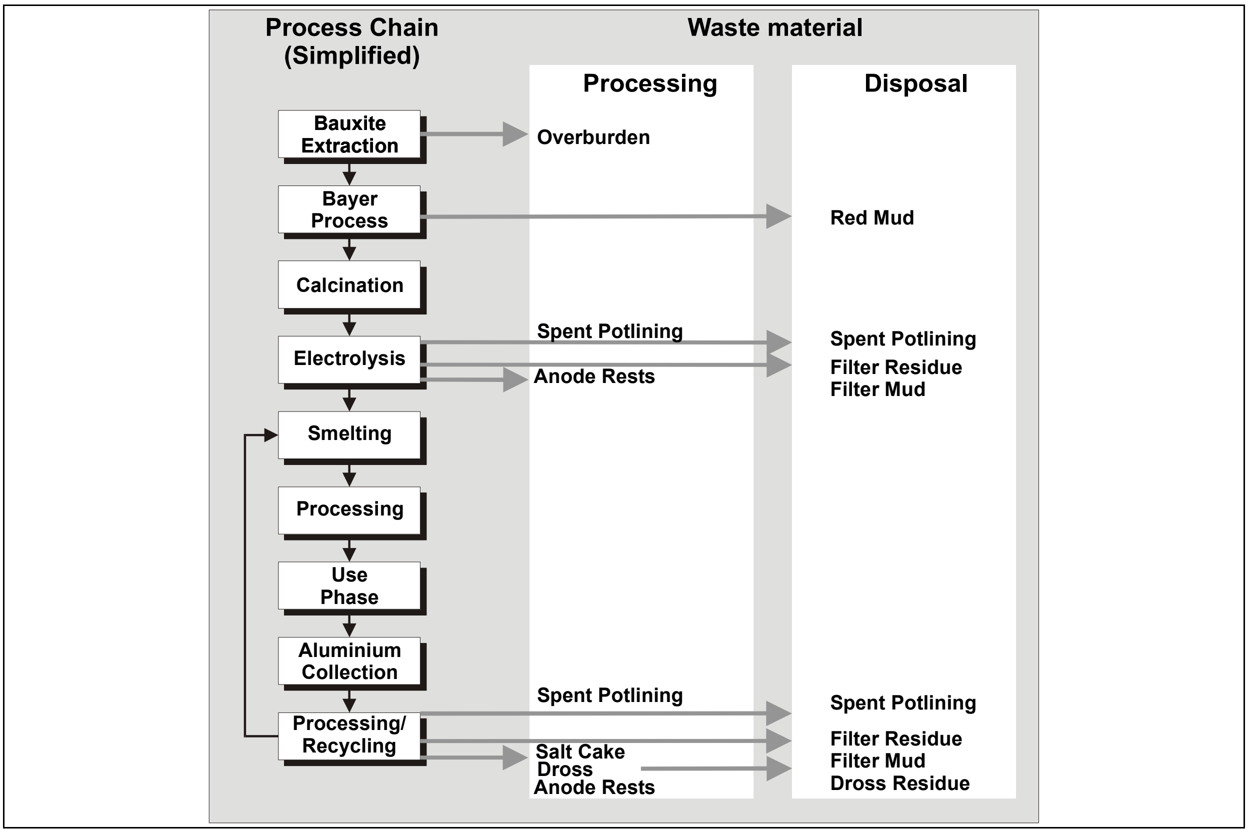

Figure 3. Simplified Process Chain of the Aluminium Production Process

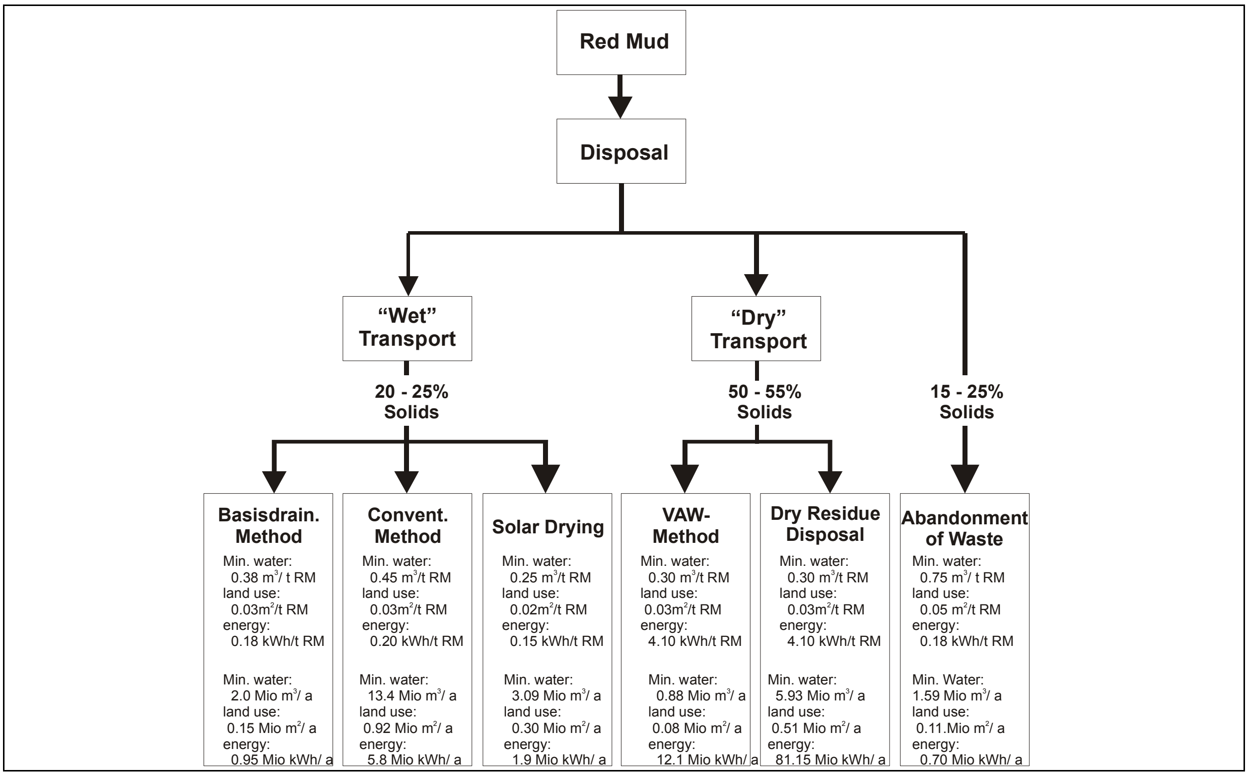

Figure 4: Red Mud Disposal with specific and absolute parameters for selected resources [Mistry et al. 1999]

Spent Potlining (SPL)

Spent Potlining is an unavoidable by-product of the aluminium smelting process. During the life time of an electrolysis reduction cell, the carbon cathode becomes saturated with cryolite bath materials and other objectionable pollutants which, degrade the lower thermal insulation. Various processes have been tried for the reprocessing of this waste. Most of the processes reported within the past few years have been unsuccessful from a technical and economical point of view. The Spent Potlining, which is declared as hazardous waste, has to be treated before being landfilled. The recently developed treatment methods for this waste can be separated into low temperature leaching on the one hand and application of moderate to high temperature on the other. A common practice of SPL treatment is the direct disposal of Spent Potlining, whereby the contents of fluoride and cyanide lead to characterization of SPL as hazardous waste. Due to the present low disposal costs of hazardous waste, SPL disposal still represents one of the major treatment methods. The processes have been provided with In- and Output figures (Table 1).

Table 1. Selected Spent Potlining waste treatment methods with Material In- and Outputs and Landfill ratios [modified after KIMMERLE et al. 1993]

	Process	Material Input			Material Output			Landfill
Leaching	LCL&L	1 t SPL	0.2 t CaO	1.4 t H_2O	0.7 t Carbon	1.7 t Bayer Liquor	0.2 t CaF_2	0
Leaching	LCL&M	1 t SPL	0.1 t $Al(OH)_3$	1.3 t H_2O	0.7 t Carbon	1.5 t Bayer Liquor	0.2 t AlF_2	0
Leaching	LCL&NaF	1 t SPL	0.3 t NaOH	0.5 t H_2O	0.7 t Carbon	0.9 t Bayer Liquor	0.2 t NaF	0
Temperature	Mini L	1 t SPL	0.3 t CaO	1 t H_2O	1.3 t Carbon	1 t Bayer Liquor	0.2 t CaF_2	0 - 1.3 t
Temperature	Slagging	1 t SPL	1.4 t Fe_2O_3	0.3 t Fe_2O_3	1.4 t Landfill	0.9 t Fe		1.4 t
Temperature	Pechiney	1 t SPL	1 t $CaSO_4$	0.2 t CaO	2.2 t Landfill			2.2 t
Temperature	Reynolds	1 t SPL	1.4 t Filter		2.4 t Landfill			2.4 t
	Landfill	1 t SPL			1 t Hazardous Waste			1 t

Filter Residues

The waste gases collected at the electrolysis plant can be cleaned by means of both a wet and a dry cleaning process. Regarding the wet cleaning process, the gaseous effluents can be leached with an acid or an alcaline solution. The remaining solids (Filter Mud) have to be deposited.

The dry cleaning process of waste gases applies alumina as an adsorbent for gaseous hydrogen fluoride, through the use of a fluidized bed reactor for the adsorption step, and of electrostatic precipitators for the waste-gas cleaning. After adsorbing the fluorides, the alumina is fed to the aluminium electrolysis. In this context the superposing of an electrostatic precipitator for the raw gas cleaning makes it possible to carry out an extensive removal of impurities which otherwise may effect the electrolysis and decrease the quality of the metal. This process is known to be very efficient in fluoride recovery, as the fluoride is adsorbed by the alumina.

Within the past few years, the dry cleaning process has been used in waste gas processing, whereas the wet gas cleaning process is only used in exceptional cases. The input and output parameters of waste gas processing are shown in Table 2.

Table 2. Input and Output parameters of dry waste gas cleaning [after Sauer et al. 1982]

	Process Input				Process Output
Dry waste gas cleaning	Energy	Al_2O_3	Waste Gases	Water	Dust
	[kWh/t Al]	[kg/t Al]	[kg/t Al]	[m^3/t Al]	[kg/t Al]
	390	480	46	2	2.3

QUANTIFICATION OF WASTE MATERIAL AND SPECIFIC RESOURCE PARA-METERS FROM PRIMARY ALUMINIUM PRODUCTION

The mass of waste material accumulating from bauxite and alumina processing is only imperfectly known and is often not considered in mass flow studies. The range of options available for the technical set-up of Red Mud disposal and the processing or waste disposal of Spent Potlining, offer significant potential for optimization. The waste material generated during the primary aluminium production process can be quantified using determined parameters.

As mentioned above, the overburden and waste material that is removed from the bauxite is commonly stored in abandonned parts of the open pit. In 1998, the volume of overburden removed from bauxite deposits totalled approximately 55 mio m^3. The mean overburden to bauxite ratio worldwide is 0.75:1. Fuel consumption of the overburden removal amounts 113 Mio. liters of diesel fuel. The land use by bauxite extraction is about 1500 ha per year, with land reclamation estimated at 80-85% of this amount (1200-1275 ha per year).

Table 3 provides an overview of Red Mud disposal worldwide in 1998. The parameters mass, volume, land use, water demand and energy consumptionhave been calculated for various disposal methods. In 1998, about 70 million tons of Red Mud were generated. The land use related to Red Mud disposal was more than 200 hectares, whereby the water content of the disposed Red Mud amounts to approximately 27 million cubic meters.

It can be shown that the major part of the Red Mud (30%) is disposed of by the Conventional Method, a disposal method associated with high values in land use and water consumption and low values in energy consumption (see also Figure 4). Other disposal techniques involve low values in land use and water consumption, such as the VAW Method or the Dry Residue Method, although these methods show high values in energy consumption. Considering the selected parameters, the Solar Drying Method (a method only applied in areas with high solar intensity, such as Jamaica) represents the disposal technology with the lowest resource values.

Table 3. Red Mud Disposal wordwide (in 1998) with calculated parameters for selected resources [after Mistry et al. 1999]

	Red Mud [mio t]	Volume [mio m^3]	Land Use [mio m^2]	Water [mio m^3]	Energy [mio kWh]
VAW Method	2.94	1.51	0.08	0.88	12.08
Dry Residue Disposal	19.78	10.14	0.51	5.93	81.16
Solar Drying Method	12.38	5.95	0.3	3.09	1.91
Basis Drained Method	5.27	2.98	0.15	2.0	0.95
Conventional Method	26.23	18.25	0.92	13.39	5.83
Abandonment of Waste	3.52	2.16	0.11	1.59	0.69
Total	70.11	39.48	2.07	26.88	102.62

The production of aluminium currently generates about 35 kg of SPL per ton of aluminium equivalent to 760.000 tons of SPL annually worldwide [KIMMERLE 1993]. A recent survey indicated that 61% of Spent Potlining was landfilled, another 17% stored in expectation of recycling. To date, only about 22% are recycled or processed [PAVLEK 1993]. Figure 5 provides an overview of SPL processing and landfill in 1998 with specific parameters.

The ratio of SPL being landfilled is considered to be about 0.47 million tons per year (estimated at a primary aluminium production rate of 21.8 million tons per year). This material is listed by the Environmental Protection Agency as a hazardous waste. The ratio of SPL being processed (and stored in expectation of being processed) and inertisized to common waste material is about 0.29 million tons. The resulting inert landfill is about 0.3 million tons. Other materials, like Bayer liquor, carbon and fluoride can be re-used in the aluminium production process.

For the landfill as both a hazardous waste and as an inert waste, figures for disposal volume and land use can be estimated, as shown in Table 4. The figures that have been taken into consideration show that the disposal of 470,000 tons of SPL as hazardous waste results in a disposal volume of nearly 300,000 cubic meters with a land use of nearly 15,000 square meters. The landfill resulting from the processing of SPL is about 300.000 tons per year. The disposal volume of this landfill of nearly 150.000 cubic meters results in a land use of 7.000 square meters. 100% processing of all Spent Potlining would result in a landfill tonnage of nearly equivalent numbers, although in this case the resulting landfill volume and land use would lead to a decrease of more than 20 percent compared to the current situation, as shown in Table 4.

Table 5 shows specific parameters for filter residues associated with the aluminium production in 1998. A total landfill mass of 50,000 tons with a volume of nearly 30,000 cubic meters has to be landfilled as a hazardous waste. Total land use is about 500 square meters.

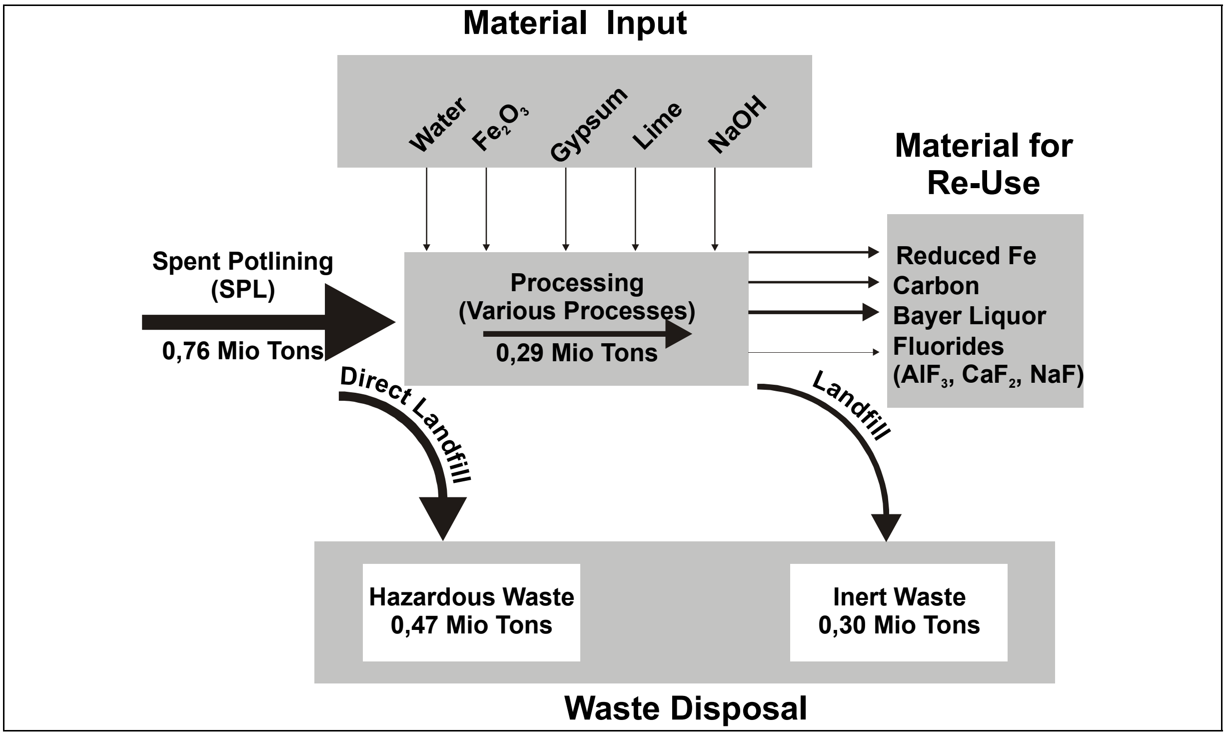

Figure 5. Specific Parameters for Processing and Disposal of Spent Potlining (SPL) in 1998.

Table 4: Actual disposal of Spent Potlining (SPL) as hazardous waste and after processing as inert waste with selected parameters for disposal.

Spent Potlining (SPL) Disposal			
	Mass	Volume	Land Use
	[t/a]	[m^3/a]	[m^2/a]
Hazardous Waste	470,000	294,000 [1]	14,700
Inert Waste	300,000	143,000 [2]	7,150

[1] The Density D of hazardous waste is considered to be D =1,7 t/m^3

[2] The Density D of inert waste is considered to be D =2,1 t/m^3

Table 5. Filter residues generated during the primary aluminium production process in 1998 with calculated disposal parameters

	Specific Parameters			
Dry waste gas cleaning	Energy	Landfill	Volume[1]	Land Use
	[Mio. Kwh/a]	[t/a]	[m^3/a]	[m^2/a]
	8,500	50,200	29,500	500

[1] Note that the density D after consolidation is considered to be D = 1,7 t/m^3

OPTIMIZATION POTENTIALS

An analysis of Red Mud disposal shows various optimization potentials, from the bauxite quality to the technology used as part of the Bayer Process or the disposal technology. By using a bauxite of higher quality or an optimized technical setting in the Bayer Process the Red Mud mass can be reduced by up to 10%. The disposal technology shows the biggest optimization potential. Application of an optimized technical setting in Red Mud disposal (e.g. Dry Residue Disposal, VAW Method or, in drier climates, the Solar Drying Method) and reduction in the use of less optimized disposal technologies (Conventional Method, Basisdrained Method) would lead to a considerable reduction of Red Mud by approximately up to 25% [MISTRY et al. 1999], and to better protection of the environmental.

The processing of Spent Potlining also shows large optimization potential. Most of the processes mentioned in this paper have moved beyond the pilot-plant stage and offer the aluminium industry a technically and economically viable process for the treatment of SPL. The complete detoxifying or inertizing of Spent Potlining would lead to a minimal increase of landfill mass with a resulting landfill that meets currently accepted standards. The fact that the Environmental Protection Agency (EPA) declared Spent Potlining due to its fluoride and cyanide contents in 1988 as hazardous waste is a sign of growing ecological awareness. It can be expected that the processing of Spent Potlining will become a commonly used process within the next decades.

SUMMARY AND CONCLUSIONS

The present study has used a methodical approach for to identify technical effects on waste generation during alumina and aluminium production from bauxite and alumina. It has shown that the optimization of technical parameters may result in a considerable reduction of waste material. In particular, the choice of specific waste disposal and waste processing technologies indicates significant optimization potentials. As a result, the optimization can only be achieved through regional or global resource management. The integrated approach adopted in this study was designed to analyze various stages of material flows related to alumina and aluminium production, from the source of the material to its final disposal. By identifying critical parameters and process stages, the resource utilization of corresponding waste treatment methods can be minimized.

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DISPOSAL OF ALUMINIUM PRODUCTION WASTE MATERIAL
–A RESOURCE-ORIENTATED VIEW–*

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ABSTRACT

The use of the raw material bauxite for the production of aluminium is linked to the initiation of a complex network of raw material flows. Especially the disposal of waste material arising from the production of alumina and aluminium is a major problem, both from the ecological and the economic point of view.

The amount of red mud, spent pot lining and filter residues generated during the aluminium production process show large variation depending on the quality of the used bauxite as well as the technical performance of the Bayer-process and the electrolysis in the aluminium smelters.

In this work parameters of the raw material bauxite, the alumina and the aluminium production process, which influence the amount of wastes generated during the unit processes, are characterized. Then, a quantification of these parameters is established and the optimization potential of the occurring quantities of red mud is shown.

Based on these results, model calculations of geographic and technical scenarios are presented, which demonstrate the released material flows at the production of alumina, primary and secondary aluminium. Furthermore, the present study provides a framework for an integration of a waste material assessment into the concept of a resource management system. Finally, conclusions are drawn and recommendations are given for an environmentally sound processing, recycling and eliminating of the aluminium-related waste materials in accordance with the concept of "sustainable development" in the minerals and metals industry.

KEYWORDS

Bauxite mining, primary aluminium production, secondary aluminium production, waste disposal, material flows, sustainable development

* Source: VI SHMMT / XVII ENTMME – 2001 – Rio de Janeiro/Brazil

INTRODUCTION

The present study forms part of the Collaborative Research Center 525 “Resource-Oriented Analysis of Metallic Raw Materials Flow" established by the Deutsche Forschungsgemeinschaft (DFG) at the University of Technology Aachen. The research program strives to develop an integrated resources management system that analyses the flow of materials and energy through the entire life cycle and thus provides a scientific base for improving production and resource-use efficiency. The first phase of the program is concerned with the bauxite-alumina-aluminium cycle and related geologic, engineering, environmental, social, and economic aspects.

ALUMINIUM PRODUCTION PROCESS

Bauxite is the principal ore for the production of aluminium metal. Most bauxite deposits show similar characteristics: thin surficial layers of bauxite with a wide lateral expansion. In 1998, about 123 Mio. t of bauxite were produced worldwide. The main producing countries were Australia, Guinea, Jamaica and Brasil, representing a share of 70% of the world production.

The most common process for the aluminium oxide (Al_2O_3) production is based on the wet-chemical extraction of alumina, the so-called “Bayer process”. In this process, the bauxite is leached in hot caustic soda and other process materials (CaO, flocculants) at temperatures ranging from 140° - 280°C, depending on the digestion process. The alumina recovery ranges between 85-98%, depending on the mineralogical composition of the bauxite and the technology used in the Bayer process. In 1998, the alumina production amounted to 44,6 Mio. t Al_2O_3. Main producing countries were Australia, Jamaica, the United States and the former USSR.

The aluminium production process is named after two scientists, Hall and Héroult (Hall-Héroult Process) who discovered the reduction process in 1886. In this process, alumina is dissolved in molten cryolite (Na_3AlF_6) in electrolytic cells or pots, where the alumina is reduced to aluminium metal. A large number of pots are arranged in series to form a potline; an aluminium production plant generally consists of several potlines. The pots operate at approximately 930°C to 960°C. The production of primary aluminium amounted in 1998 to 22,1 Mio. t Al.

Due to high energy consumption during the Hall-Héroult Process, the collection, processing and production of secondary aluminium and the direct use of aluminium scrap represents an economic alternative. Therefore the aluminium recovered from various collection systems is remolten. To avoid aluminium oxidation, the material is covered with a salt layer. In 1998, the aluminium recovery rate amounted to 25% of the total aluminium production. Main producing countries were the United States, Japan, Italy and Germany.

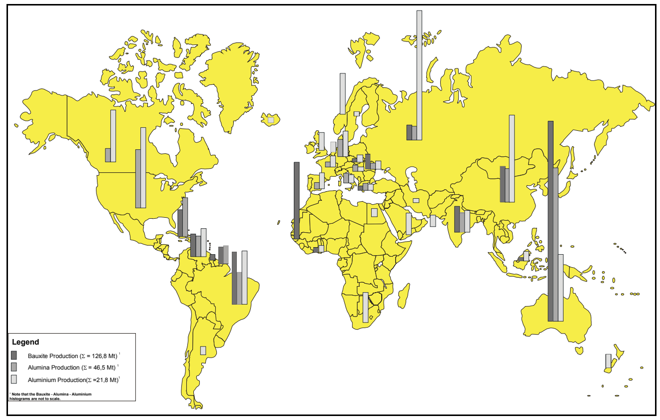

Figure 1 – Worldwide Distribution of bauxite, alumina, aluminium production. Note that the histograms are not to scale.

WASTE MATERIAL GENERATED DURING ALUMINIUM PRODUCTION

Waste material is generated during several steps of the aluminium production process, as shown in Figure 2. The investigations have shown that it has to be distinguished between waste material that is disposed (e.g. red mud) and waste material that is processed (e.g. spent potlining) or re-used (e.g. overburden for land reclamation). This disposal, processing or re-use of waste material is mostly depending on technical and economical parameters.

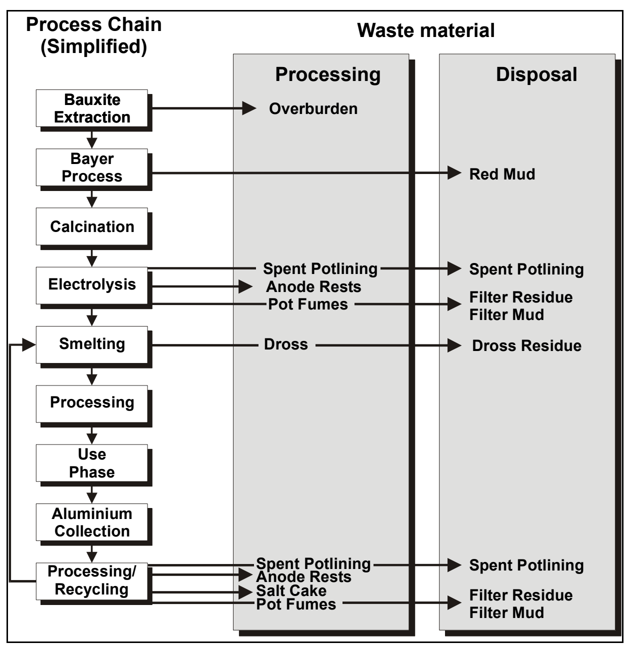

Figure 2 – Aluminium production process chain and related waste material

Red mud is generated during the Bayer process. The remaining insoluble contents of the bauxite ore, silicate bound Al_2O_3 as well as the process materials and not recovered caustic soda form the so-called red mud. Quantitatively the red mud represents the largest waste amounts generated during the aluminium production process. Red mud is commonly stored in tailing ponds or waste dumps, as there is no way of its economic utilization.

The investigation resulted in the identification of six disposal methods, as shown in Figure 3.

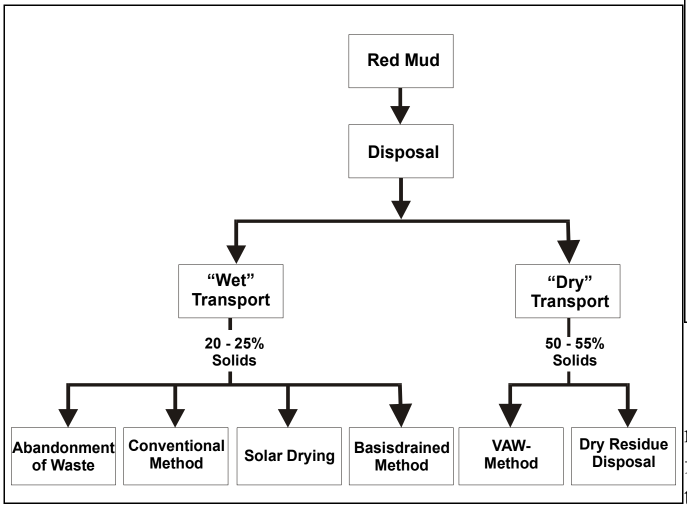

Figure 3 – Red mud disposal methods

Focussing on the red mud disposal techniques, the industry relies on five different methods of red mud disposal, of which three are based on wet and two on dry transport conditions for the waste material. Other technical variations include the presence or absence of drainage and sealing devices in the system, and also the geometry of the disposal site. A detailed investigation of the disposal methods led to the identification of resource parameters, as shown in Table 1.

Table 1 – Selected resource parameters for red mud disposal

	Water [m^3/t]	Land Use [m^2/t]	El. Energy [kWh/t]
Conventional Method	0.45	0.03	0.20
Basisdrained Method	0.38	0.03	0.18
Solar Drying	0.25	0.02	0.15
VAW Method	0.30	0.03	4.10
Dry Residue Disposal	0.30	0.03	4.10
Waste abandonment	0.75	0.05	0.18

Spent potlining (SPL) is a by-product of the aluminium smelting process. During the life time of an electrolysis reduction cell, the carbon cathode becomes saturated with cryolite bath materials and other objectionable pollutants which degrade the lower thermal insulation (Figure 4).

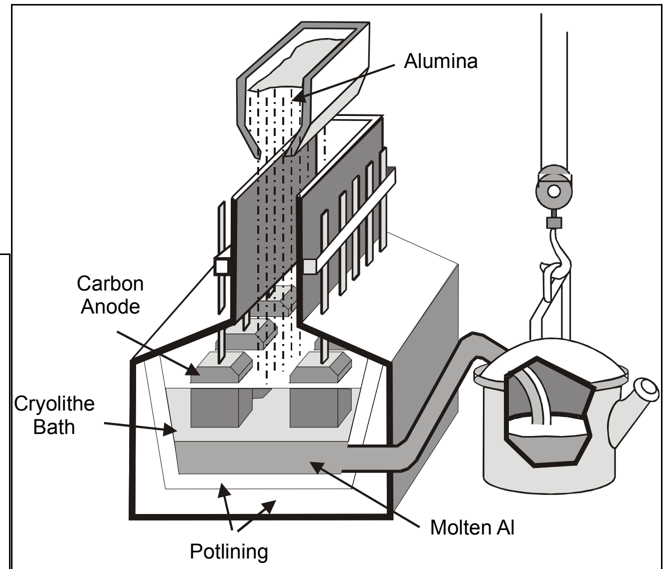

Figure 4 - Schematic section through an electrolysis cell

Various processes have been developed for the treatment of SPL. Most of the processes reported within the last few years have been unsuccessful from an economical and technical point of view. Therefore, 61% of the SPL are directly disposed as a “hazardous waste”. Only 39% are treated in low temperature leaching processes or high temperature treatment, as shown in Figure 5.

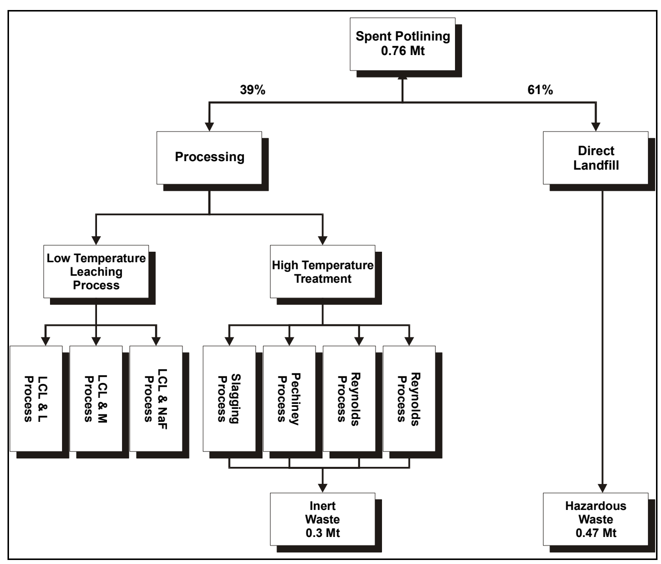

Figure 5 - SPL processing and disposal.

The production of aluminium in the electrolysis process is connected to the generation of pot fumes. To avoid losses on fluoride, the pot fumes are treated in dry or wet gas cleaning processes. The most economic method of fluoride recovery represents the dry wet gas cleaning, as shown in

Figure 6. In this process, the fluoride and other particles in the pot fumes are adsorbed by alumina. The pot fume treatment results in filter residues and filter mud that has to be disposed as “hazardous waste”. In this process, the amount of waste material can be reduced from 46kg/t Al to less than 3kg/t Al.

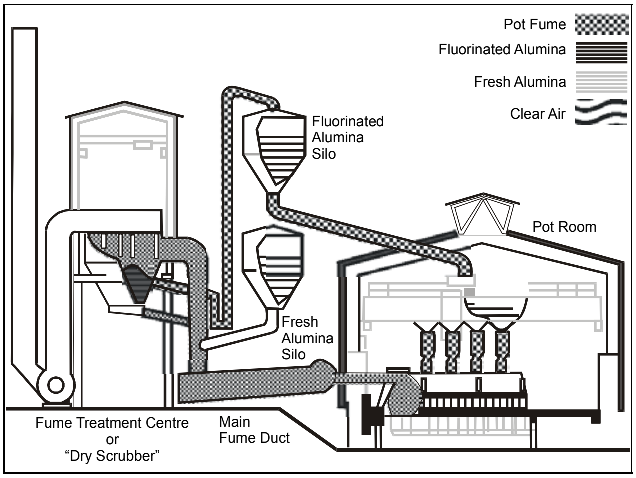

Figure 6 - Dry gas cleaning of pot fumes from the electrolysis reduction cell.

Dross is an undesirable by-product of all processes involving molten aluminium. The oxide layer on the molten aluminium has to be removed in order not to influence the quality of the final product. This waste material mainly consists of aluminium oxides, oxides of alloying elements, aluminium nitride and other metals in smaller portions. The amount of dross varies between 0.8 – 10%, depending on the process technology. The metal content varies from 20% – 80%. Several processing methods were established to minimize dross generation and to recover 30-55% of the metal content. The processing results in the generation of dross residues to be disposed. The amount of residues varies from 200 – 600kg /t dross, depending on the applied processing technology.

WASTE MATERIAL DISPOSAL QUANTIFICATION

The amount of waste material from the aluminium production is inadequately known and often not considered in mass flow studies. The range of options available for the technical set-up of red mud disposal, the processing of spent potlining (SPL), pot fumes and dross show significant optimization potential. The waste material generated during the aluminium production can be quantified using determined parameters.

Table 2 provides an overview of red mud disposal in 1998. The parameters mass, volume, land use, water demand and energy consumption have been calculated for various disposal methods. In 1998, about 72 Mio. t red mud were disposed. The land use related to red mud disposal was more than 200 hectares, whereby the water content in the consolidated red mud amounted to nearly 27 Mio. m^3. A total of more than 100 Mio. kWh energy was consumed for the transportation process by pumps via pipeline.

Table 2- Red mud disposal worldwide in 1998

Red Mud Diposal 1998	Red Mud [Mio t/a]	Min. water [Mio m^3/a]	Land Use [Mio m^2/a]	El. Energy [Mio kWh/a]
Basisdrained Method	5,26	2,01	0,15	0,95
Conventional Method	29,77	13,40	0,92	5,80
Solar Drying	12,36	3,09	0,3	1,90
Abandonment of Waste	2,12	1,59	0,11	0,70
VAW- Method	2,93	0,88	0,08	12,10
Dry Residue Disposal	19,76	5,93	0,51	81,15
Total	72,20	26,90	2,07	102,60

The production of 1t aluminium currently results in the generation of 15-50 kg of SPL, depending on the applied electrolysis cell technology. A total of 760,000 t of SPL per year has to be processed or disposed. About 470,000 t or 61% are directly disposed as landfill, the remaining 290,000 t or 39% are processed. This processing of the remaining 39% results in the generation of 300,000 t of inert waste material. An amount of 770,000 t waste material have to be disposed. The disposal parameters are shown in Table 3.

Table 3 - Disposal of waste material from SPL treatment/direct landfill with selected parameters.

Process		Landfill Ratio	Waste [t]	Density [t/m^3]	Volume [m^3]	Land Use [m^2]
Leaching	LCL&L	0	0	0	0	0
	LCL&M	0	0	0	0	0
	LCL&NaF	0	0	0	0	0
Temperature	Mini L	0 - 1.3 t	32.500	2,1	15.500	775
	Slagging	1.4 t	65.000	2,1	31.000	1.550
	Pechiney	2.2 t	97.500	2,1	45.000	2.250
	Reynolds	2.4 t	105.000	2,1	50.000	2.500
	Landfill	1 t	470.000	1,7	275.000	13.750
	Total		**770.000**		**416.500**	**20.825**

The disposal of 770,000 t of waste material from SPL processing results in a volume of 415,000 m^3. The land use amounts to 2 hectares. More than 60% of the waste material results from the direct landfill; the remaining 40% waste material are generated during the inertization in the temperature-based processes. The leaching processes are based on a material recovery from the SPL with a 100% reduction of material to de disposed.

Pot fumes are generated in the electrolysis process during the primary and secondary aluminium production. The fumes generally are high in fluoride content. The cleaning of the fumes results in the generation of filter residues (dust or mud), depending on the dust cleaning technology. Table 4 gives an overview of the pot fume treatment in 1998.

Table 4 – Pot fumes treatment and resulting filter residues

		Input				Output
		El. Energy	Al_2O_3*	Pot fumes	Water**	Filter residues***
per t Al		[kWh/t Al]	[kg/t Al]	[kg/t Al]	[m^3/t Al]	[kg/t Al]
		390	480	46	2	2,3
1998		[Mio. kWh]		[Mio. t]		[t]
		8500		1,02		50.140

* Al_2O_3 as adsorber

** Process water is recycled

*** Filter residues for landfill

In 1998, the dross recycling led to the generation of 540,000 t of dross residues with a volume of 257,000 m^3. The land use amounts to more than 12,850 m^2. Due to the problematic content (e.g. nitrides, carbides), the dross residues are declared as "hazardous waste".Table 5 gives an overview of the waste material from aluminium production.

Table 5 – Overview of Waste material from aluminium production

Waste Material	Input [Mio t]	Processing [Mio t]	Re-Use [Mio t]	Disposal [Mio t]
Overburden	115,80		115,80	
Red Mud	72,20			72,20
Spent Potlining	0,76	0,29		0,77
Pot Fumes	1,04	1,00		0,05
Anode Rests	2,94		2,94	
Dross	0,90	0,90		0,54
Total	**193,64**	**2,19**	**118,74**	**73,56**

In 1998, an amount of 194 Mio. t waste material was generated during aluminium production. More than 60% of the waste material were re-used (in major parts overburden for land reclamation). About 38% were disposed (mainly red mud); only 1% of the waste material (mainly SPL) was processed. The waste diposal from aluminium production resulted in a land use of 2,1 hectares with a disposal volume of more than 40 Mio. m^3. A portion of more than 98% from the considered disposal parameters results from the disposal of red mud.

OPTIMIZATION POTENTIALS

The red mud disposal shows various optimization potentials, from the bauxite quality to the technology used as part of the Bayer process as well as the disposal technology. By using a bauxite of higher quality or an optimized technical setting during the bayer process the red mud mass can be reduced by up to 10%. The disposal technology shows the biggest optimization potential. An application of an optimized technical setting in red mud disposal (e.g. Dry Residue Disposal Method, VAW Method or Solar Drying Method in drier climates) and a reduction in the use of less optimized disposal technologies (Conventional Method, Basisdrained Method) would lead to a considerable reduction of red mud by approximately up to 25% and to better protection of the environment.

Table 6 – Optimization of red mud diposal

	Red Mud [Mio t/a]	Min. water [Mio m^3/a]	Land Use [Mio m^2/a]	El. Energy [Mio kWh/a]
Red Mud Disposal 1998	72,20	26,90	2,07	102,60
Optimized Disposal	**63,15**	**18,33**	**1,62**	**210,24**
Increase/ Decrease	**-12,5%**	**-31,9%**	**-21,7%**	**104,9%**

The processing of SPL also shows large optimization potential. Most of the processes mentioned in this paper have moved beyond the pilot plant stage and offer the aluminium industry a technically and economically viable process for the treatment of SPL. The complete detoxifying or inertizing of SPL would lead to a minimal increase of landfill mass with a resulting landfill that meets currently acceptable standards. Furthermore, a 100% treatment of SPL in leaching processes would result in a 100% reduction of landfill. In addition, materials like Bayer liquor, carbon or fluoride can be re-used in the production process.

The fact that in 1988 the U.S. Environmental Agency (US EPA) declared the SPL as a "hazardous waste" due to its fluoride and cyanide contents is a sign of growing ecological awareness. It can be expected that the processing of SPL will become a commonly established process within the next decades.

SUMMARY

The present study used a methodical approach for to identify technical effects on waste generation during alumina and aluminium production from bauxite, alumina and secondary aluminium. It has shown that the optimization of the raw material quality and technical parameters may result in a considerable reduction of waste material. In particular, the choice of specific waste disposal and processing technologies indicates significant optimization potentials. As a result, the optimization can only be achieved through a regional or global resource management. The integrated approach adopted in this study was designed to analyze various stages of materials flows related to alumina and aluminium production, from the source of material to its final disposal. By identifying critical parameters and process stages, the resource utilization of corresponding waste treatment methods can be minimized.

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A RESOURCE-ORIENTED ANALYSIS OF MASS WASTES FROM ALUMINIUM AND COPPER PRODUCTION

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ABSTRACT[1]

This research project describes the development of a methodical approach that can be used to gain an understanding of resource utilization in the disposal of waste materials generated by aluminium and copper production. The goal of this work is to identify a framework to account for and quantify resource utilization in the waste disposal processes that are associated with the production of metallic raw materials.

The methodology is developed using the material flows associated with aluminium production. Of particular interest is the generation and accumulation of red mud. The material flows within the value-added process chain are described, as are the red mud wastes. Current disposal techniques are classified as either indiscriminate or controlled disposal methods. The resource demand triggered by disposal activity is the modelled for each specific disposal method. Using 1998 as a reference year, the current state or resource utilization for the disposal of red mud is ascertained. Different operating scenarios are then simulated and compared to the current state. Trends and optimisation potentials are highlighted and the impacts of resource utilization are discussed.

This methodology is then transferred to the waste streams generated in copper production. This transfer is used to identify flaws within the methodology and to examine the possibility of using this approach for waste streams generated in the production of other raw materials. A description of the process chain is followed by a characterization of the waste streams generated by copper mining, beneficiation, processing and leaching. As with aluminium, the disposal methods are categorized according to indiscriminate or controlled disposal. Disposal methods within each of these categories are then further classified on the basis of techniques employed. Due to the variable material characteristics, a new system for the categorization of disposal techniques is adopted. The models used for the quantification of resource utilization associated with red mud disposal are then transferred and adapted to the waste materials generated by the beneficiation, processing and leaching of copper. Computer models are used to simulate various operating scenarios and to compare the resource utilization of these scenarios with the current state of resource utilization.

The possibility of transferring this methodology to other metallic and non-metallic raw materials as well as to raw materials used in energy production is examined. The measures, modifications and information necessary for the transfer of this methodology are also discussed

KEYWORDS

Red mud, copper tailings, resource use, material flow analysis, mass wastes, leaching residues

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[1] Summary of Ph.D. thesis

METHODIK UND ANWENDUNG EINES ENERGIEMODELLS ZUR BESTIMMUNG ENERGIEBEDINGTER STOFFSTRÖME AM BEISPIEL DER PRIMÄRALUMINIUMERZEUGUNG

(METHODOLOGY AND APPLICATION OF AN ENERGY MODEL FOR THE DETERMINATION OF ENERGY RELATED MATERIAL FLOWS FOR PRIMARY ALUMINIUM)

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ABSTRACT

For the energy-intensive production process of primary aluminium by fused mass electrolysis, the provision of large amounts of low-cost power is required. Apart from this, ecological aspects of energy provision become more and more important in this area of conflict between technology and ecology.

Effects on the environment due to power generation are induced, for example, by space occupation and particularly by process streams. These energy-related process streams include, amongst others, emissions, the use of raw material and primary energy and the demand for air and water. The process streams vary significantly according to the primary energy carrier applied, the manner of production and conversion as well as the cooling methods.

The energy model developed at the Institute of Reactor Safety and Technology serves a substantial and energetic balancing of the process chains in power generation. Different power plants are shown, as well as power generation mixes of different nations, including the preliminary process chains of fuel provision, and the process streams and distribution losses related to the import and export of power. The current situation as well as technical developments is taken into account, which allows illustrating the forecasted changes in the power generation structures for the year 2010.

Considering primary aluminium electrolysis as an example, the energy related process streams for the different scenarios of power provision (depending on location, fuel and power plant system) are estimated and compared.

The results of the analyses proof the resource intensity and the emissions in the air depending on the way of power provision, and can therefore be used as a basis for ecological assessment.

On the basis of selected locations of electrolysis, the potentials for a less expensive design of energy related process streams, varying the energy supply structure and considering future technologies, are analysed and pointed out.

KEYWORDS

Final energy, aluminium production, energy model, national grid, electricity supply, power plants, energy saving

* Source: VDI-GET-Fachtagung: Entwicklungslinien der Energie- und Kraftwerkstechnik, Essen 1999

Einleitung

Die mit der Bereitstellung von elektrischer Energie und Brennstoffen verbundenen Wirkungen auf die Umwelt sind in den vergangenen Jahren zunehmend zum Gegenstand von Untersuchungen geworden. Diese Wirkungen resultieren zum einem aus der Emission von Schadstoffen wie z.B. Stick- und Schwefeloxiden, von klimawirksamen Gasen wie Methan und Kohlendioxid, zum anderen aber auch durch den Verbrauch oder die Nutzung von begrenzten Ressourcen. Hier sind die fossilen und nuklearen Energieträger beispielhaft zu nennen. Die Grundlage für die Ermittlung der Wirkungen auf die Umwelt, wie sie u.a. bei Ökobilanzen angestrebt wird, bildet in jedem Fall eine Sachbilanz, durch die stoffliche In- und Outputs identifiziert und quantifiziert werden.

Energieintensiven Prozessen kommt hierbei wegen der durch sie hervorgerufenen großen energiebedingten Stoffströme besondere Bedeutung zu. Das Beispiel der primären Erzeugung von Aluminium ist gut geeignet, um die Bedeutung der Energiebereitstellung hinsichtlich der Stoffströme sowie möglicher Einsparpotentiale auf der Ebene der End- und Primärenergie aufzuzeigen.

Wie in Bild 1 dargestellt, wird in der Prozeßkette der primären Aluminiumherstellung Energie in verschiedenen Formen genutzt. Während beim Prozeß der Verhüttung der Tonerde in der Schmelzflußelektrolyse fast ausschließlich Elektrizität benötigt wird, erfordert z.B. die Tonerdeherstellung in erster Linie Erdgas oder Heizöl. Der Energiebedarf von Transportprozessen zwischen den einzelnen Prozessen (in Bild 1 nicht dargestellt) wird meist aus Dieseltreibstoffen oder bei Schifftransporten aus Schweröl gedeckt. Diese Betrachtungen zeigen, daß für die Abbildung der Energiebereitstellung entlang der Prozeßkette der in Bild 1 beispielhaft dargestellten Aluminiumherstellung sowohl für Prozeßketten der Bereitstellung von Brennstoffen als auch insbesondere der Stromerzeugung detaillierte Stoff- und Energiebilanzen zu erstellen sind.

Innerhalb des Sonderforschungsbereichs 525 „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“ bearbeitet der Lehrstuhl für Reaktorsicherheit und -technik der RWTH Aachen das Teilprojekt „Energie“. Ziel der Arbeiten ist die Entwicklung eines Energiemodells, mit dessen Hilfe Untersuchungen bezüglich verschiedener Aspekte der Energiebereitstellung für sämtliche Gewinnungs-, Herstellungs-, Transport-, Recycling- und Entsorgungsprozesse in Metallprozeßketten durchgeführt werden können.

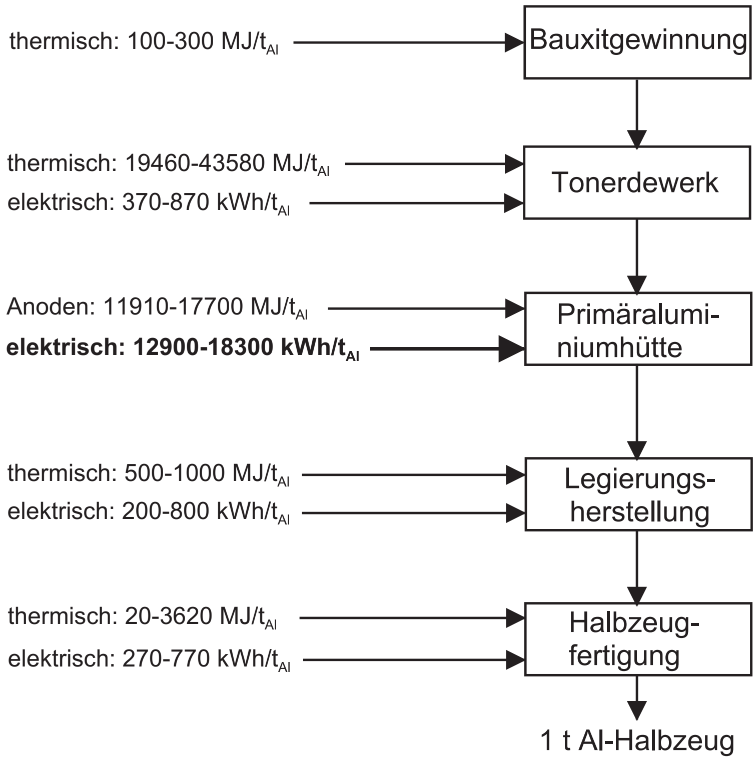

Bild 1: Bandbreiten der Endenergieeinsätze in der Prozeßkette der Primäraluminiumherstellung (Lagerstätte - Halbzeugfertigung)

Das Energiemodell besteht aus mehreren Teilmodellen. In den Modellen der Energiebereitstellung werden die Prozeßketten hinsichtlich stofflicher und energetischer In- und Outputs und Kosten abgebildet. In den Modellen der Metallprozeßketten werden die Energiebilanzen für die einzelnen Verfahrensschritte erstellt. Mit einer Bilanzierungssoftware zur ganzheitliche Bilanzierung lassen sich die einzelnen Prozesse der Metallprozeßkette und der Energiebereitstellungsketten modular abbilden und miteinander verknüpfen. Die in der Prozeßkette der Metallherstellung erfaßten Endenergieverbräuche können dann mit Hilfe des Modells der Energiebereitstellung im Hinblick auf Primärenergie-, Energieressourcennutzung (z.B. Steinkohle, Uranerz), ökonomische (z.B. Kosten der Energiebereitstellung) und ökologische Aspekte (z.B. CO_2-Emissionen) berechnet und dem Endprodukt (z.B. 1 t Aluminium) des Metallherstellungsprozesses zugewiesen werden. In den Modellen der Energiebereitstellung werden sowohl einzelne Kraftwerke als auch Stromerzeugungsmixe verschiedener Staaten inklusive der vorgelagerten Prozeßketten der Brennstoffbereitstellung sowie die mit Im- und Export von Strom verbundenen Stoffströme und Verteilungsverluste abgebildet. Berücksichtigt werden neben der heutigen Situation auch technische Entwicklungen, so daß prognostizerte Veränderungen in den Stromversorgungsstrukturen für das Jahr 2010 dargestellt werden können.

Gegenwärtig konzentrieren sich die Arbeiten auf die Abbildung der Energiebereitstellung für die Aluminiumerzeugung. Besondere Bedeutung kommt hierbei der Strombereitstellung zu, da der Prozeß der Verhüttung der Tonerde in der Schmelzflußelektrolyse mit im Mittel rund

15000 kWh_{el}/t_{Al} den weitaus größten Endenergiebedarf aufweist und damit für die Ermittlung der energiebedingten Stoffströme von großer Bedeutung ist.
In dem folgenden Kapitel wird zunächst die Methodik des Energiemodells ausführlicher erläutert. Nach Darstellung einiger wichtiger Ergebnisse werden am Beispiel der Primäraluminiumelektrolyse für verschiedene Szenarios der Strombereitstellung die energiebedingten Stoffströme ermittelt und vergleichend gegenübergestellt.
Die Ergebnisse der Analysen weisen die von der Art der Strombereitstellung abhängige Ressourcenintensität sowie die Emissionen in Luft aus und können damit als Basis für eine ökologische Bewertung dienen.

Methodik des Energiemodells

Die Bereitstellung der elektrischen Energie für die Al-Elektrolyseanlagen erfolgt weltweit überwiegend durch Wasserkraft, wobei national die verschiedenen Primärenergieträger zu sehr unterschiedlichen Anteilen eingesetzt werden. In Deutschland und auch insbesondere in Australien wird überwiegend Kohle genutzt, während in Frankreich der Anteil der Kernenergie mit rund 46% sehr hoch ist und in Staaten wie Norwegen und Kanada die Strombereitstellung ausschließlich durch Wasserkraft erfolgt. Die mit der Erzeugung von Aluminium verbundenen energiebedingten Stoffströme sind entsprechend den am Produktionsstandort eingesetzten Stromerzeugungstechniken äußerst unterschiedlich. Für fast alle Staaten ergeben sich damit für die Primäraluminiumproduktion unterschiedliche Stoffströme.
Deutschland gehört zu den Staaten, in denen weniger Primäraluminium erzeugt als verarbeitet wird, es ist daher auf Importe angewiesen. 1995 betrug in Deutschland der Importanteil am insgesamt verfügbaren Hüttenaluminium 65,9% [1]. Die Analyse der Herstellung von Aluminium in Deutschland darf sich daher nicht auf die heimische Produktion alleine beschränken, sondern muß auch die Staaten mit einschließen, die als wesentliche Quellen des Primäraluminiums dienen. Bild 2 zeigt die unmittelbaren Bezugsländer und deren Anteile an dem von Deutschland importierten Hüttenaluminium. Hierbei ist anzumerken, daß das aus den Niederlanden bezogene Aluminium zum überwiegenden Teil selbst von diesem Staat importiert wurde.
Diese vereinfachte Darstellung zeigt bereits sehr deutlich, wie komplex die Analyse der Energieversorgung und damit auch die energiebedingte Schadstoffbilanzierung bei industriellen Produkten in der Regel sind.
Das im Rahmen des Sonderforschungsbereichs zu entwickelnde Energiemodell ist daher so angelegt, daß die Strukturen der Energiebereitstellung für verschiedene Staaten auf einer einheitlichen Datenbasis und methodisch konsistent abgebildet werden. Bisher wurden für die unter den Gesichtspunkten der Aluminiumwirtschaft interessanten Staaten Australien, Kanada, Deutschland, Griechenland, USA sowie für Indonesien Prozeßketten der Stromer-

zeugung bilanziert. Für weitere Staaten (u.a. Norwegen, Dänemark, Großbritannien, Frankreich) sind analoge Betrachtungen zur Zeit Gegenstand der Arbeiten.

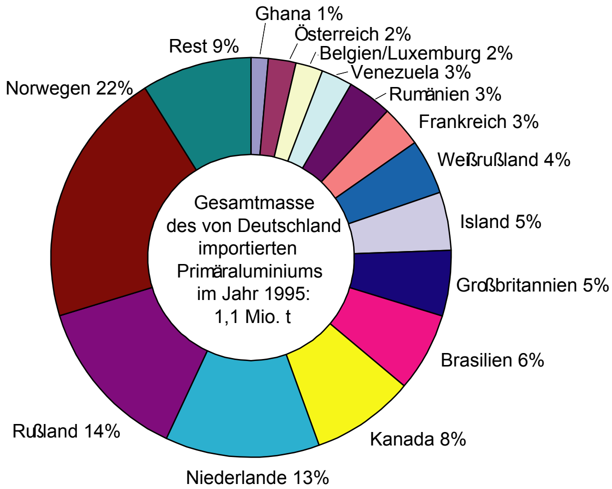

Bild 2: Anteile verschiedener Herkunftländer an dem von Deutschland importierten Primäraluminium [1]

Insbesondere in Staaten mit großem Wasserkraftanteil beziehen Hütten meist Elektrizität aus einem eindeutig zuordenbaren Kraftwerk. Diese Versorgungsstruktur kann als „Inselversorgung“ bezeichnet werden. In anderen Staaten wiederum wird ein Teil der Hütten aus dem öffentlichen Verbundnetz gespeist (Verbundnetzversorgung).

Für die möglichst realitätsnahe Abbildung der Versorgungsstrukturen wurden daher einerseits Prozeßketten aufgestellt und stofflich bilanziert, die die Stromversorgung aus dem landestypischen Strommix beschreiben. Die Bilanzierung reicht von den Primärenergieträgern bis zur Bereitstellung der elektrischen Energie beim Verbraucher. Der elektrische Eigenbedarf der Kraftwerke wird ebenso berücksichtigt wie die Aufwendungen der Brennstoffbereitstellung. Auch Verteilungsverluste sowie Stromimporte und –exporte werden von dem Modell erfaßt. Weiterhin wurden für alle Staaten einzelne Kraftwerke zur Verstromung verschiedener Energieträger definiert (Referenzkraftwerke), die nationale Emissionsgrenzwerte für SO_2, NO_x und Staub sowie den durchschnittlichen Stand der jeweils etablierten Kraftwerkstechnik hinsichtlich des Wirkungsgrades berücksichtigen. Die den Kraftwerken vorgelagerten Prozeßketten der Brennstoffbereitstellung sind bisher weniger detailliert dargestellt. Die Abbildung beschränkt sich hier auf Module, die landesunspezifisch durchschnittliche stoffliche und energetische Ströme für die Bereitstellung von Steinkohle aus Tagebauen und aus Tiefbauen, Dieselöl, Schweröl, Erdgas sowie Brennelemente erfassen. Für die Braunkohlebereitstellung werden Daten der Gewinnung aus einem deutschen Tagebau angesetzt.

Die Versorgung der Prozesse der Brennstoffbereitstellung erfolgt entweder über das jeweilige zugeordnete Kraftwerk oder ein geeignetes Verbundnetz.

Im Bild 3 sind vereinfacht die Strukturen der Modelle wiedergegeben, durch die die entsprechenden Prozeßketten abgebildet werden.

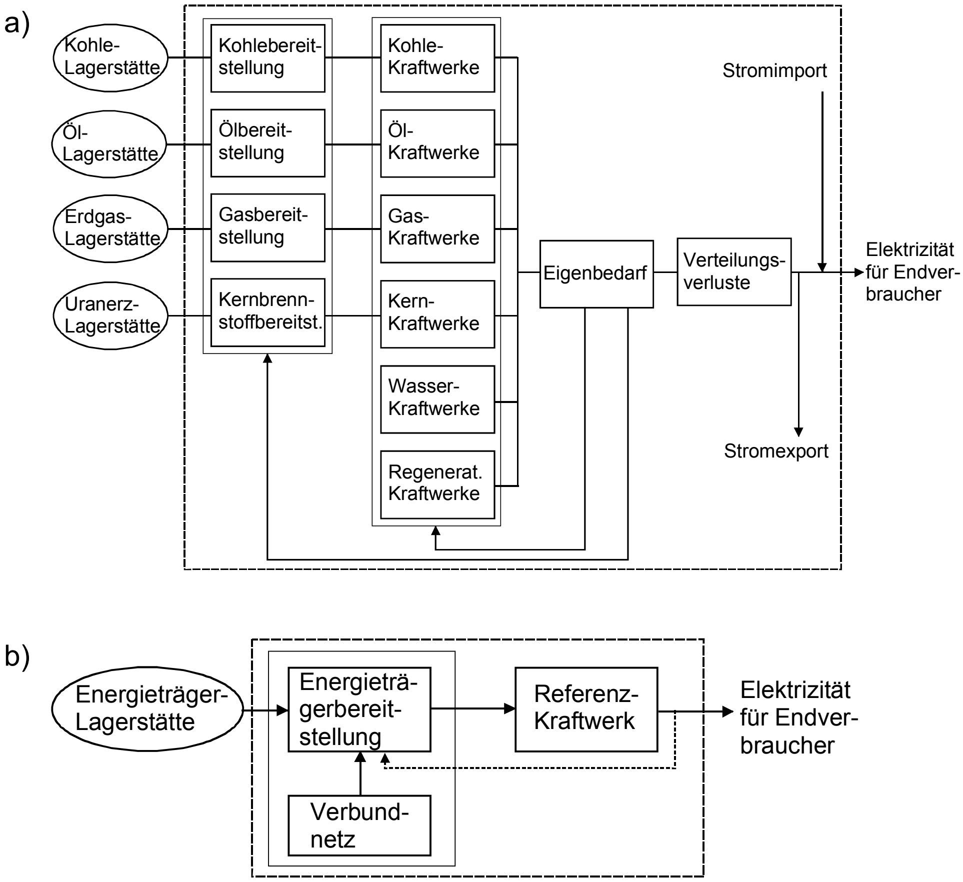

Bild 3: Modellstrukturen zur Abbildung von Landesverbundnetzen (a) und Inselversorgungen (b)

Die Datengrundlage wird im wesentlichen durch umfangreiche statistische Kompendien der IEA/OECD zur Energiewirtschaft, zu Emissionen und nationalen Grenzwerten sowie durch Informationen von Herstellern und Betreibern verschiedener Kraftwerke gebildet. Ergebnisse aus Rechnungen zu Stoff- und Energiebilanzen, eigene Datenerhebungen und in der Literatur dokumentierte Ergebnisse anderer Untersuchungen vervollständigen die Datenbasis. [2-15]

Strombereitstellung aus Landesverbundnetzen

Auf dieser Grundlage wurden für die oben genannten Staaten Bilanzen erstellt, mit denen die mit der Stromversorgung aus dem Landesverbundnetz verbundenen Stoffflüsse berechnet werden konnten. Tabelle 1 gibt eine Übersicht über die Anteile der verschiedenen Energieträgergruppen an der Stromerzeugung im Landesmix sowie eine Übersicht über einige der mit der Stromerzeugung verbundenen Stoffe.

Tabelle 1: Übersicht über landestypische Strommixe – Anteile der Energieträger sowie spezifische Massen und Energien (vorläufige Ergebnisse, Stand 7 `99)

	Australien	Kanada	Deutschland	Griechenland	Indonesien	USA
Anteile an der Stromerzeugung						
Kohlen [%]	76,9	15,1	55,3	69,6	23,5	51,2
Öle [%]	1,7	1,9	1,7	21,5	26,8	2,4
Gase [%]	10,3	3,9	8,0	0,2	32,0	14,8
Kernbrennstoffe [%]	0	17,7	28,7	0	0	19,9
Wasserkraft [%]	9,3	60,6	4,5	8,6	14,2	9,4
Erneuerbares [%]	1,8	0,8	1,8	0,1	3,6	2,3
Input						
Primärenergie [MJ/kWh_{el}]	10,34	6,78	11,54	12,72	11,16	10,50
Hydro [MJ/kWh]	0,42	2,73	0,19	0,39	0,80	0,42
Steinkohle [g/kWh]	158	19	112	3	116	139
Braunkohle [g/kWh]	445	66	340	1650	0	118
Erdgas [g/kWh]	27	9	10	<1	100	47
Rohöl [g/kWh]	9	5	5	66	63	9
U_3O_8 [10^{-3}g/kWh]	0	4,64	9,72	0	0	5,57
Output						
CO_2 [g/kWh]	913	202	710	1108	840	678
SO_2 [g/kWh]	4,87	1,12	2,75	2,40	7,78	3,60
NO_X [g/kWh]	3,39	0,48	0,83	2,03	3,05	1,91
Staub [g/kWh]	0,27	0,20	0,07	0,28	1,50	0,17
CO [g/kWh]	0,31	0,16	0,20	0,26	0,14	0,10
g_{el}	0,348	0,531	0,313	0,283	0,323	0,343

Hier wurden auf der Inputseite die wichtigsten Energieträger und auf der Outputseite CO_2 sowie die bekanntesten Luftschadstoffe ausgewählt. Zusätzlich wurde der Bereitstellungsnutzungsgrad g_{el} bestimmt, der als Verhältnis aus der für den Endverbraucher zur Verfügung gestellten Elektrizität und der Summe der primärenergetischen Aufwendungen definiert ist. Er beschreibt ähnlich einem Wirkungsgrad die Effizienz der Energiebereitstellung von Endenergie aus Primärenergieträgern unter Einbezug aller energetischen Aufwendungen und Umwandlungs- sowie Verteilungsverluste. Aufwendungen für die Herstellung und Entsorgung von Betriebsmitteln wurden hier aufgrund des vernachlässigbar geringen Einflusses abweichend von der VDI-Richtlinie 4600 [16] nicht berücksichtigt. Die Wirkungsgrade von Kernkraftwerken wurden einheitlich zu 33% und von Wasserkraftwerken zu 80% gesetzt. Soweit möglich wurden die landestypischen Heizwerte und Schwefelgehalte von Kohlen berücksichtigt.

Die hohen spezifischen SO_2-Emissionen im Jahr 1995 für den deutschen Verbundmix resultieren aus der Verstromung von ostdeutscher, vergleichsweise schwefelreicher Braunkohle in Kraftwerken ohne REA. Mittlerweile sind die SO_2-Emissionen auch hier stark gesunken.

Die nationalen Verbundnetze der meisten Staaten sind mit Netzen benachbarter Staaten verknüpft. Zwischen diesen Staaten wird Elektrizität ausgetauscht. Bei der Bestimmung der mit der Bereitstellung der in einem Staat verfügbaren Elektrizität verbundenen Stoffströme kann die Berücksichtigung von Importstrom sinnvoll sein. Einige Staaten wie Frankreich und Norwegen waren 1995 Nettostromexporteure, während andere Staaten wie Italien und die Niederlande wesentliche Anteile ihrer Elektrizität durch Importe deckten. Aber auch Staaten wie Deutschland, deren Stromhandelsbilanz zwar in diesem Jahr weitgehend ausgeglichen war, bezogen dennoch erhebliche Mengen Strom aus dem benachbarten Ausland. In Bild 4 sind die Größen der zwischen den mitteleuropäischen Staaten transferierten Energien skizziert.

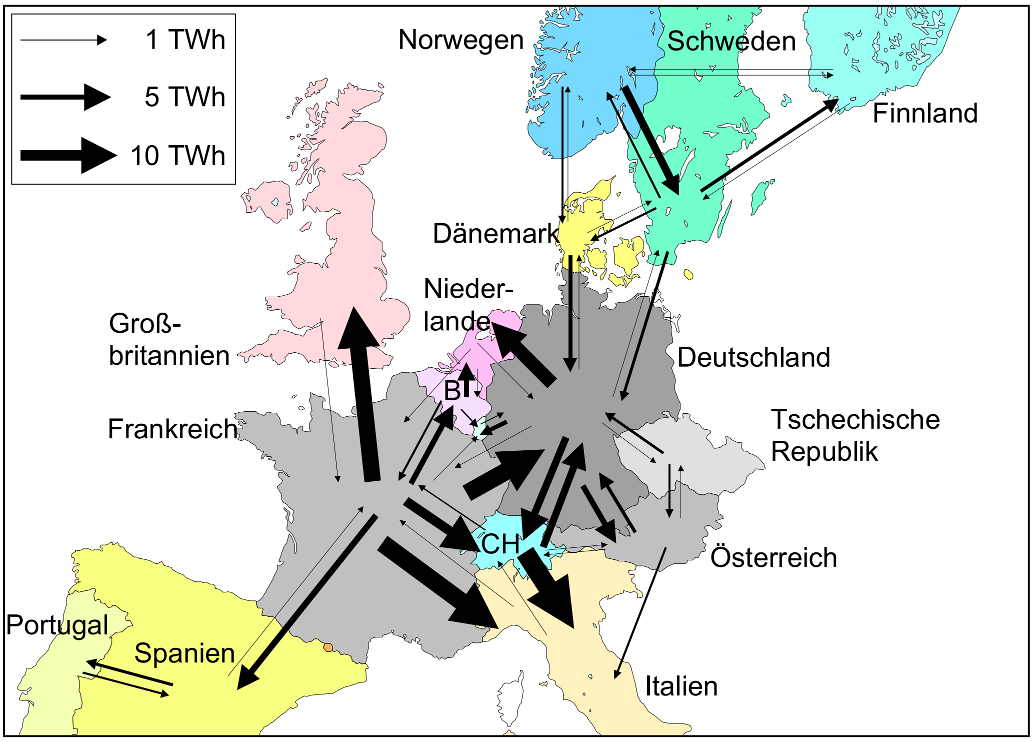

Bild 4: Transfer von Elektrizität in Europa 1995 [14]

Auf die Bruttostromerzeugung von 1995 bezogen wurden in diesem Jahr von Deutschland 3,2% alleine aus Frankreich importiert. Insgesamt betrug der Importanteil 7,4%. Im Bild 6 sind maßstäblich die Bruttostromerzeugungen, die Menge der von Frankreich nach Deutschland transferierten Elektrizität sowie die landesspezifischen Strommixe dargestellt.

Die Bruttostromerzeugung in Frankreich erfolgte 1995 zu 77% aus Kernenergie und zu rund 15% aus Wasserkraft, mit lediglich 8% sind fossile Energieträger an der Stromerzeugung beteiligt. Dementsprechend sind die für die Nutzung fossiler Energieträger typischen Stoffströme (Kohlen, Gase, CO_2, SO_2, usw.) in diesem Staat äußerst gering. Werden der aus Frankreich importierte Strom und die mit seiner Bereitstellung verbundenen Stoffe berücksichtigt, verändern sich die spezifischen Stoffströme, die mit der in Deutschland beim Endverbraucher verfügbaren Elektrizität verbunden sind, merklich. Die spezifischen Massen von Kohlendioxid sowie der Schadstoffe CO, NO_x, SO_2 und Staub verringern sich um 2,5 - 4% relativ, während aufgrund des großen Kernkraftanteils die spez. Massen abgebrannter Brennelemente und von Uranerz um rund 5,5% steigen. Analoge modellbasierte Betrachtungen für Kanada zeigen, daß durch den Import von Elektrizität aus den USA relative Änderungen der spezifischen Stoffströme von bis zu plus 9% bewirkt werden. Nach dem gegenwärtigen Stand der Arbeiten scheint es sinnvoll, für jeden betrachteten Staat durch eine Sensibilitätsanalyse zu prüfen, ob die Berücksichtigung von Stromimporten und den damit verbundenen Stoffströmen sinnvoll ist.

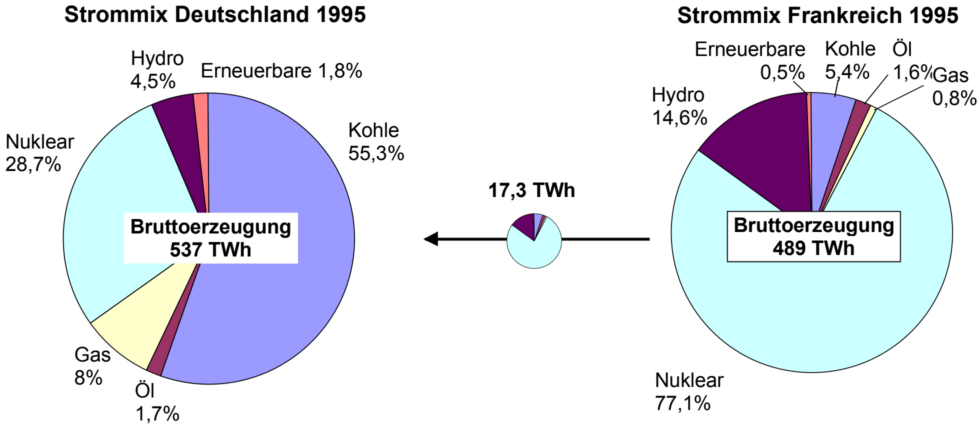

Bild 5: Strommixe Deutschland - Frankreich, transferierte Elektrizität

Strombereitstellung durch Einzelkraftwerke

Die Stromversorgung von Primäraluminiumhütten erfolgt in den meisten Fällen im Inselbetrieb, d.h. einer Hütte kann für die Bereitstellung von elektrischer Energie eindeutig ein Kraftwerk zugeordnet werden. Eine solche Zuordnung ist zwar im Falle eines bestehenden Verbundnetzes physikalisch nicht völlig korrekt, da z.B. während Revisionsarbeiten am vertraglich zugeordneten Kraftwerk die Stromversorgung durch andere Kraftwerke gedeckt wird. Die hieraus resultierenden Ungenauigkeiten können aber im Vergleich zu dem Fehler, der durch die Bilanzierung auf der Grundlage des Verbundnetzmixes entsteht, vernachlässigt werden.

Zur Abbildung von Insellösungen sind innerhalb des Energiemodells Referenzkraftwerke unter Berücksichtigung verschiedener Randbedingungen definiert und bilanziert worden. Dabei sind jeweils Daten zum Betrieb bei Nennlast zugrunde gelegt worden.

Durch eine parametrisierte Darstellung ist die Modellierung von speziellen Kraftwerken in Abhängigkeit von Energieträger, Standort, Technik und Zeit möglich.

Im einzelnen werden bislang acht Steinkohle-, vier Braunkohle-, vier Öl-, neun Gas- und drei Kernkraftwerke sowie ein Wasserkraftwerk unterschieden, die verschiedene Techniknivaus in unterschiedlichen für die Aluminiumwirtschaft relevanten Ländern (s.o.) repräsentieren.

Die Identifizierung der jeweiligen Stromversorgungsstruktur einer Hütte ist in einigen Fällen schwierig. In Deutschland werden z.B. alle Primäraluminiumhütten über Kraftwerke versorgt, die gleichzeitig Strom in das öffentliche Netz einspeisen, so daß hier physikalisch eine eindeutige Trennung zwischen Insel- und Verbundnetzversorgungen nicht möglich ist. Für die Bilanzierung der energiebedingten Stoffströme folgt aus dieser Betrachtung, daß nur in Einzelfällen die Energieversorgungsstrukturen zutreffend abgebildet und die energiebedingten Stoffströme genau analysiert werden können.

Ergebnisse für verschiedene Szenarios der Strombereitstellung

Auf der Basis der bisher im Rahmen des Energiemodells abgebildeten Prozeßketten der Stromerzeugung werden im folgenden für verschiedene Szenarios der Strombereitstellung Schwankungsbreiten der energiebedingten spezifischen Stoffströme aufgezeigt, die mit der Herstellung von Primäraluminium verbunden sind. Betrachtet wird beispielhaft eine moderne Hütte mit PFPB-Elektrolysesystem[1], für das ein spezifischer Strombedarf von 13000 kWh_{el}/t_{Al} angesetzt wird. Als Stromversorgungsstrukturen werden zum Vergleich folgende in Tabelle 2 charakterisierten Systeme betrachtet:

Tabelle 2: Ausgewählte Systeme der Stromversorgung

Kennzeichnung/Beschreibung	$\eta_{el,netto}$	Stand der Technik	Kühlverfahren
BrK-35: Braunkohle-KW (rhein.), unterkrit. DT-Prozeß, REA, E-Filter, Trockenstaubfeuerung	35%	≈ 1975	Naßkühlturm
BrK-42: Braunkohle-KW (rhein.), überkrit. DT-Prozeß, REA, E-Filter, Trockenstaubfeuerung	42%	≈ 1999	Naßkühlturm
StK-38: Steinkohle-KW, unterkrit. DT-Prozeß, REA, DENOX, E-Filter, Schmelzfeuerung	38%	≈ 1985	Naßkühlturm
StK-46: Steinkohle-KW, überkrit. DT-Prozeß, REA, DENOX, E-Filter, Schmelzfeuerung	46%	≈ 1999	Naßkühlturm
GuD-58: Erdgas-GuD-Prozeß	58%	≈ 1999	Fließwasser
DWR-33: DWR-Kernkraftwerk, unterkrit. DT-Prozeß	33%	≈ 1985	Naßkühlturm
D-1995: Landesverbundmix D-1995	32,8%	(1995)	Fließw./Naßkühlt.[2]

Hier wurden Techniken der 70iger, 80iger sowie modernste Techniken vorausgesetzt. Speziell bei Steinkohle (StK-46) und GUD-58 wurden Wirkungsgrade benutzt, die erst bei Anlagen, die sich derzeit im Bau befinden, erreicht werden.

Für Kernkraftwerke wurde ein elektrischer Nettowirkungsgrad von 33% angesetzt, der für den Betrieb von Druck- und Siedewasserreaktoren gegenwärtig typisch ist.

Aus den Bilanzen des deutschen Verbundnetzes folgt unter Berücksichtigung des Strommixes im Jahr 1995 und der realen Betriebscharakteristik (Grund-, Mittel-, Spitzenlast) ein

[1] PFPB: Point Feeder PreBaked – Schmelzflußelektrolyse mit Punktdosierung und vorgebackenen Anoden

[2] Modellannahme: 80% der KW-Abwärme wird über Naßkühltürme, 20% über Fließwasserkühlung abgeführt

durchschnittlicher Wirkungsgrad der Stromerzeugung mit Kraftwerken und Heizkraftwerken von 32,8%.

Tabelle 3 gibt im Vergleich die Massen einiger bilanzierter Stoffe wieder, die energiebedingt zur Herstellung von 1 t_{Al} eingesetzt werden. Die verstromte Braunkohle wird hierbei durch einen westdeutschen Tagebau bereitgestellt, Steinkohle wird in diesem Modell untertägig gewonnen. Die elektrische Energie zur Gewinnung der Kohlen wird durch das jeweilige Kraftwerk bereitgestellt. Für die Bereitstellung von Erdgas und Kernbrennstoffen und die damit verbundenen Prozeßenergien werden Durchschnittswerte angesetzt.

Tabelle 3: Übersicht über energiebedingte Stoffströme zur Herstellung von 1 t Primäraluminium für verschiedene Szenarios der Strombereitstellung, gerundete Werte (vorläufige Ergebnisse, Stand 7'99)

	BrK-35	BrK-42	StK-38	StK-46	GuD-58	DWR-33	D-1995
Inputs							
Wasser [kg/t_{AL}]	99.265	82.122	33.940	24.800	521	35.300	57.020
Luft [kg/t_{AL}]	57.500	47.570	44.650	36.700	90.860	156	32.700
Braunk. [kg/t_{AL}]	15.690	12.980	0	0	0	21	4.420
Steink. [kg/t_{AL}]	0	0	4.220	3.470	0	12	1.451
U_3O_8 [kg/t_{AL}]	0	0	0	0	0	<1	<1
Erdgas [kg/t_{AL}]	0	0	0	0	2.040	<1	125
Rohöl [kg/t_{AL}]	2	2	3	3	0	<1	66
NH_3 [kg/t_{AL}]	0	0	29	23	0	<1	9
Kalkstein [kg/t_{AL}]	168	139	226	185	0	<1	63
Outputs							
Abwasser [kg/t_{AL}]	68.218	56.437	7.950	6.540	521	885	3.320
Schwaden [kg/t_{AL}]	30.160	24.950	25.950	18.000	0	34.410	25.710
CO_2 [kg/t_{AL}]	16.270	13.460	12.020	9.880	4.260	44	9.224
CO [kg/t_{AL}]	3	2	1	1	<1	<1	3
SO_2 [kg/t_{AL}]	6	5	9	7	3	<1	36
NO_x [kg/t_{AL}]	6	5	5	4	4	<1	11
NMVOC [kg/t_{AL}]	6	5	<1	<1	<1	<1	<1
Staub [kg/t_{AL}]	2	1	1	1	<1	<1	1
Asche [kg/t_{AL}]	785	648	0	0	0	<1	155
Schlacke [kg/t_{AL}]	0	0	155	128	0	<1	100
Gips [kg/t_{AL}]	170	139	226	185	0	<1	120
Abgebr.BE [kg/t_{AL}]	0	0	0	0	0	<1	<1

Insbesondere der Stoffstrom des Wassers ist zwischen den betrachteten Ketten äußerst unterschiedlich. Der Wassermassenstrom der Braunkohleverstromung von bis zu 100 t_{Wasser}/t_{Al} wird im wesentlichen durch die bei der Braunkohlenförderung abzupumpende Grundwassermasse hervorgerufen. Da fast ausschließlich Elektrizität für die Gewinnung von Braunkohle eingesetzt wird und Transporte zwischen Lagerstätte und Kraftwerk nur über kurze Strecken erfolgen, werden außer Braunkohle kaum andere Energieträger eingesetzt. Für die untertägige Steinkohlengewinnung sowie Transporte werden hingegen auch Ölprodukte wie Dieseltreibstoff verwendet. Der geringe Wasserbedarf der Strombereitstellung durch das GuD-Kraftwerk folgt aus der Fließwasserkühlung, deren Wassermassenstrom nicht bilanziert wurde, da dieser weder eine Änderung seiner Zusammensetzung erfährt noch sich seine Phase bei der Nutzung als Kühlmedium ändert. Hierin ist ein wesentlicher Unterschied zum Naßkühlturm zu sehen, dessen Zusatzwasser verdampft und damit nicht mehr direkt zur Verfügung steht. Allerdings werden auch durch die Temperaturerhöhung eines fließenden Gewässers bei Nutzung als Kühlmittel ökologische Auswirkungen hervorgerufen, die hier jedoch nicht betrachtet werden können.

Energieeinsparpotentiale bei der Primäraluminiumherstellung

Mit dem hier vorgestellten Energiemodell sollen auch zeitliche Entwicklungen hinsichtlich der Effizienz in der Energieumwandlung abgebildet werden, um erreichte Reduktionen des Primärenergieaufwandes, Einsparpotentiale durch Energieträgersubstitution und deren Einfluß auf die Massen von umweltrelevanten Stoffen aufzuzeigen.

Der Primärenergiebedarf der Stromerzeugung wird bei fossiler und nuklearer Strombereitstellung vom Kraftwerkswirkungsgrad dominiert. Durch Verbesserung der Prozesse, Entwicklungen in der Werkstofftechnik und Optimierungen der Komponenten konnten die Wirkungsgrade der fossilen Kraftwerke in den vergangenen Jahrzehnten erheblich gesteigert werden. In der Kerntechnik sind innerhalb der Druck- und Siedewasserreaktorbaulinien keine vergleichbaren Fortschritte möglich gewesen, Optimierungen einzelner Komponenten brachten hier Steigerungen der Wirkungsgrade im Bereich von etwa einem Prozentpunkt [17].

In Bild 6 ist der spezifische Energieaufwand (kWh_{th}/kWh_{el}) der Stromerzeugung für ausgeführte und projektierte Kohle- und Erdgas-GuD-Kraftwerke in den letzten 40 Jahren dargestellt. Den Kraftwerken vorgelagerte Prozeßketten der Brennstoffbereitstellung wurden hierbei nicht betrachtet. Die Trendlinien für Steinkohle- und Braunkohleblöcke zeigen, daß seit 1960 die spez. Energieaufwendungen um 23% (Braunkohle) bzw. 28% (Steinkohle) gesenkt werden konnten.

Seit Mitte der siebziger Jahre sank der spez. Energieaufwand der Stromerzeugung mit GuD-Kraftwerken sogar um rund 36%. Bei allen Kraftwerkssystemen wird auch in den nächsten Jahren mit weiter steigenden Wirkungsgraden und entsprechend sinkendem spezifischen Primärenergiebedarf gerechnet.

Ein Vergleich mit der zeitlichen Entwicklung des spezifischen Strombedarfs von PFPB-Schmelzflußelektrolysen (Bild 7) zeigt, daß in der Prozeßtechnik der Aluminiumherstellung Einsparungen im gleichen Zeitraum (40 Jahre) von nur knapp 15% erreicht werden konnten.

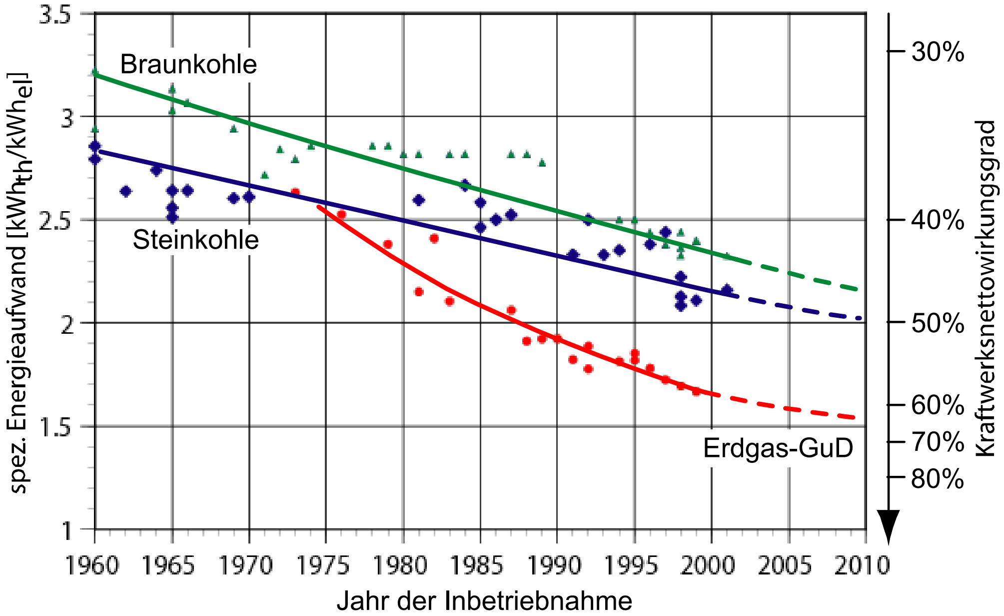

Bild 6: Zeitliche Entwicklung des spezifischen Energieaufwandes der Stromerzeugung fossiler Kraftwerke

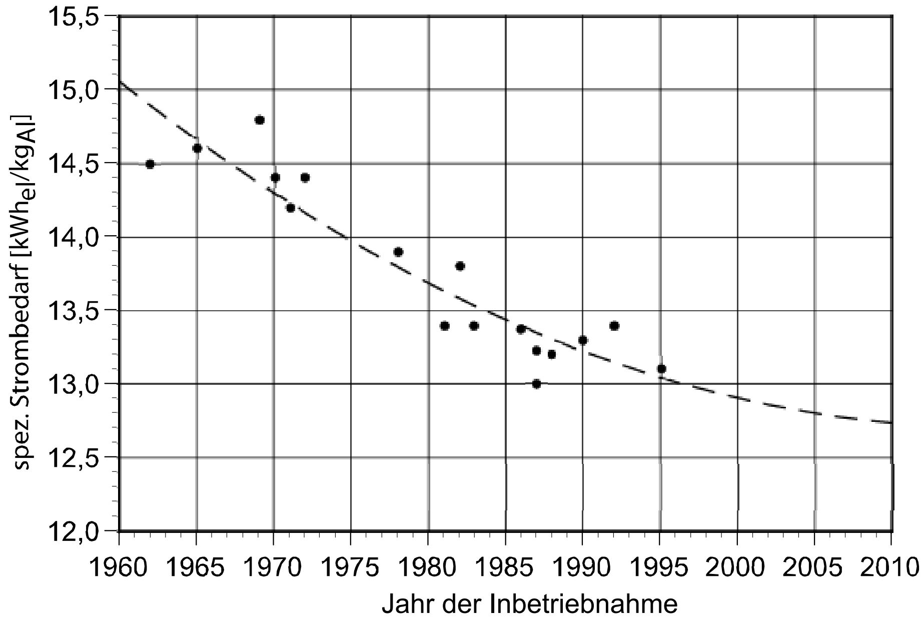

Bild 7: Zeitliche Entwicklung des Strombedarfs von PFPB-Schmelzflußelektrolysen

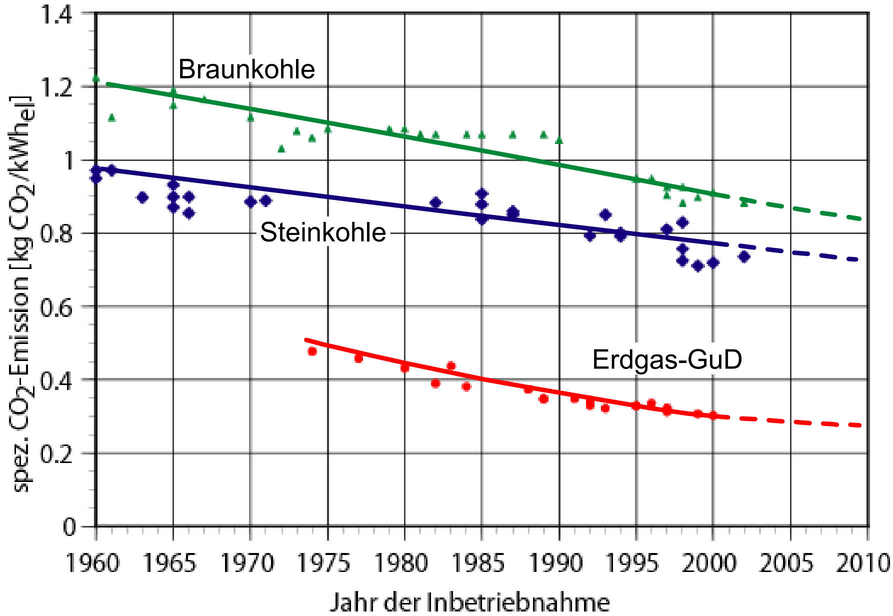

Bild 8: Zeitliche Entwicklung der spezifischen CO_2-Emissionen von fossilen Kraftwerken

Die spezifischen CO_2-Emissionen betragen bei modernen erdgasgefeuerten GuD-Blöcken weniger als ein Drittel der mit Braunkohle gefeuerten Blöcke aus den frühen siebziger Jahren.

Zusammen mit dem spez. Strombedarf der Elektrolyse nach Bild 7 können im Rahmen von Szenariorechnungen die spezifischen stromerzeugungsbedingten CO_2-Emissionen der Primäraluminiumherstellung z.B. für die Jahre 1960 und 2000 berechnet werden. Werden jeweils dem Stand der Technik entsprechende Kraftwerks- und Elektrolysesysteme betrachtet, ergeben sich die spezifischen CO_2-Emissionen nach Tabelle 4.

Tabelle 4: Spezifische stromerzeugungsbedingte CO_2-Emissionen der Primäraluminiumherstellung für verschiedene Szenarios der Strombereitstellung

Jahr	Braunkohle-KW	Steinkohle-KW	Erdgas-GuD
1960	18,4 $kgCO_2/kg_{Al}$	14,7 $kgCO_2/kg_{Al}$	7,0 $kgCO_2/kg_{Al}$ (Bezugsjahr1975)
2000	11,5 $kgCO_2/kg_{Al}$	9,6 $kgCO_2/kg_{Al}$	3,8 $kgCO_2/kg_{Al}$

Die Zahlen weisen je nach Energieträger Reduktionen der spez. Emissionen zwischen 35 und rund 45% (Bezugsjahr 1960 bzw. 1975) auf. Die Betrachtung der CO_2-Emissionen einer über ein Braunkohlekraftwerk mit Strom versorgten Hütte von 1960 und einer Elekrolyse, die Elektrizität eines modernen Erdgas-GuD-Kraftwerks bezieht, zeigt, daß sich insgesamt durch Optimierungen der Elektrolysetechnik und der Substitution von kohlenstoffreichen zu kohlenstoffärmeren Energieträgern sowie Optimierungen der Kraftwerktechnik die spezifischen stromerzeugungsbedingten CO_2-Emissionen um fast 80% reduzieren ließen. Der Beitrag durch die verbesserte Elektrolysetechnik beträgt hierbei entsprechend dem Rückgang des

Strombedarfs nur rund 15%, die übrige Reduktion ist auf die Energiebereitstellung zurückzuführen.
Der große Einfluß der Techniken der Energiebereitstellung auf die energiebedingten Stoffströme unterstreicht die Notwendigkeit der Identifikation des tatsächlich für die Stromversorgung relevanten Systems. Gerade im Rahmen von Sachbilanzen, die die Grundlage für die Abschätzung von Wirkungen auf die Umwelt bilden, ist die differenzierte und detaillierte Abbildung der wesentlichen Charakteristika der realen Energieversorgungsstrukturen unerläßlich.

Zusammenfassung und Ausblick

Das vom Lehrstuhl für Reaktorsicherheit und -technik entwickelte Energiemodell dient der Bestimmung von Stoffströmen, die mit der Bereitstellung von Energieträgern verbunden sind. Zeitliche Entwicklungen insbesondere in der Kraftwerkstechnik, Standortabhängigkeiten sowie technische Parameter werden erfaßt, abgebildet und erlauben damit Analysen der Prozeßketten der Energiebereitstellung hinsichtlich der Stoffströme - insbesondere Emissionen - und des Primärenergieaufwands.
Am Beispiel des energieintensiven Prozesses der Primäraluminiumherstellung in der Schmelzflußelektrolyse wird die Bedeutung der differenzierten Betrachtung der Techniken der Energiebereitstellung hinsichtlich der Stoffströme und Primärenergieeinsparpotentiale diskutiert. Während der Prozeß der Metallherstellung unter energetischen Gesichtspunkten weitgehend optimiert ist, weisen die Techniken der Stromerzeugung noch erhebliche Potentiale auf. Diese liegen zum einen in der Steigerung der Wirkungsgrade, zum anderen bietet die Substitution von Energieträgern die Möglichkeit der Einflußnahme sowohl auf die Art als auch auf die Quantität der mit der Stromerzeugung verbundenen Stoffströme.
Die Zielsetzung bei der insgesamt günstigsten Gestaltung der Energieversorgung wird international unterschiedlich definiert. In dichtbesiedelten und hochindustrialisierten Staaten wie Deutschland genießen Aspekte des Umweltschutzes große Priorität und Maßnahmen zur Emissionsminderung von Schadstoffen werden durch strenge Grenzwerte vorgeschrieben. In vielen Staaten gelten erheblich abweichende Grenzwerte. Das vorgestellte Energiemodell erlaubt nach dem bisher erreichten Entwicklungsstand die Abbildung von Prozeßketten der Energiebereitstellung in einigen ausgewählten Ländern unter Berücksichtigung nationaler Charakteristika wie Strommix, Brennstoffarten, Verteilungsverluste, Technikstand und Emissionsgrenzwerte. Es bildet hiermit eine Basis für eine umfassende Analyse der energiebedingten Stoffströme von Rohstoffen, die wie Primäraluminium nicht auf ein Land bezogen sondern stets im globalen Zusammenhang betrachtet werden müssen.

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ENERGY MARKET DEVELOPMENTS AND THE IMPACT ON NON-FERROUS METAL PRODUCTION*

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ABSTRACT

The specific use of energy for the production of important non-ferrous metals is very high. This explains why the production, manufacturing and recycling costs of these materials are very much influenced by developments on the energy market. Low energy and raw material costs, a long-term ensured supply under clear conditions, as well as environmental laws, which keep in view the competitiveness of industrial production, are essential requirements to determine whether new investments in power plants can be made or if existing plants can be economically operated in the future.

At the times of liberalisation not only the production costs and costs for electric power have changed, there are as well many aspects of supply which are already modified: Mergers of companies on the supply side caused changes; the liberalised market could be tangent to questions of availability, security of supply and questions of energy exports and imports. Also the discussion on the carbon Dioxide Climate Problem and questions in respect to the conditions of the future use of fossil energy carriers have to be addressed differently in a liberalised market. Already today there exists a varying starting position of energy utilisation in the various countries of the European Union. Without realistic assessments it could result in strong market distortions and for instance lead to electricity imports from countries with very low production costs.

KEYWORDS

Energy supply, primary energy demand, non-ferrous industry, aluminium price, energy supply safety, energy costs, power plants, renewable energy, nuclear energy, fossil energy

* Source: Proceedings EMC 2001, Friedrichshafen

1 Importance of the energy supply for the non-ferrous manufacturing industry

For industrialised economies mineral raw materials, especially metallic raw materials, are of crucial importance. The following figure 1a shows the development during time concerning the production of selected metallic raw materials, which are used in technical applications. Especially aluminium shows a significant rise in importance [1,2].

These metallic raw materials are nowadays produced by means of metallurgical processes which are usually very energy-intensive. The average primary energy demand for the primary production of the mentioned metallic raw materials is displayed in figure 1b. Besides the primary energy demand for the reduction process, also the primary energy demands for processes belonging to the backward- and forward linkages of the production chain are considered. The primary energy demands shown here can vary significantly depending on the applied production process as well as the utilisation ratio of the final energies used. Therefore the supply of energy for the single process steps is of great avail besides the raw material supply of such metallurgical processes.

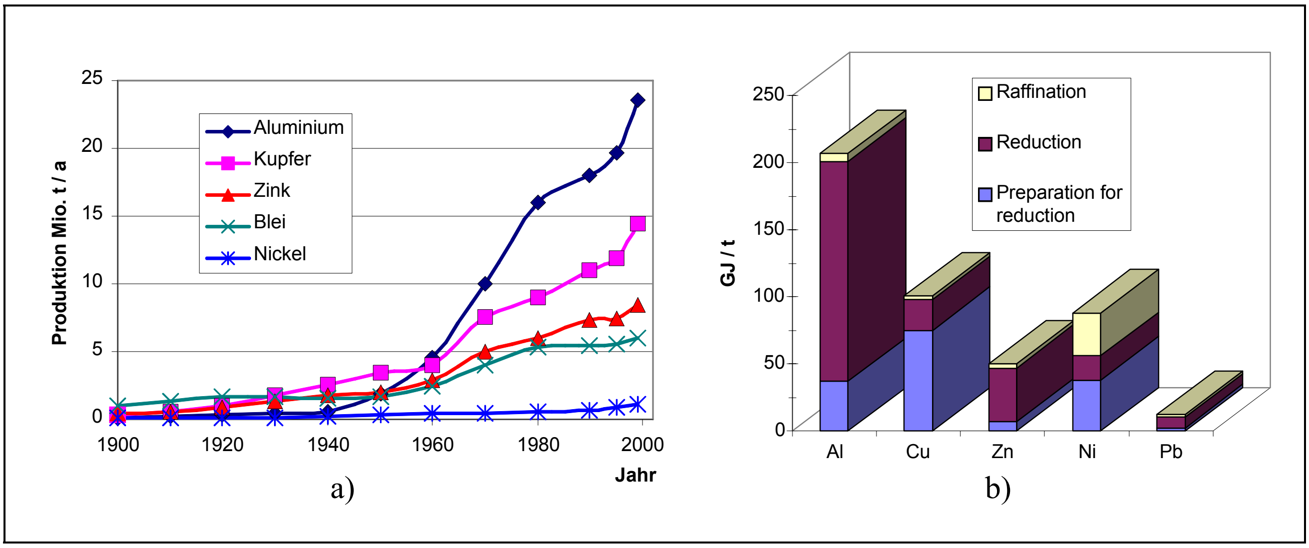

Figure 1: Aspects of the NF-industry
a) Development of world-wide non-ferrous (NF) metal production [1]
b) Primary energy demand of various NF-metals [2 and own calculations]

Moreover the high energy input significantly influence the overall costs, e.g. the overall productions costs of aluminium. As can be seen in figure 2, the share of energy costs concerning the overall costs of aluminium production amounts to approximately one third [3]. The costs for electricity used in the smelter accounts for most of these costs.

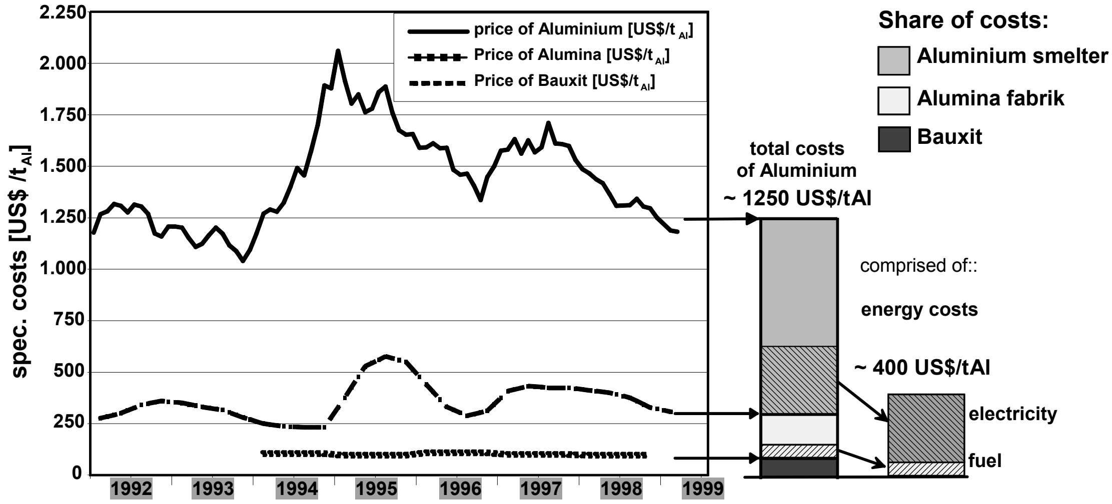

Figure 2: Development of aluminium price and share of energy costs in relation to the price of aluminium in 1998 [3]

In summary it can be stated, that the energy supply for those processes has to be provided with a primary energy input which is as low as possible, it has to be ecologically justifiable and at the same time it has to result in an acceptable level of competitiveness on the world market.

Besides the NF-metals shown in figure 1, also the production of silicon will attain a great importance. Silicon is a key material for the electronics industry as well as the future photo-voltaic energy production. Like aluminium it requires a high input of electrical energy which amounts to an average of about 15,000 kWh_{el}/t of silicon.

2 Energy supply for the NF-industry in Germany and the EU

In figure 3a the development of final energy consumption in the NF-industry of Germany and the EU during time is shown [4]. The introduction of modern energy-efficient technologies lead to a stabilisation of the final energy input. In 1997 the final energy input in the NF-industry in the EU amounted to some 0,9% and 1% in Germany as far as the respective shares of the entire final energy consumption is concerned. Electricity use amounts to more than half of the overall final energy input (approx. 59% in Germany and 56% in the EU). Also in this case technical progress in the process range contributed to a restriction of the overall increase of electricity consumption. This shows the great overall importance of electricity supply for the NF-industry. Figure 3b shows the development of electricity input for Germany and the EU during time. Also in this case technical progress in the range of the processes applied contributed to a restriction of the overall increase of electricity consumption.

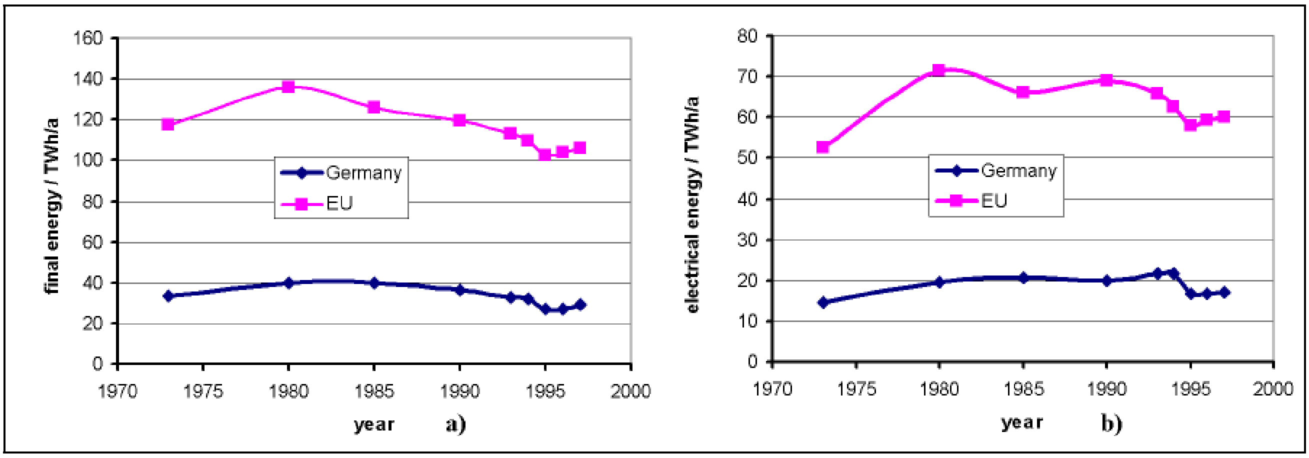

Figure 3: Energy demand (a: final energy; b: electric power) for the production of NF-metal in Germany and the EU [4]

3 Energetical aspects of the production of NF-metals – Example of primary aluminum production

The comparatively high energy consumption of primary aluminium production is mainly caused by the electrolysis. The largest potential for energy savings therefore lies with an optimisation of the electrolysis technology. As shown in figure 4, the specific electricity demand of the electrolysis could be constantly lowered during the recent decades by means of technical improvements in the range of electrolysis technology [5]. As an example the final energy demand of a PFPB-electrolysis during time as a function of the year of operation initiation is displayed. Since 1960 an approximate overall decrease of final energy demand of about 15% could be achieved. The increasingly flat graph gradient leads to the assumption, that no further significant saving potentials for the PFPB-technology can be expected. Improvements concerning other electrolysis-technologies can still be possible, but will probably be limited to approx. 1kWh/kg Al taking into account the already achieved development levels.

Furthermore it has to be considered that energy savings in many cases will have to be bought at the cost of ever greater technical expenses. Consequently there always occurs an optimisation problem. By increased investments the specific energy input as well as the energy costs can be reduced. Therefore in practice it will be mandatory to search for a compromise between the investments and the energy costs. It will be especially reasonable to apply technical improvements in order to achieve the specific energy demand, if the specific energy costs (fuel costs and electricity costs) are high. Due to the fact that the overall operation time often amounts to some decades and a lot of cost parameters can significantly vary during that period – especially given the fact that energy prices are expected to distinctly escalate -, a dynamic analysis of the costs, e.g. by applying the life-cycle cost calculation method, may be required.

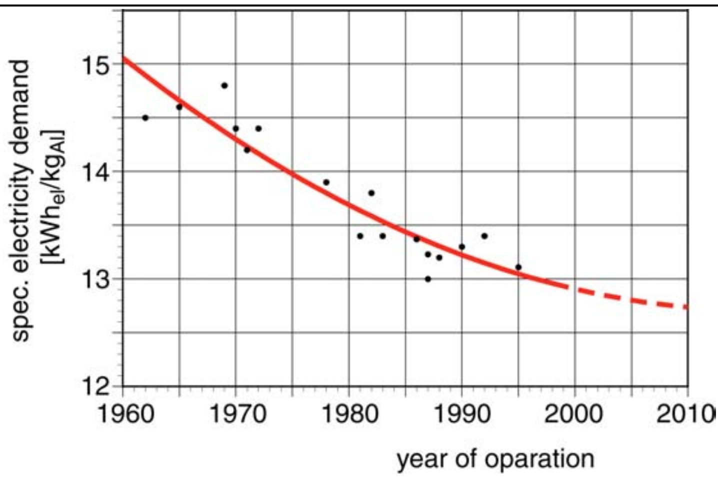

Figure 4: Development of electricity demand – Example of a electrolyses for the production of primary aluminium [5]

4 Aspects of energy supply safety for the industry

In the preceding sections it was demonstrated, that the NF-industry is dependent on fossil fuels (40%) and on electricity (60%), with the electricity in Germany being produced from fossil fuels by likewise 60%. For a secure energy import supply it is therefore important to know, how the dependence on energy imports of a country viewed is structured. Correspondingly the dependence of Germany on energy imports is shown in figure 5 [6].

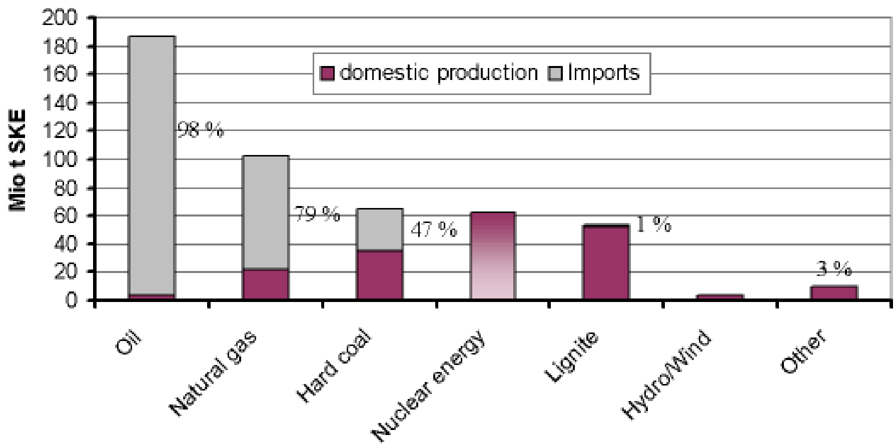

Figure 5: German dependence on energy imports in 1999 [6]

The country is nearly completely (98%) dependent on oil imports while dependence on natural gas imports amounts to a rather similar high figure (79%). As far as hard coal imports are concerned, the import share is still comparatively low (47%) which is likely to significantly rise in the future though. The most important countries supplying primary energy carriers to Germany are Russia

(Oil & Gas: ca. 85 Mio.tSKE/a), Norway (Oil & Gas: ca. 50 Mio.tSKE/a), Great Britain (Oil & Gas: ca. 22 Mio.tSKE/a), Netherlands (Gas: ca. 20 Mio.tSKE/a) and Libya (Oil: ca. 18 Mio.tSKE/a) [6]. The origin of the imported crude oil has largely changed over time. While more than 96% of overall imports were still obtained from OPEC member countries in 1973, those countries only contributed some 28% in the year 2000. Almost 31% accounted for production areas in the North Sea region with the remainder originating from the Middle East (13%), Africa (21%), Russia/Eastern Europe & Asia (33%) and South America (2%). The significantly increased supply share from production countries, which are not members of the OPEC organisation, such as Norway, Great Britain or Russia, which evolved after the negative experiences of the oil price crisis, resulted in a decisive reduction of the formerly predominant import dependence from OPEC member countries. This development of diversifying the supply sources with a strong supply component based on politically stable European countries such as Norway or Great Britain will in any case only remain a temporary phenomenon. This is due to the fact that there is a vast discrepancy between the current supply countries` production levels and their respective oil reserves. The oil reserves of Norway will only last for other 13 years at current production levels. Great Britain's oil reserves have a static range of about 10 years while the expected remaining production time for Saudi-Arabia amounts to 81 years with the figure for the Commonwealth of Independent States (CIS), mainly Russia, amounting to about 41 years. The quantitatively outstanding reserves of the OPEC countries, especially of the member countries in the Middle East, as well as the reserves of the CIS region, therefore will inevitably gain a much greater importance in the medium- or long-term.

5 Current costs of electrical energy supply

Especially the generating costs of electrical energy are strongly depending on the energy carrier used. Furthermore they are largely determined by the plant utilisation ratio and the technical design respectively the age of the plant as well as the depreciation modalities. As can be derived from table 2, already amortised plants in Germany such as older nuclear plants have the lowest generating costs for electricity. New power plants on the basis of natural gas have the highest generating costs in spite of low investment costs. The low electricity generating costs of fossil-fired power plants shown in the table can be explained by the currently low fuel costs as well as the cost reduction pressure imposed on the utilities by liberalisation and deregulation of the electricity markets. Those low electricity generating costs can significantly increase in the future assuming probable future price hikes for fossil energy carriers. This is due to the fact that the share of fuel costs concerning the overall electricity generating costs amounts to some 41% in the case of hard coal power plants, 45% in the case of lignite-fired power plants and 68% for power plants operated with natural gas (Combined cycle power plants). In contrast to that, nuclear power plants are much less susceptible to fuel price hikes, in this case uranium, as far as the cost share of the fuel amounts to a mere 3% (new plants) respectively 5% (old plants) of the overall electricity generating costs (Figure 6).

Table 2: Current electricity generating costs

Primary energy	Specific investment costs ($ / KW_{el})	efficiency (%)	fuel costs (ct / KWh_{th})	Total generating costs (ct / KWh_{el})
hard coal (world market price)	1,000	42	0.75	3.5
Lignite	1,100	40	0.75	4
natural gas (combined cycle)	500	57	1.5	4
nuclear power plant (old)	750	33	0.4	2.5
nuclear power plant (new)	1,500	33	0.4	3

Assumptions: annuity factor: 10% / year, full power operation: 7500 h / year

As far as renewable sources of energy are concerned, only hydro-power currently is an economically viable option of electricity generation. Already amortised plants with a high utilisation factor allow generating costs as low as 1 ct/kWh_{el} in certain locations.

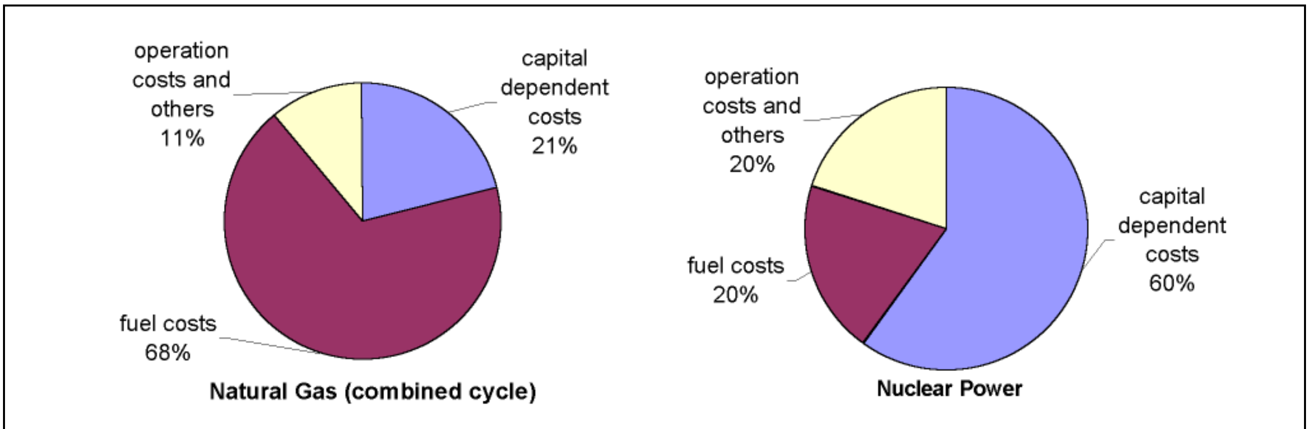

Figure 6: Comparison of cost shares between a natural gas-fired combined cycle power plant and a nuclear power plant

Considering possible future developments a closer look at the historical development of energy prices is an administrable approach (Figure 7) [7,8]. The price of oil has been subject to great fluctuations during the recent decades while the price of coal traded on the world market has been rather constant. The price of uranium also has been comparatively constant except for a short period in between. Considering the life-span of a power plant project including the construction and operating period which amounts to approximately 50 years, those price changes are apparently of great significance. Approaches using the life-cycle calculation method are therefore essential.

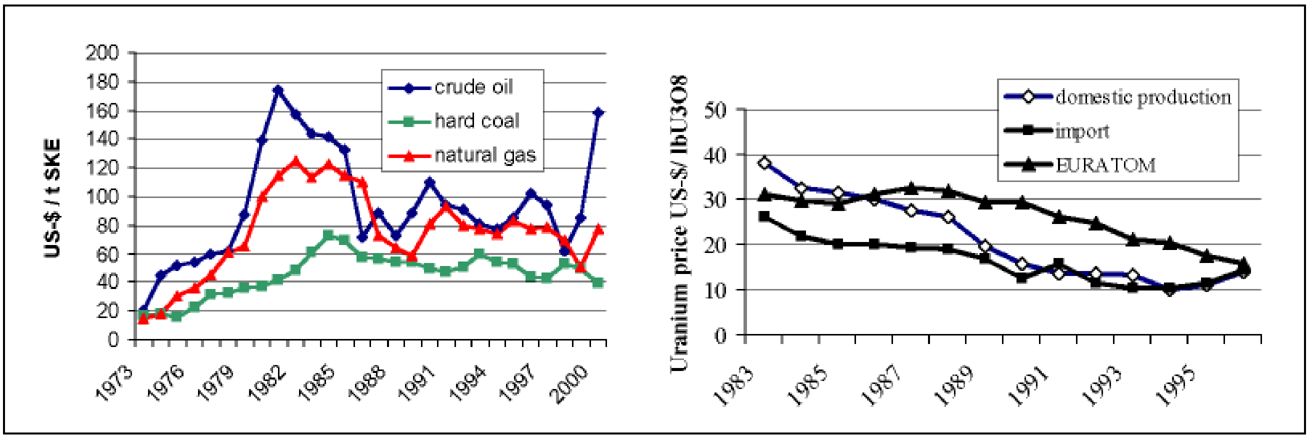

Figure 6: Development of fossil fuel and uranium ore prices over time [7, 8]

6 Future possible costs of electric power supply

Expected future cost increases of energy carriers can be simulated by means of escalation models, such as assuming an annual percentage increase for energy prices (Figure 8).

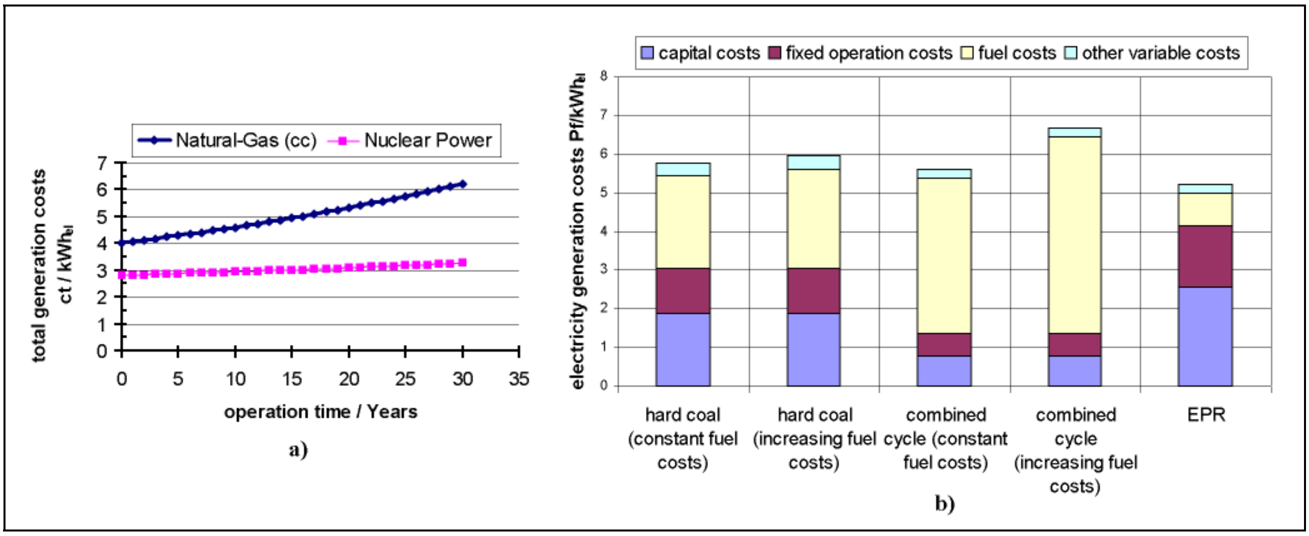

Figure 8: Comparison of electricity generation costs

a) Development of electricity generation costs with an annual escalation of fuel costs of about 2% for a capital-intensive and a fuel-intensive power plant

b) Costs expected in the future for various types of power plants [9] (1 Pf=0,5 ct; German market conditions)

Postulating for instance an annual increase of fuel prices of about 2% for a capital-intensive and a fuel-intensive system, this calculation results in an approximate increase of the electricity generating costs of natural gas-fired power plants by about 60% in comparison with a nuclear power plant, the generating costs of which only show a very weak increase during that period (Figure 8a). This clarifies that the development of fuel prices have a crucial influence on the electricity generating costs in the case of power plants which require a high fuel input. In contrast, capital-intensive power plants, thus especially nuclear power plants, have economic advantages during the entire operating period. More detailed analysis concerning this topic can be carried out by means of applying life-cycle calculations. An example of such a cost calculation is shown in Figure 8b. It proves, that also in the future nuclear power from LWR-plants can be offered on the European energy market under economically attractive conditions.

7 Perspectives of renewable energies in the electricity economy

Hydro-power is the only renewable energy which can be operated under economically attractive terms at certain locations. All other renewable energies nowadays involved in the electricity economy still have to be heavily subsidised (Figure 9a).

The ranges of electricity generating costs shown in figure 9a clarify, that electricity production from renewable energy carriers causes significantly higher costs than production from fossil or nuclear fuels. The costs of photo-voltaic electricity production rank as the highest, especially if the system is designed to work with hydrogen storage for an all-the-year electricity supply. In the case of wind-power, the systems have to be designed including backup systems due to their non-permanent availability. This has a negative influence on the wind-power economy. Solar-thermal plants may offer some economically viable options in certain favourable locations, e.g. in southern Europe.

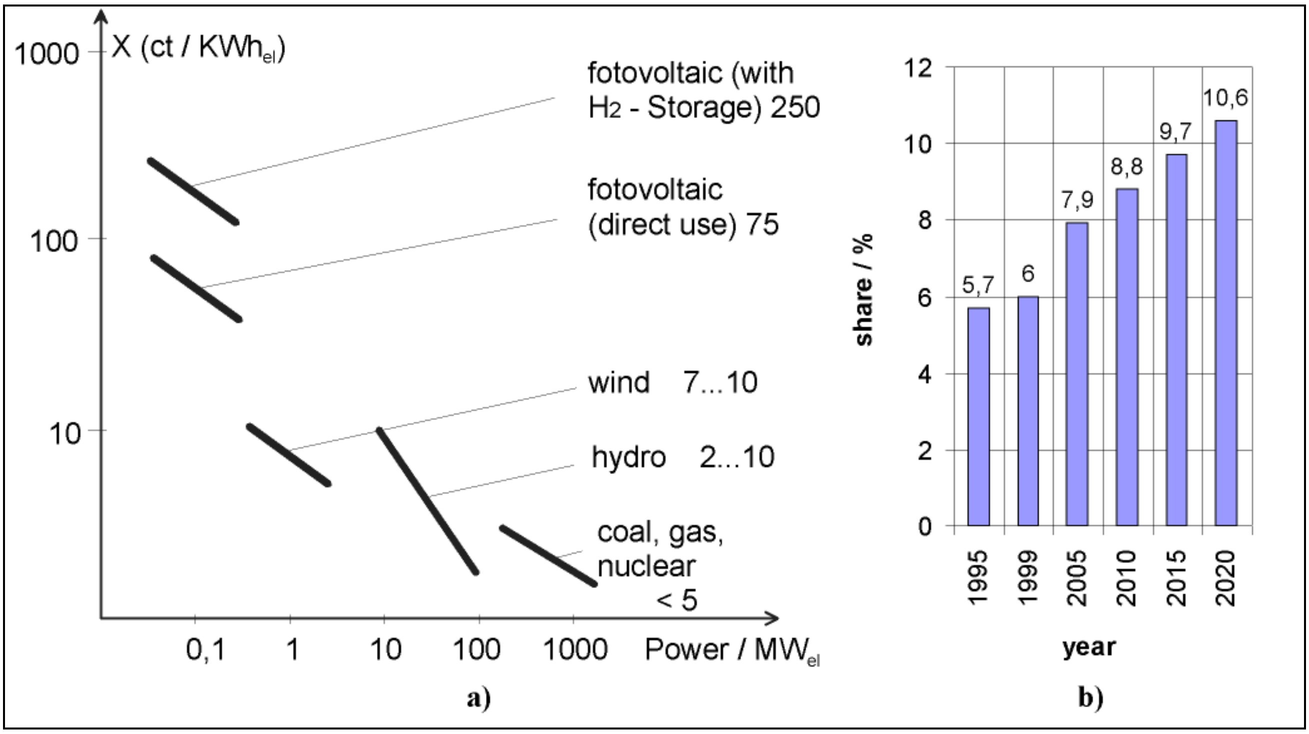

Figure 9: Perspectives of renewable energies in the electricity economy
a) Electricity generation costs of various power plant systems

b) Expected future development of the share of renewable energy carriers in electricity generation (Germany) [10]

Generally the expectation predominates in the energy economy, that the market shares of renewable energies for electricity generation will remain below 11% during the next decades in spite of substantial efforts and subsidies to promote them in Germany and the entire European Union. Hydropower will have the largest share among them. Figure 9b shows the results of a prognosis referring to that topic which was created by the VDEW based on previous analysis done by PROGNOS [10].

8 Perspectives of nuclear energy in the electricity economy

Currently there are 436 nuclear power plants with an overall net-capacity of 350 GW_{el} in operation world-wide. They contribute about 17% to the global electricity production. Within the European Union nuclear power had a share in electricity production of about 34% in 1999 and a share of approximately 30% in Germany. Figure 10 shows the capacity growth of operational nuclear power plants in the European Union and Germany [11].

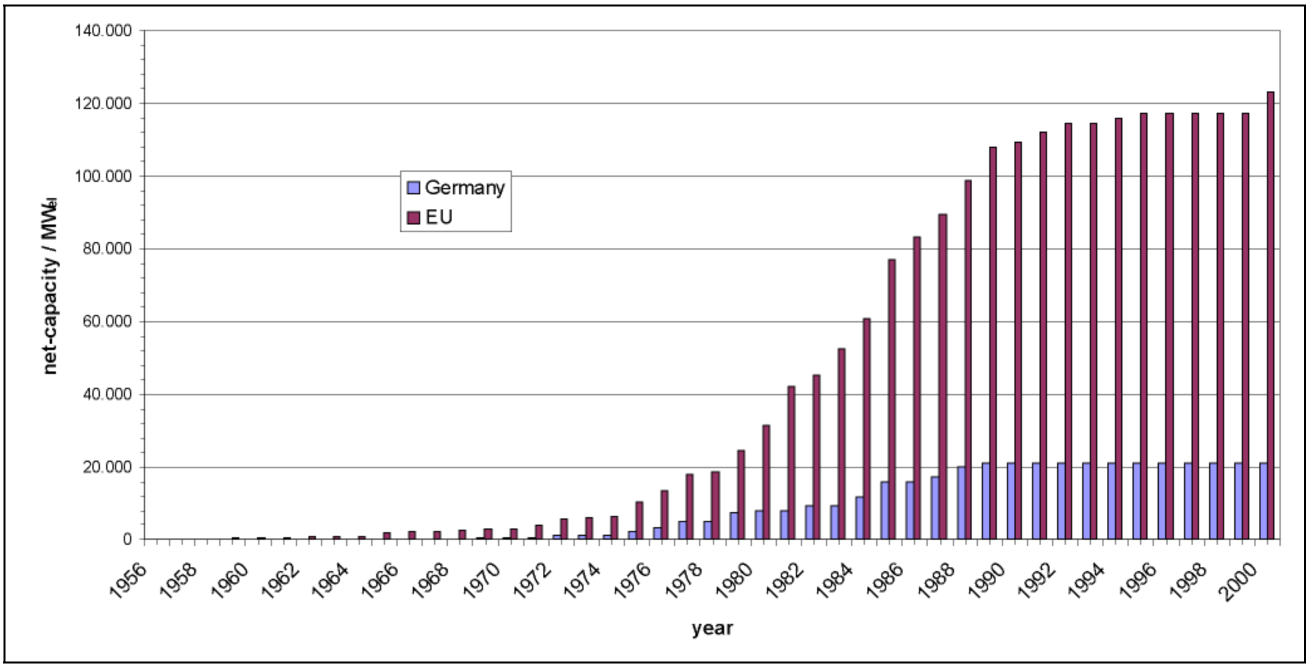

Figure 10: Development of installed nuclear power plant capacities in Germany and the European Union over time [11]

The preceding descriptions already made clear that nuclear electricity generation is economic. Furthermore considering green-house-gas (GHG) and other environmentally detrimental emissions, nuclear energy has some distinct advantages towards fossil-fired power plants. An obstacle for the further expansion of nuclear energy utilisation is the problem of public acceptance after the catastrophic nuclear accident at Chernobyl (1986) as well as the core-melt incident at Harrisburg (1979). The safe final storage of radioactive waste material is considered to be yet another grave problem.

A large range of options is currently being researched and developed world-wide aimed at solving these problems. Various concepts show that such problems can be solved in the future.

Figure 11 shows two concepts of safety for future nuclear reactors with novel safety characteristics. Accordingly, reactor systems can be designed such that radioactive fission materials are held back inside the plant making any catastrophic radiological impacts outside the plant impossible in case of an incident.

Moreover a solution for a safe final storage of radioactive nuclear waste material is possible. In the future the concept of partitioning as well as transmutation will offer feasible solutions. Long-lasting radioactive particles (actinides) are separated from the spent fuel elements and are then transformed in a transmutation plant into short-lasting materials by application of high-energetic protons. This results in a radio-toxicity of the waste material which can be lower than that of natural uranium after a comparatively short time period of about 1,000 years (Figure 12) [12].

In principle a nuclear technology involving all process steps from the reactor to the fuel cycle can be realised in the future, which has distinct “catastrophe-free” characteristics due to the fact that no radioactive releases with catastrophic consequences are possible. Therefore a significant expansion of world-wide nuclear energy use compared to current levels should not be opposed anymore.

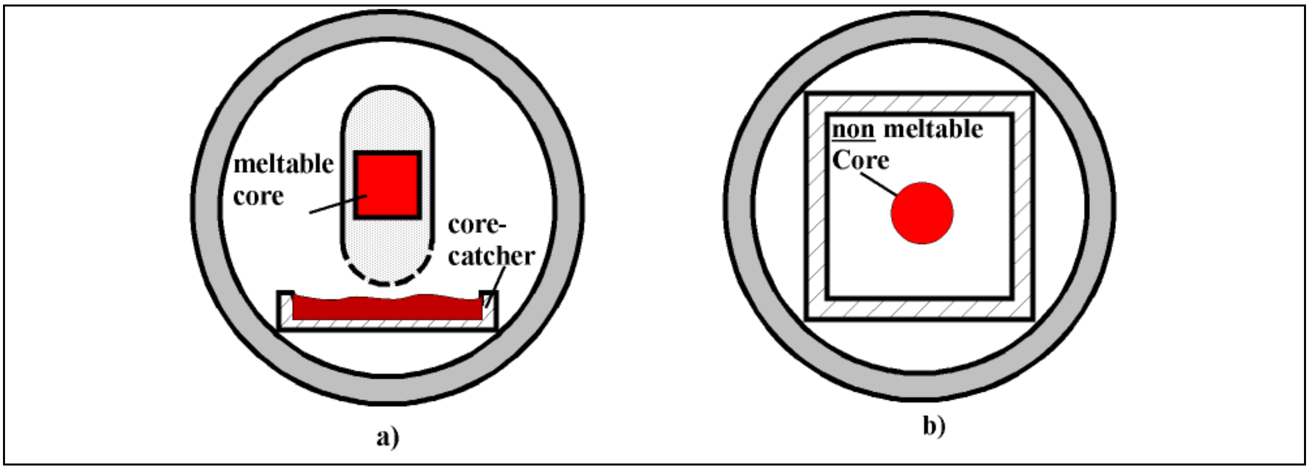

Figure 11: Novel safety characteristics of future reactors
a) Concept of reactors with control of core melt
b) Concept of reactors without core melting

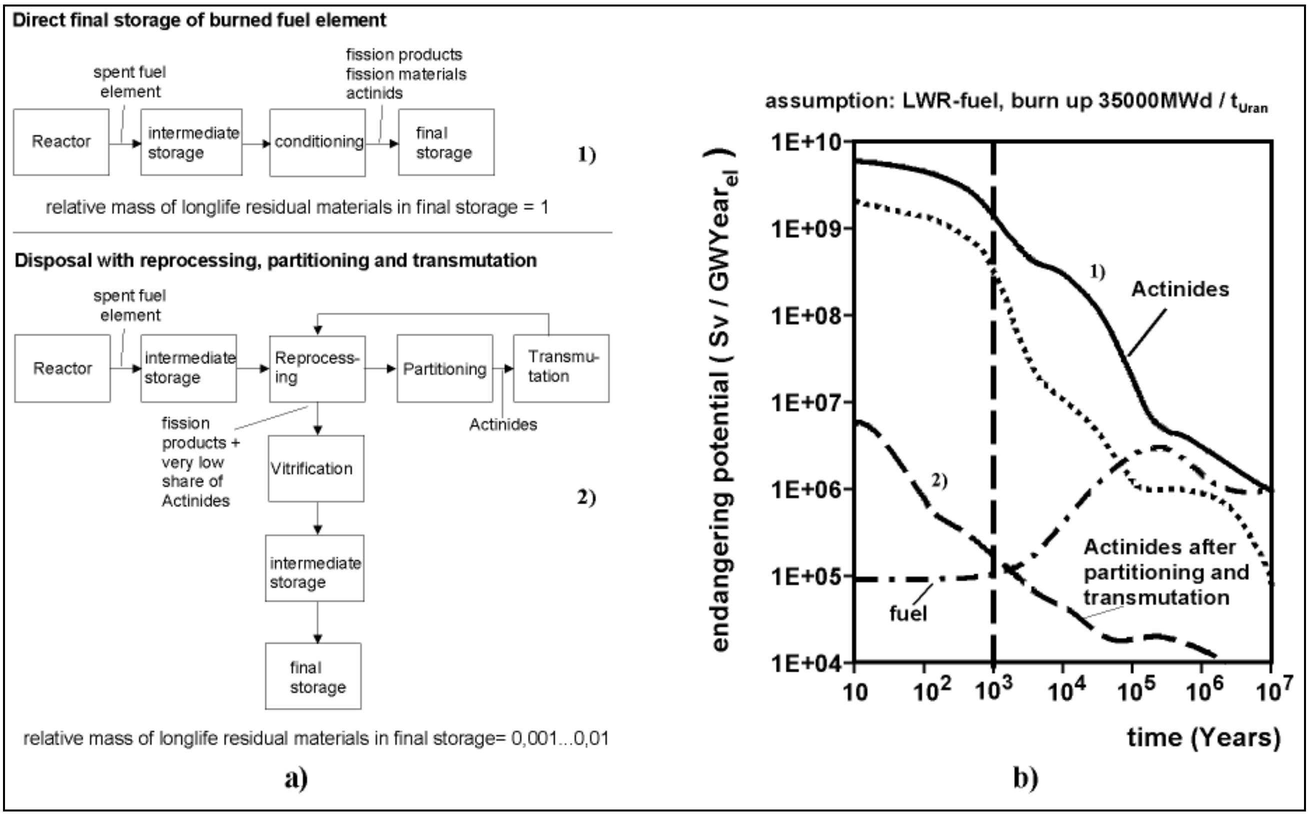

Figure 12: Final storage of radioactive waste material [13]
a) Various ways of disposal
c) Radio-toxicity for two ways of disposal

9 Technical and ecological aspects of power plants

The technology of producing electric power from fossil fuels, hydro-power and nuclear fuels has nowadays reached a very high level, especially in the industrialised countries. Figure 13 shows the efficiency and the increase of the efficiency ratio for various thermal power plant processes depending on the upper process temperature. The efficiency ratios have an upper limit though which is determined by the maximum process temperature depending on the maximum allowed material temperatures. Questions concerning material characteristics are therefore crucial to technical progress. In the case of coal-fired power plants, improvements concerning the combustion process in the boiler, improvements of the circuit process as well as especially the continuous improvements achieved in the range of turbo machinery and devices lead to the mentioned significant increases of the efficiency ratio. From a technical point of view especially the progress made in the range of live steam conditions respectively the increase of the gas turbine inlet temperature were remarkable and contributed to making the mentioned improvements possible.

Especially in the case of combined power plants – gas turbines and steam turbine plants (combined cycle) – based on natural gas as a fuel, an ever accelerating development resulting in progress made concerning an increasingly efficient energy use has taken place. The introduction of highly heat-resistant materials for turbine blades as well as the introduction of efficient cooling processes and insulation layers for these components, but also the overall optimisation of the process including the connected steam turbine process, made these significant process improvements possible. Net efficiency ratios on the basis of natural gas of more than 60% will be attainable for combined cycle plants in the near future by further raising temperatures and optimising the entire process.

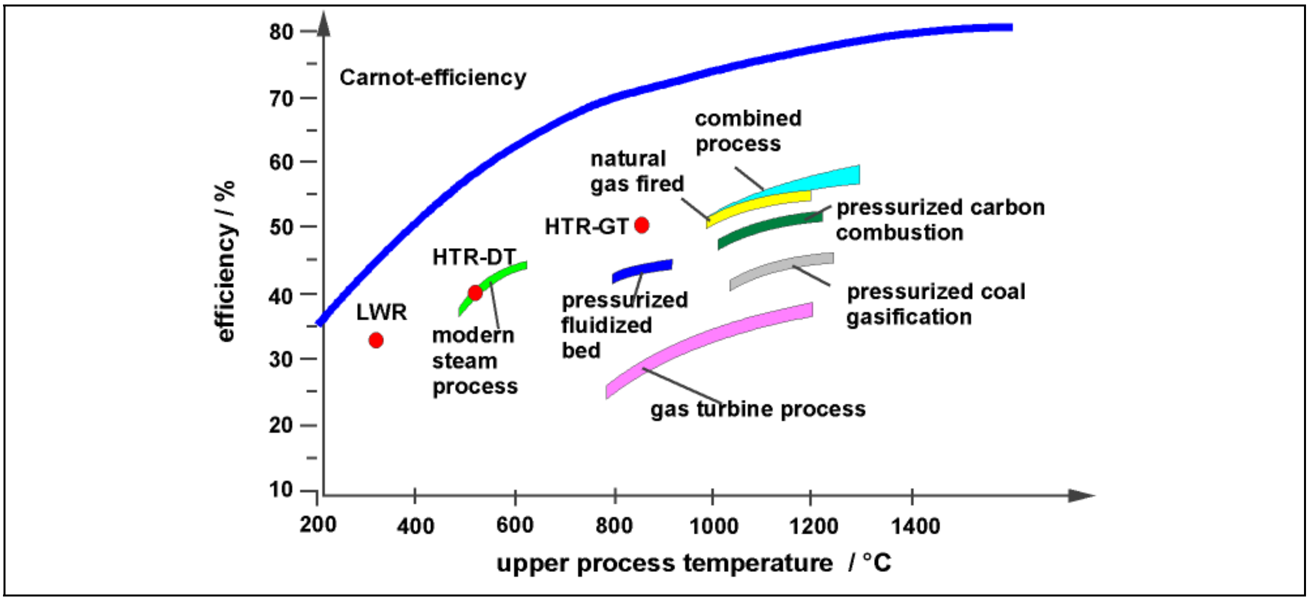

Figure 13: Efficiency ratio of various thermal power plants

In connection with the use of coal, processes are developed and tested, which promise a distinct improvement of the emission characteristics as well as higher efficiency ratios (see figure 13). These mainly include plants with coal gasification or fluidised bed coal combustion. Correspondingly pressurised fluidised bed coal combustion's are planned, which should achieve a net efficiency ratio of about 48%.

The development of power plants with ever higher efficiency ratios is an important aim in the energy economy due to a number of factors. On the one hand the specific fuel costs decrease thus enhancing the plants` economy, on the other hand emissions of CO_2 are lowered in the case of electricity production from fossil fuels (figure 14).

Nevertheless the realisation of higher efficiency ratios requires an ever greater technical effort which in turn requires large investments thus resulting in increasing overall investment costs. This leads to the general requirement of finding a compromise in the colliding fields of interest between technology and economy as well as the ecology.

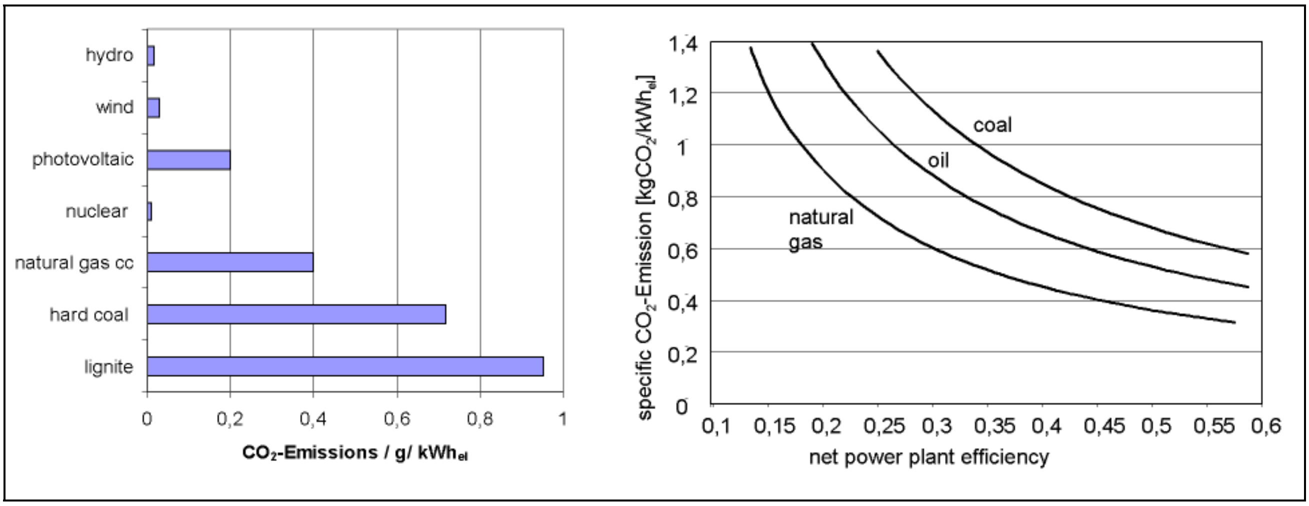

Figure 14: Specific CO_2-emissions depending on the type of power plant and the efficiency [14]

10 Overall optimisation of electricity supply

Concerning the optimisation of power plant technologies it is always mandatory to find a compromise between the various requirements to the entire system. It is for example necessary to consider the issues of ecology, economy and a resource use which is as sustainable as possible at the same time while using the available technological options and taking matters of public acceptance into account. In former times it was usual only to consider issues and compromises concerning technology and economy. In recent years ecological concerns have aroused an ever greater attention, in nuclear technology the aspect of safety was strongly emphasised. In the future the sustainable use of resources will require even more attention (Figure15).

In figure 15a the electricity generating costs are qualitatively displayed in dependence from the efficiency ratio of the plant. A parameter (ζ) which characterises the environmental impacts of the process is added, e.g. allowed SO_2-emissions, NO_x-emissions or ecological strains caused by waste heat in conventional power plants. In the case of nuclear power plants this can for instance be the release of fission products during normal operation or eventually damages occurring as a consequence of severe incidents. In the future, nuclear energy use will have to be judged on by additionally including the consumption of uranium as well as the production of highly radioactive waste materials in the considerations. This would contribute to paying sufficient attention to the resource aspect (σ) on the supply- as well as on the disposal side. Moreover emissions of CO_2 and its enrichment in the atmosphere will have to be considered in future resource-related judgements.

Electricity generation costs are generally a suitable target value to carry out such optimisations. Other optimisation aims such as investment cost which are as low as possible, safety standards which are as high as possible or a raw material or primary energy input which is as low as possible can be of course interesting as well.

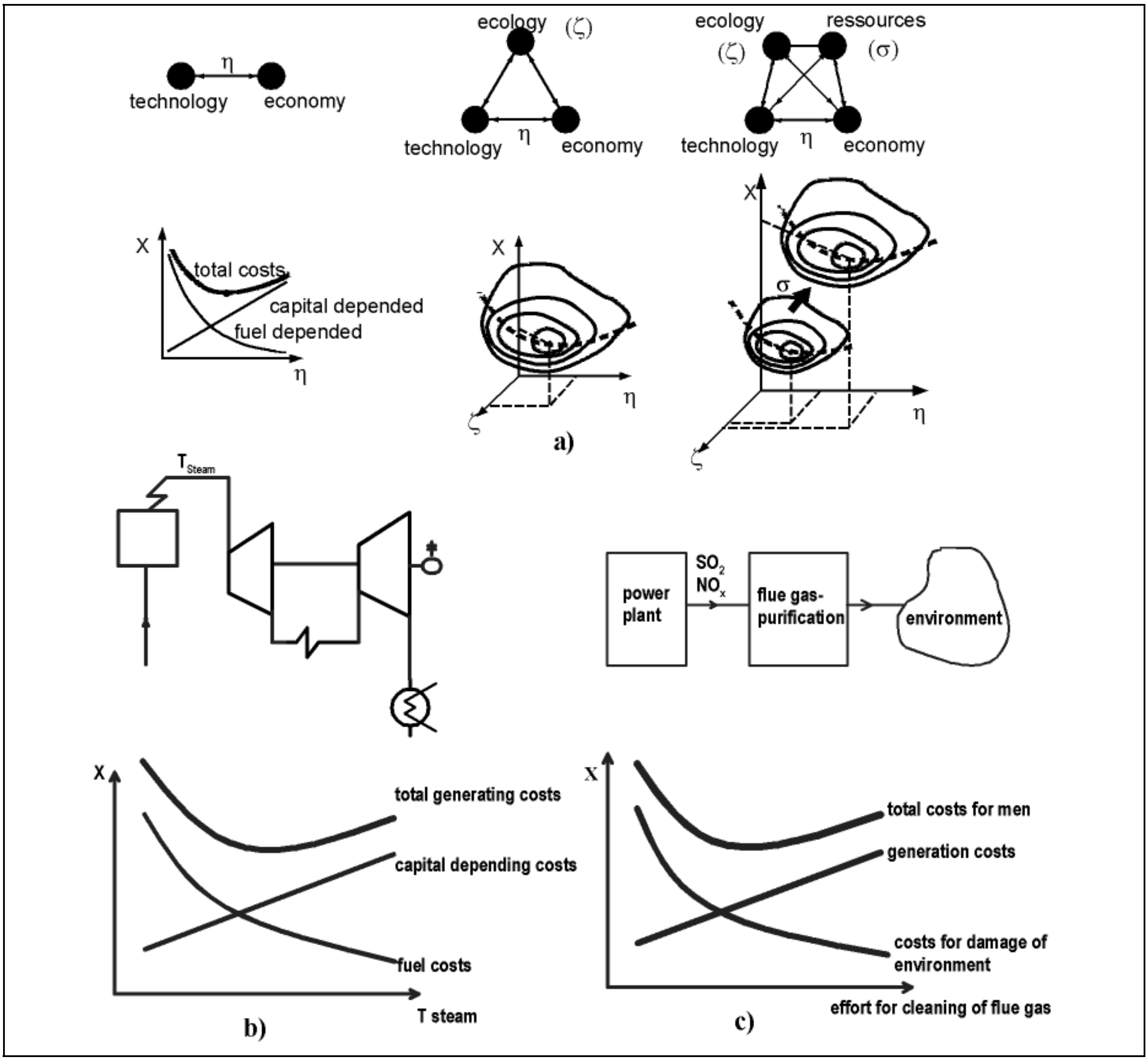

Figure 15: Optimization of entire systems for electricity production

a) Basics concerning the compromise in the range of colliding interests between technology/economy/ecology/resources

b) Example of an optimisation concerning Technology/Economy

c) Example of an optimisation concerning Economy/Ecology

In figure 15b the optimisation by increasing the live steam temperature as an example of a compromise between technology and economy is shown. Of all parameters, the live steam temperature has the greatest influence on the efficiency ratio. Currently the maximum live steam temperature which can be achieved for commercial power plants amounts to a figure of approximately 600°C.

This can be explained by the solidity characteristics of the materials applied, which decrease with rising temperatures. Higher temperatures and pressures require the application of austenitic steels the additional costs of which have to be compensated for by the increased efficiency of the process. An optimisation between fuel costs and capital-dependent costs while considering the entire plant life-time (life-cycle analysis) is required here.

Besides technical and economic optimisations which were in the main focus hitherto, ecological aspects gain an ever greater importance for the overall process rating. A very convincing example of a successful compromise between economy and ecology in recent time was the desulfurisation of coal-fired power plants. By increasing requirements concerning the residual content of SO_2 in the flue gas, the electricity generating costs were increased and environmental damages were decreased or even prevented. A monetarisation of both aspects usually leads to a graph corresponding to figure 15c. A reasonable compromise between ecological requirements and the demand for an economic electricity production suggests to fix the legal limit values for SO_2 near to the minimum of the entire curve. Also in this case the question of the entire operating time of the plant has to be posed, this means that a dynamic optimisation is required. Furthermore enlarging on finding a compromise between economy and ecology, it has to be considered that some technical boundaries exist concerning the lower limits of SO_2-concentration in the flue gas as well as the fact that no high emission values can be tolerated.

11 Aspects of the liberalisation of the electricity market

The aims of liberalisation of the electricity market are the creation and promotion of a free market competition. An enhanced international competitiveness of the European economy by decreasing electricity prices as well as the promotion of European cross-border electricity exchanges are the main aims of the process. Furthermore it is expected that the liberalisation will result in an improvement of the high-voltage transport grids, an optimisation of the power plant portfolios as well as the creation of compatible structures within the European electricity economy.

In the course of increasing market competition the concentration ratio among companies significantly increases. The largest share of electricity production in the EU is contributed by a comparatively small number of large-sized utilities. The utilities enumerated in table 3 currently control about 60% of the overall electricity production in the EU. The largest utility in 1999 was the French EdF followed by the Italian ENEL which is still also mainly owned by the state. Both utilities mentioned have virtual monopolies in their countries. The German utilities RWE and E.On Energy achieved third and fourth position in the ranking in 1999 as far as the amount of electricity sold to the market was concerned.

Table 3: Data of large utilities in the European Union [15]

Country	Name of utility	Electricity sales [TWh]	Share of national electricity production [%]
France	EDF	461	93
Italy	ENEL	231	91
Germany	RWE	209	41
Germany	e.on Energie	196	38
Sweden	Vattenfall	87	58
Spain	Endesa	80	42
Belgium	Electrabel	71	88
Spain	Iberdrola	66	35
Great Britain	British Energy	63	18
Great Britain	National Power	63	18

Corresponding to the leading motive of creating a free european domestic market for goods, finances and services, all hitherto mostly regulated and closed electricity markets of the EU member states were deregulated and therefore became subject to market competition. The long-term aim is to create a single domestic european electricity market. The basis for the exchange of electricity is provided by the already long existing european exchange grid UCTE where electricity already had been exchanged or traded long before the initiation of liberalisation. In the first place the grid was designed to enhance the supply safety of the member states. Sudden failures of power plants can require a compensation of great electricity amounts which otherwise could only be supplied by a respective national power plant reserve. In the future these exchange grids will contribute always more to an increasing competition in electricity trade. Figure 16 shows the exchange grid of the european countries including the respective data for electricity imports and exports. Some spatial focal points of electricity exchange can be identified. An especially large exchange takes place in the central european region, with Germany, France, Switzerland, Austria and the Lowland Countries (Netherlands, Belgium, Luxembourg) being the main participants. Concerning the overall balance of electricity exchange for the european countries a special role is taken on by France and Italy.

While France belongs to the main exporters of electricity with an outstandingly positive trade balance, Italy yields a very deficitary trade balance signifying very large electricity imports. The Netherlands and Great Britain also belong to the countries with a highly negative trade balance. Germany can currently be categorised as nearly self-sufficient as far as the electricity trade balance is concerned. In the course of growing market competition in Europe and an increasing level of liberalization in all national electricity markets it can be expected, that the exchange of electricity between the European countries will keep on expanding.

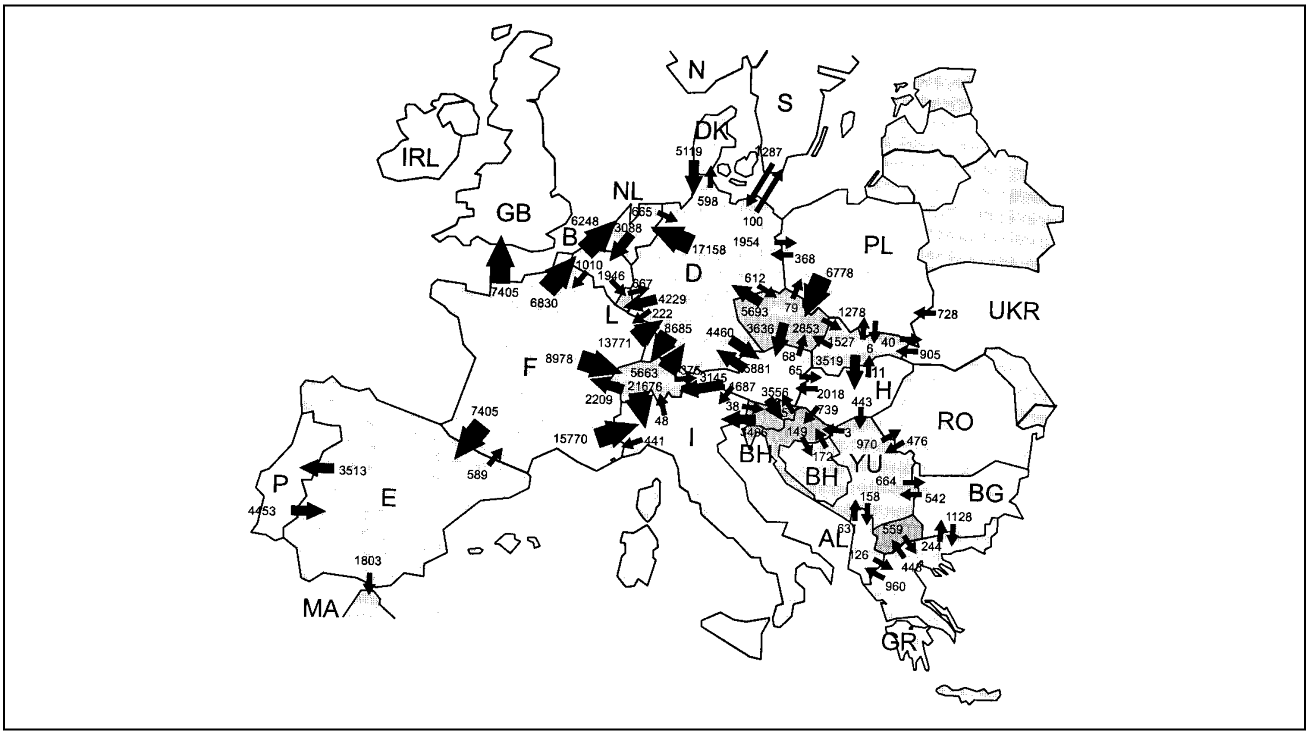

Figure 16: Electricity exchange between western and eastern Europe (UCTE-grid) [16]

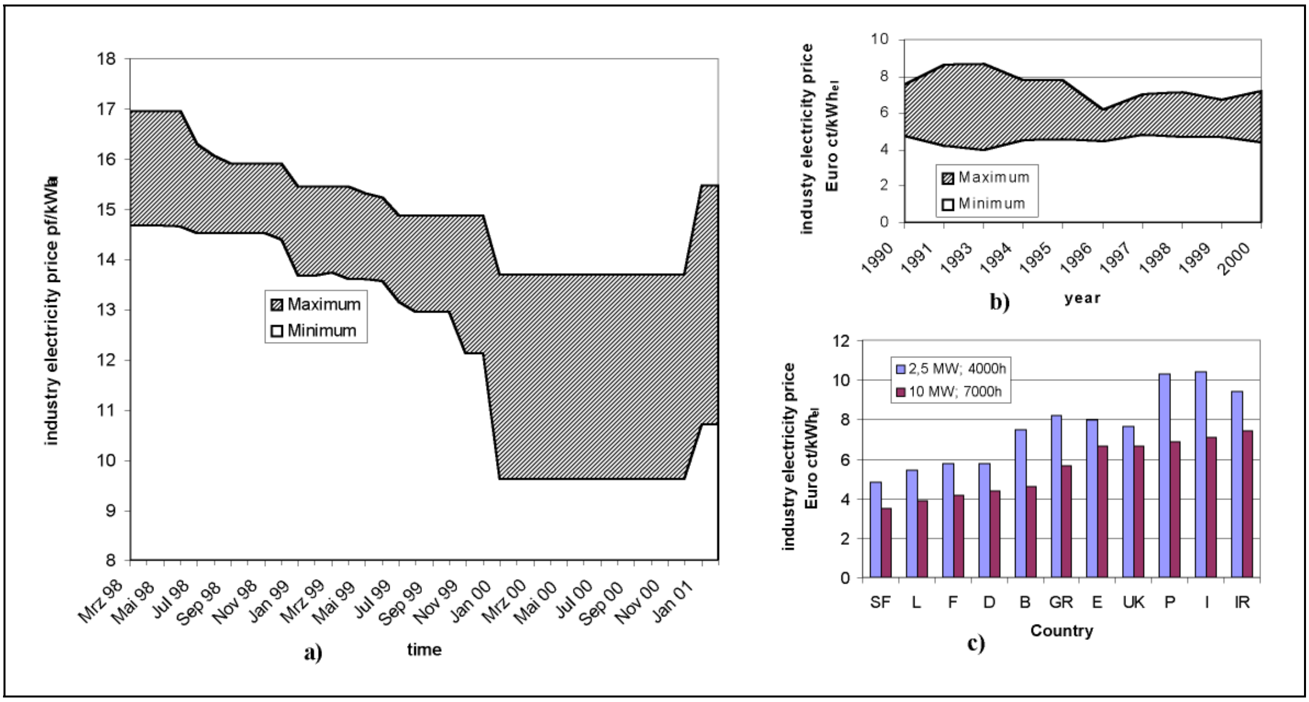

Fig. 17: Electricity prices for the German industry and some European countries

a) Development of electricity prices for the industry in Germany [17]

b) Development of electricity prices for the industry in the EU (4 MW, 6.000 h/a) [18]

c) Comparison of electricity price for the industry in european countries by various power sizes and annual full load hours (1. January 2000) [19]

The liberalization results in significant price decreases, especially for industrial customers. In figure 17a the development of electricity prices for the manufacturing industry in Germany is displayed. It can be observed that the average electricity prices for the industry in the time period viewed have significantly decreased. On average the decreases amount to some 20% while in the recent period a clear stagnation in price cuts and a respective price bottoming can be observed. None of the utilities could resist to the strong market pressures towards ever lower prices imposed during the recent three years. Similar developments can be expected to take place all over the European Union when the electricity markets will be finally completely opened (Figure 17b). As can be seen in figure 17c, France will probably have a strong stand in the looming market competition.

12 Possible influence of the climate discussion on the future electricity supply

An essential determinant of the future development of the world energy economy as well as the national energy economy will be the question of CO_2 and the limiting of the respective greenhouse-gas emissions (Figure 18)[20].

Currently the use of fossil fuels still dominates the global energy supply with a share of approximately 80%. Basically fossil fuels are still available to the energy economy in sufficient quantities for the next decades. If the question of CO_2 should really be an issue of crucial importance and the global community decides to react accordingly, then the use of fossil fuels and anthropogenous emissions of CO_2 will have to be vastly reduced in the coming years. According to the requirements formulated within the scope of the conferences on climate protection in Montreal and Toronto, the use of fossil fuels will have to be diminished on a global scale. In the year 2020 a reduction to 2 tons of CO_2/person*year and to 1 ton of CO_2/person*year in 2050 would have to be achieved (Figure 18c), around the climatic influence by humans to stop.

This means that the aim of a 25% reduction in Germany until the year 2005 can only be considered as a very first step. Based on the current specific emission level in Germany a reduction by the factor 6 until 2020 and a reduction by a factor of 10 in the long-term (2050) will be mandatory. This requirement clearly poses the demand for a completely novel energy economy which would have to be virtually carbon-free (Figure 18b).

Even necessary and feasible measures aimed at saving energy in Germany do not basically change the dimension of this challenge. The question of CO_2 has not yet been completely resolved or concludingly answered to full extent. Therefore precautionary measures have to be taken and future steps should be well thought over in advance. In this case, in the long-term a reasonable energy-mix comprised of fossil fuels which are used to a sufficient level of efficiency, renewable energies and a sufficiently large share of nuclear energy will have to be included in the energy portfolio.

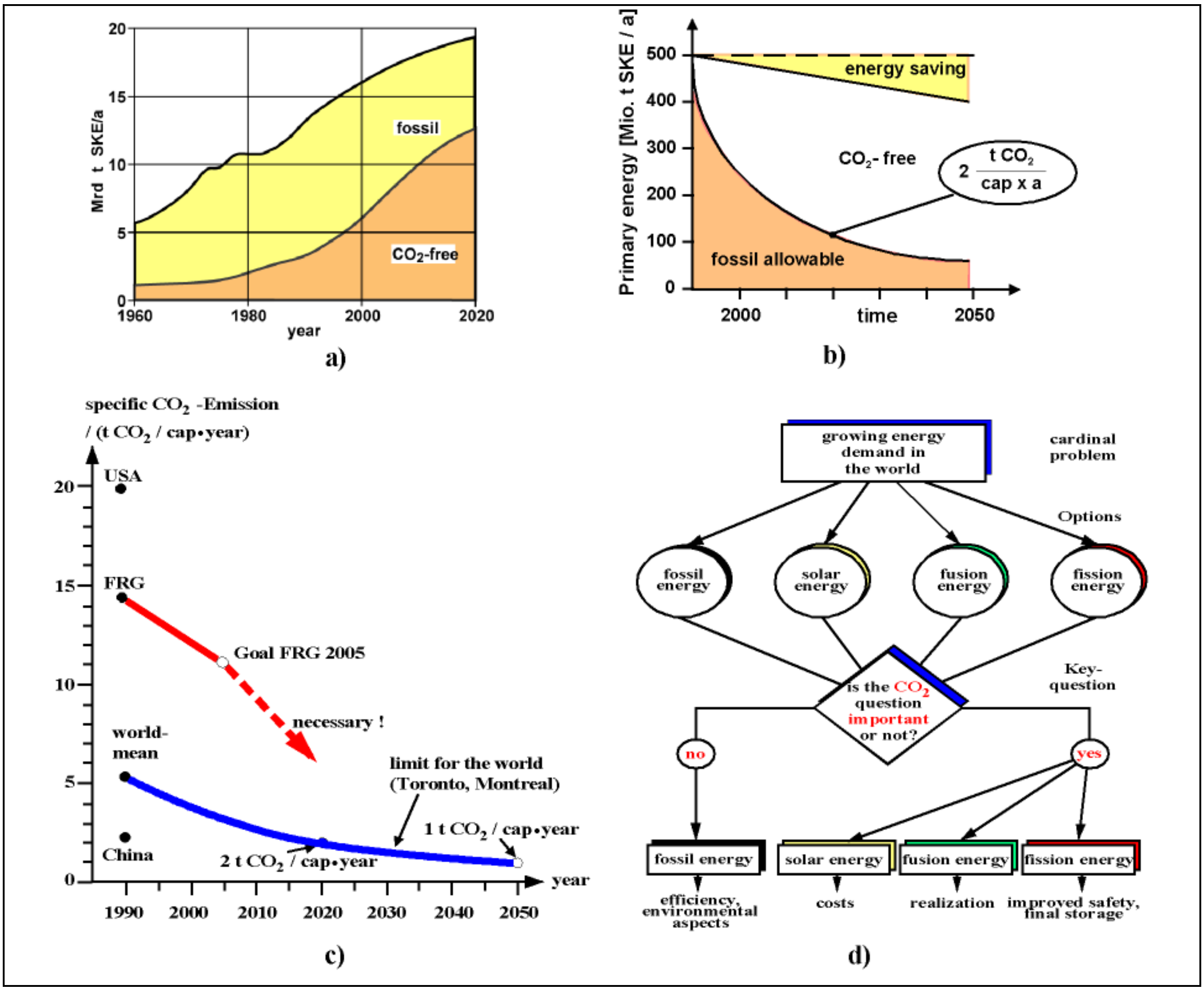

Figure 18: Questions concerning CO_2-Emissions and the climate problem

a) Allowed maximum share of fossil fuels in the world energy supply fulfilling the demands set by climate scientists

b) Allowed maximum share of fossil fuels in the German energy supply fulfilling the demands set by climate scientists

c) Development of the annual per capita emissions of CO_2 if the climate researchers demands are to be fulfilled

d) Options of a future world energy supply with consideration of the CO_2-question

The requirements aiming at a reduction of CO_2-emissions are similarly grave to Germany on a global scale. Corresponding to figure 18a it would be mandatory to achieve an energy supply which consists of CO_2-free energy sources by more than 50% already within the next three decades. Therefore it is obvious that only a few options remain to achieve this goal: nuclear energy and renewable energies have to be applied to attain these extensive reduction aims. Considering the economic aspect, there lies a distinctive advantage with nuclear energy (Figure 18d).

The tasks for future efforts in the range of the energy economy are therefore clearly defined:

- a rational use of energy in all stages of energy transformation, energy transport, energy storage and its final usage
- Development of renewable energy sources, especially the reduction of electricity generating costs; solutions for questions of storage
- Developments aiming at nuclear fusion: Proof of physical and technical realisation of power plants; proof of economic aspects
- Development of a nuclear energy with solutions to the safety questions in respect to several reactor incidents and the final storage of nuclear waste materials

A reasonable mix of the various primary energies will ensure the supply for the manufacturing industry, in this case especially the NF-industry, for the decades lying ahead.

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LCA Case Studies

A Method to Calculate the Cumulative Energy Demand (CED) of Lignite Extraction

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Abstract. For the utilisation of an energy carrier such as lignite, the whole life cycle including necessary energy supply processes have to be considered. Therefore using the 'Cumulative Energy Demand' (CED) is especially suited to determine and compare the energy intensity of processes.

The goal of the CED is to calculate the total primary energy input for the generation of a product, taking into account the pertinent front-end process chains. So the CED is in many steps similar to the LCA, especially in the 'inventory analysisstep'. The statements of the CED for energy supply-systems are concerned with the (primary) energy-efficiency of the energy supply and pointing out the life cycle steps which high energy-resources demand. Due to the great environmental impacts of energy supply and use which have to be laboriously assessed in LCA, the CED provides a useful, additional, energy-related 'screening-indicator' to LCA.

This case study analyses the extraction of lignite in an opencast mine in West-Germany as the first step of energy carrier provision. Our data for the inventory analysis arise from a measuring campaign about the period of one year. The results underline the great energy demand of lignite extraction in West-Germany.

With reference to the energy contents of lignite, the fraction of primary energy demands for its' mining amounts to about 6.2%. This accounts to 93.8% of the lignite energy content being available as usable energy for further processes, which is obviously worse than other studies have shown.

Keywords: CED; Cumulative Energy Demand (CED); energy analysis; Life Cycle Impact Assessment; life cycle inventory analysis; lignite; overall efficiency of supply

Introduction

In 1997, the Collaborative Research Center 525 entitled 'Resource-Orientated Integrated Analysis of Metallic Raw Material Flows', funded by the Deutsche Forschungsgemeinschaft (DFG), was established at the Aachen University of Technology (RWTH). This program aims to develop tools for a resource-sensitive utilisation of metallic raw materials covering economic, environmental and social constraints.

To this purpose, nine institutes of the Aachen University of Technology (RWTH) and the Forschungszentrum Jülich are in co-operation. Each of the nine sub-programs of the Collaborative Research Center, shown in **Fig. 1**, contributes to the development of a tool for shaping material flows with their own submodels.

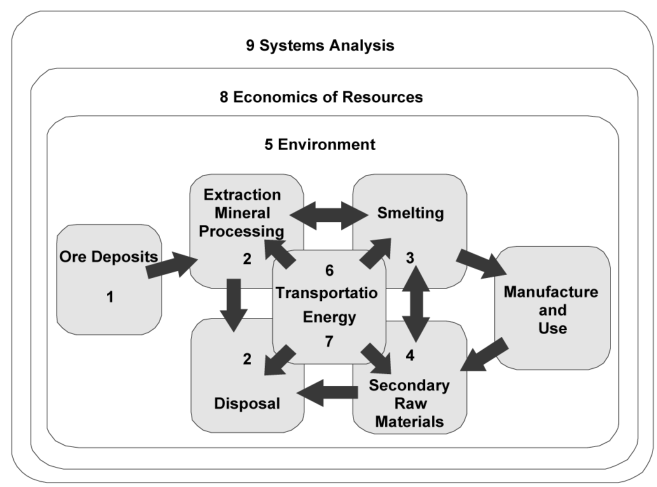

Fig. 1: Structure of the Collaborative Research Center 525

Here, the co-operation of the sub-programs 'Extraction and Disposal' and 'Energy' of the Collaborative Research Center 525 is shown in the field of determining the CED for the supply of lignite.

1 Method of Investigation

1.1 The concept of the cumulative energy demand

The life cycle of a product can generally be subdivided into the three phases of 'production' (P), 'use' (U) and 'disposal' (D) in which final energies, e.g. electricity or fuel, are engaged.

Beside the direct energy input for production, use and disposal of a product, production facilities, as well as raw materials, auxiliary materials and consumables are also used. These are products which need energy for their own production process. Furthermore, the final energy applied in the processes is a product of mining, transformation and transport processes which again are performed using machines and consuming different energy carriers and materials.

The question of the energy expenditure for the energy supply is answered by determining the necessary amount of primary energy. The total of all energy inputs, concerning the consumption of primary energy, is called the Cumulative Energy Demand of a product [1].

With respect to the three life phases (production, use and disposal), the CED can be expressed as:

$$CED = CED_P + CED_U + CED_D \tag{1}$$

The Cumulative Energy Demand is a parameter which forms the basis for further energetic assessment values (like energy pay-back time or amortisation time). Of special significance is the overall efficiency of supply.

1.2 The overall efficiency of supply

Many processes require different final energies, e.g. fossil fuels, process steam and electricity. These energies have different physical qualities and thermodynamic properties, for example, it is not suitable to compare 1 MJ of electricity with 1 MJ of low-temperature heat. Therefore, the question of energy demand cannot be answered adequately by simply summing up the final energies which are employed in a process.

However, it is possible to determine the required primary energies from the different final energies using the overall efficiency of supply, which means that the comparison of processes becomes possible. The overall efficiency of supply g describes the relation of the final energy provided and the Cumulative (primary) Energy Demand.

$$g_{el} = \frac{W_{el}}{m_{fuel}^{prim} \cdot H_u^{prim} + \sum_i CED_{plant,i}} \tag{2}$$

$$g_{fuel} = \frac{m_{fuel} \cdot H_u}{m_{fuel}^{prim} \cdot H_u^{prim} + \sum_i CED_{plant,i}} \tag{3}$$

where:

g_{el}	the overall efficiency of supply of electricity
g_{fuel}	the overall efficiency of supply of fuels
$m_{fuel}^{prim} \cdot H_u^{prim}$	the energy of the primary energy carrier
W_{el}	the supplied electricity
$m_{fuel} \cdot H_u$	the supplied energy of fuel and
$CED_{plant,i}$	the Cumulative Energy Demand for installing, running and disposing of machines, plants and consumables providing the electricity or the fuel

The dimensionless overall efficiency of supply characterises, like an effectiveness, the efficiency of an energy supply from the deposit of a primary energy carrier up to the supply of final energy, respecting all energy demands.

1.3 The procedure of determining the CED using the process chain analysis

The CED of a product can be determined using economic statistics (input-output-tables of the energy input-output-analysis) or by means of a detailed process chain analysis. The energy input-output-analysis is suitable to calculate usable values for the CED of mass products with little effort. However, it shows methodological disadvantages concerning goods which are only produced in small numbers. Additionally, the high aggregation of input-output-tables does not allow a detailed analysis of the quantities causing the CED.

In contrast, the process chain analysis is well suited to produce detailed, precise and transparent results. A disadvantage is the considerable work caused by this method. The approach to determine the CED using the process chain analysis is shown below.

- I Set-up of the process chain
- II Selection of relevant processes and definition of cut-off criteria
- III Balancing of the processes (inventory analysis)
- IV Determination of primary energy
- IV.I Determination of the primary energy demands for raw materials, auxiliary materials and consumables as well as equipment of all processes
- IV.II Determination of the primary energy for the supply of final energy
- V Calculation of the CED demand as a sum of all primary energy inputs

In **Fig. 2**, the diagram shows the material and energy flows which have to be analysed in order to determine the CED of any process.

For some frequently used materials (e.g. metal, synthetic materials, glass, concrete), detailed examinations concern-

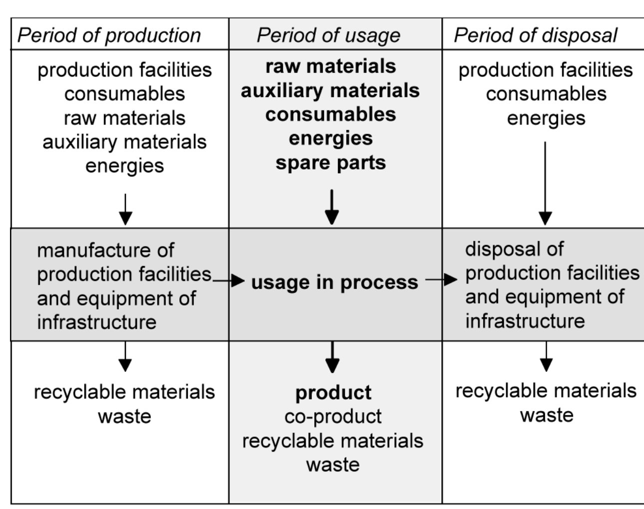

Fig. 2: Flow diagram of an inventory analysis of a process to determine the CED

ing the CED on the level of semi-finished products have been carried out by different authors. For many products, the energy demand for the production of a final product from a semi-finished one can be neglected regarding the energy demand of the production of a semi-finished product. Thus, within the process chain analysis, it is often sufficient to use corresponding values of semi-finished products which can be found in literature.

Summing-up all primary energies finally leads to the CED which can be assigned to an amount, a mass or another functional parameter of the product.

2 Application of the CED method to lignite extraction

2.1 The opencast mine

In this paper, the extraction of lignite in an opencast mine in western Germany is examined. Overburden and lignite are mined continuously by bucket-wheel excavators. The material is transported around the pit by a conveyor system to a central belt junction where it is spread by conveyors to the stockpile or the overburden spreaders.

2.2 The mining process

In order to examine all processes which are necessary for the mining of lignite, a (local) point, which experiences all stages of the mining process, is regarded. Considering this, the process chain for an opencast mine is shown in **Fig. 3**.

In the first step, buildings, infrastructure, or installations and vegetation have to be removed. Then topsoil and overburden are mined selectively by bucket-wheel excavators, transported continuously by the conveyor system and stacked by overburden spreaders. When the seam is uncovered, the lignite is extracted by bucket-wheel excavators and conveyed to a loading point where it is passed to a hauling system for transportation to customers. The transportation to customers is not taken into account (cf. boundaries of examination in Fig. 3).

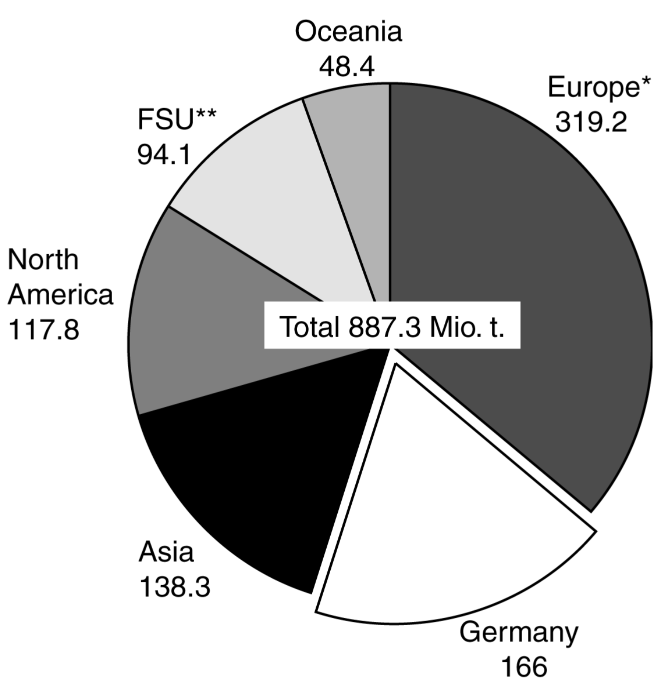

Fig. 3: Macro process chain for an opencast mine

3 Balancing of Lignite Mining

For the opencast lignite mine examined, it was possible to collate the consumption of fuels and electricity for one year [2]. In this case, 45.3 kWh of electricity per metric ton of lignite were used for running the equipment and to supply different general electrical consumption. A detailed distribution of the electricity demand of the included processes is shown in **Fig. 4**.

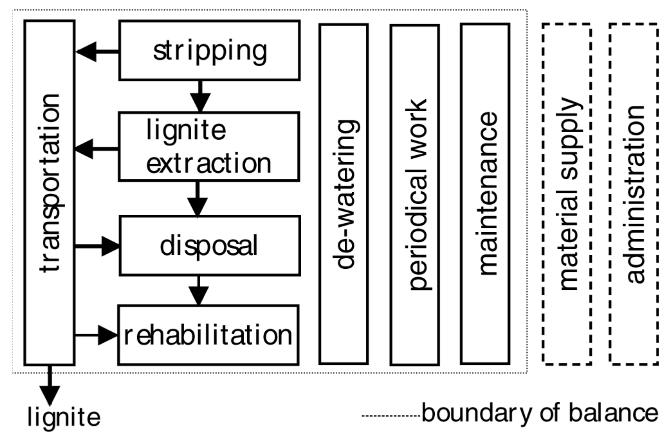

Fig. 4: Distribution of electricity demand to the processes of lignite mining

Due to the large conveyor system of the analysed opencast mine, the electrical demand is mainly influenced by the transportation of lignite, and especially of overburden (relation overburden – lignite: 8.6:1 m^3/t), and less by the consumption of the extraction equipment. Thus, 74% of all applied electricity refers to the mining and transportation equipment. The electricity consumption for drainage (21.7%) is the next relevant contribution. Other separately realised processes play only minor roles concerning the electricity consumption.

As the conveyor system is powered by electricity, the consumption of fuels (diesel) in the analysed opencast mine is relatively low (0.14 l/t_{Lign}). **Fig. 5** shows a rough distribution of the fuel demand for the operation of auxiliary devices, motor vehicles and drainage processes.

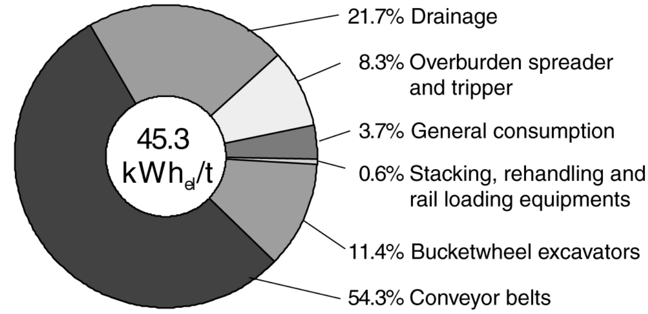

Fig. 5: Distribution of fuels for the operation of auxiliary devices, motor vehicles and drainage processes

The auxiliary devices include machines for surface preparation during the development phase and for the rehabilitation after mining or which are applied as mobile sprinkling devices for dust reduction.

4 Determination of Primary Energy Demand

For the primary energy assessment of the final energy inputs (see above), the Overall Efficiencies of Supply, listed in **Table 1**, are used. They characteristically describe the supply of electricity and fuel-oil in Germany. [1]

Table 1: Overall efficiency of supply for the calculation of primary energy in Germany

	Overall efficiency of supply	Annotations
fuel	0.88	
electricity	0.325	electricity mix Germany 1995: 55.8% coal, 28.9% nuclear, 8.1% gas, 3.7% hydro, 1.7% oil, 1.8% others

Within the calculations of the primary energy, the energy demands for production as well as for the use (especially maintenance or spare parts) and disposal of mining equipment are taken into account. The disposal of the employed equipment has only a subordinate share of the total energy demand and does not have to be taken into account because of its long utilisation period.

The energy demand for the provision of mining equipment has been determined using the masses of steel, copper and rubber. The relevant period of utilisation relative to 1 metric ton of mined lignite in the time period were taken into account. Values from literature are used, such as the CED of steel (28 GJ/t [4]), copper wire (100 GJ/t estimated by [4]), an estimate concerning the CED for rubber (96 GJ/t, balanced for the production of butadiene-elastomer [5] and our own calculations) and some different, estimated supplements for manufacturing. Furthermore, the energy demand for the supply of auxiliary devices is determined, assuming that sheet steel (33 GJ/t [4]) is used.

5 Results

In **Table 2**, concerning the mining equipment in the opencast mine, the CED of the production relative to 1t of lignite is summed up. This also includes material demands for the replacement of essential parts of the conveyor system. The calculation is based on the estimated working life of individual components, producer information and company experiences, as well as on the values in the literature for different materials.

The conveyor system is responsible for a great part of the energy demand for the production of the equipment. This is

Table 2: CED for the production of mining equipment in the opencast mine

Mining equipment	CED [MJ/t_{Lign}]	percentage [%]
Conveyor system	20.7	79.1
Bucket-wheel excavator	3.0	11.3
Overburden spreader and tripper	1.4	5.4
Drilling and drainage	0.4	1.6
Auxiliary devices	0.4	1.4
Stacking, rehandling and rail loading equipment	0.3	1.2
Total	26.2	100

based on the fact that the life-time of the conveyor belts is limited by attrition and the frequent replacement of this component. Thus, the conveyor system turned out to be the most energy consuming part, as it requires both much electrical process energy and expenditures for equipment production.

The distribution of the assessed primary energy of the final energy demand (electricity and fuel), as well as the energy demand concerning the production of mining equipment, are shown in **Fig. 6**.

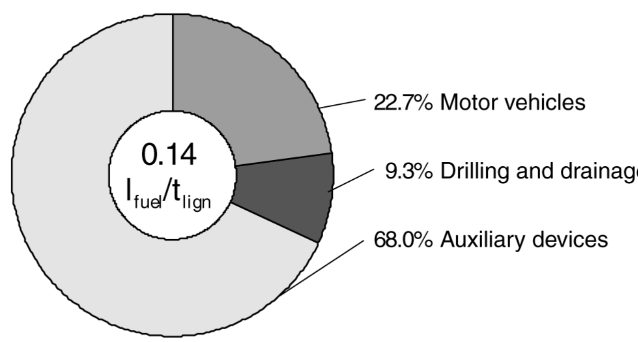

Fig. 6: Distribution of Cumulative (primary) Energy Demands of an opencast lignite mine

The high electricity demand of an opencast mine and the considerable primary energy demand for the supply of electricity are reflected in the share of 94% of the total primary energy demand. Furthermore, in the analysed opencast mine it is more important to determine the primary energy demand for the production of the equipment than for the consumption of fuel.

With reference to the energy content of lignite (net calorific value 8540 MJ/t [6]), the share of the primary energy demand for its extraction amounts to about 6.2%. This means that 93.8% of the lignite energy content is available as usable energy for further processes.

Our results of CED in opencast lignite mining in West-Germany obviously shows greater values than that seen in published data to date (**Table 3**). It seems to be that other studies have not considered the great electricity demand in lignite mining sufficiently.

[1] The Overall efficiency of supply for the electricity from lignite power stations, normally supplying the opencasts, is shown by the overall efficiency of supply for the electricity mix as estimated in Germany.

Table 3: Results of different studies about CED of lignite mining in West-Germany

	CED [MJ/t_{Lign}]	prim. energy de-mand for extraction [%]
this study	533.6	6.2
GaBi 3.0 (Germany)	459.6	4.9
GEMIS 3.x	281.8	3.3
GEMIS 3.x [a)]	310.6	3.5
IfE TU-M nchen	357 [b)]	4.18

[a)] Source: German Electricity Association (VDEW)
[b)] estimated with a net calorific value of 8540 MJ/t

Owing to favourable geological conditions, the CED in lignite extraction in East-Germany ranges between 90 and 160 MJ/t. So the share of primary energy demand for lignite mining amounts to only 0.8% to 1.8% [6,7,8].

6 Conclusion

Within an entire energy assessment of the utilisation of lignite as an energy carrier, the energy demanded for the supply of energy carriers must also be respected. Due to the predominantly West-German lignite mining in Germany (about 60%), the great CED of 533.6 MJ/t in Rhenish-area has to be considered.

Caused by different geological circumstances and frequently varying mining conditions, the results of this analysis cannot be transferred simply to other mines or operating years. It has to be checked whether boundary conditions, especially the relation between overburden and water to lignite or the supply of the mining equipment with electricity or fuel, allow a transfer of the determined values.

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DEVELOPMENT OF AN ENERGY MODEL FOR ANALYSIS OF ENERGY SUPPLY STRUCTURES

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ABSTRACT[1]

The transformation of primary energy carriers and the energy supply for consumers is directly connected to the use of renewable and non-renewable resources, emissions into air, soil and water and the production of waste. These energy-related material flows are of main interest in the assessment of an energy intensive product's resource intensity. Objective of this paper is the development of a methodology and its application in a model for determination of the material flows related to the electricity supply. As an example, the model is applied to the analysis of primary aluminium production. Different structures for electricity supply are balanced for several countries. These structures include national grids as well as specific process chains for power production from different fuels. The influence on the resulting material flows by different system boundaries, defined by the different structures of the electricity system (for example, electricity system based on entirely domestic production or the system that considers the import options from other countries) is investigated in detail. Additionally, potentials for primary energy savings and reduction in green house gas emissions associated with the improvement of the electricity and primary aluminium production processes are assessed.

KEYWORDS

Energy model, electricity, energy supply, energy flows, emissions, aluminium, smelter, energy demand

[1] Summary of Ph.D. thesis

ENVIRONMENTAL ASPECTS OF BAUXITE SUPPLY IN GLOBAL MATERIAL FLOW STUDIES*

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ABSTRACT

The global characterization of the environment in the vicinity of mining sites and the land area used during mineral extraction is a first step in quantifying impacts on nature. Bauxite, the main raw material for the production of aluminium, mostly occurs as a thin shallow ore-blanket that is predominantly extracted in open-pit mining. Thus, bauxite extraction results in considerable use of land area and consequently mining has to compete with other potential users. The impact on land area by mining is mainly a function of the geological properties of a given ore deposit and the environmental inventory of the surrounding land. Here, we have merged a geological database on bauxite deposits with an environmental database. Spatial data of mine-sites and land characteristics are linked by the geographic co-ordinates to quantify mining activities on a global scale and their impact on the environment. Currently, the total annual land used by bauxite mining amounts to almost 14 km^2, the average land area used per ton Al_2O_3 is 0.25 m^2. Almost 70 % of the current world bauxite production comes from sparsely populated areas (i.e. < 20 inhabitants per km^2) and nearly 60 % of the world production takes place outside areas covered by tropical rain forests. Furthermore, the main mining activities and reserves are situated outside or at least within a large distance away from wilderness areas, i.e. areas that are not inhabited or used by men.

KEYWORDS

Bauxite, deposit, land use

* Source: Pinyak, S. (ed.): Mine Planning and Equipment Selection 1999

1. INTRODUCTION

Global materials flow studies gain increasingly more importance before the background of Global Change and Sustainability. It has been recognized for a long time that the use of resources necessarily affects the environment. But it is not widely known that the total mass of mineral resources consumed annually by humans exceeds the mass of sediments transported to the sea by all rivers of the world (e.g. Skinner, 1994).

Recognizing the environmental concerns about mineral resources the 'Deutsche Forschungsgemeinschaft (DFG)' has established at the University of Technology Aachen a Collaborative Research Center (CRC)' entitled 'Resource Oriented Analysis of Metallic Raw Material Flows'.

The aim of this program is to identify policies and practices for a resource sensitive utilization of metallic raw materials within the framework of economic, environmental and social considerations. Taking aluminium as a first example, main objective of research is a systems approach to understanding the materials flow of Al from its source (i.e. bauxite deposits) through processing of alumina and aluminium to recycling of used products and the ultimate disposition of waste.

Within this framework, the present study is concerned with the global distribution of bauxite mines and the estimation of the size of land areas and characterization of land properties occupied by these mines. The support square concept introduced by Skinner (1994) provides an estimate of the size of a land area that must supply all of the resources an individual uses throughout his life. Today's support square is 155 m by 155 m of which an area of 13 m by 13 m is occupied by mining. This figure includes all mining activities but does not specify the characteristics of the land used.

Here a more detailed approach is adopted for the global analysis of land areas occupied by bauxite mining.

2. BAUXITE CHARACTERISTICS

Geologic factors of bauxite deposits have a significant effect on the availability of alumina and the quantity of resulting waste material in the subsequent technical steps as well as the land occupied by the mining process. Therefore, the development of methods for a mine-scale, regional, and global evaluation of bauxite-quality has to be performed through the investigation of the following steps:

- selection and assessment of geologic criteria relevant to land use by bauxite mining (e.g. ore grades, production rates, thickness and geometry of the ore body)
- global analyses of bauxite quality and land use
- assessment of possible changes in the future

In 1997 the total world production of metallurgical grade bauxite amounts to ca. 109 million metric tons and, thus, represents an enormous anthropogenic global mass flow with considerable impact on nature. The ore is predominantly extracted in open-pit mines which plays an important role for land use assessment methods.

2.1 *Bauxite supply database*

The present study is based on a comprehensive collation of data, including site-specific characteristics of bauxite deposits, accounting for almost 100% of the present bauxite production and reserves. The database contains information on 155 bauxite deposits worldwide. Almost 60 deposits are currently in operation and, thus, represent the present supply with bauxite. About 95 sites are still in an exploration status and may play an important role for future bauxite supply.

The database is designed as a relational database where the data are stored in several tables depending on the category of information they belong to. The tables are related to each other through the definition of adequate Key-ID's (e.g. the site name). The data-output, which depends on the actual problem the user wants to solve, is managed by a 'Structured Query Language (SQL)'. The results are structured output-tables that can be used as an input for another relational database, in the present study for the environmental database (see Chapter 3).

2.2 *Global land use quantification*

The annual minimum area occupied by the bauxite blanket or pocket respectively of a certain deposit is estimated using equation (1), and the land use for the extraction of bauxite equivalent to 1 ton alumina is calculated by equation (2):

$$\textbf{annual land use} = \frac{PR}{A \cdot D} \quad [km^2] \qquad (1)$$

$$\textbf{land use per ton } \mathbf{Al_2O_3} = \frac{100}{A \cdot D \cdot av.Al2O3} \quad [m^2] \qquad (2)$$

where PR = annual crude bauxite production in million metric tons; A = average thickness of the ore body in meters; D = average in situ density of the ore in metric tons per cubic meter, and $av.Al_2O_3$ = available alumina content of the ore in weight-%.

Thus, the land use is mainly a function of the quantity of bauxite extracted in a certain period of time, the quality of the ore (i.e. available alumina content) and the thickness of the ore body.

Table 1 serves information about the annual land use resulting from bauxite mining worldwide as well as the average land use per ton alumina distinguished by the deposit type. The total minimum annual area occupied by bauxite mining is 13.9 km^2. The average land use per ton alumina accounts to 0.25 m^2. In Addition, Table 1 demonstrates the effect of the deposit-type (i.e. lateritic bauxites, karst bauxites) on the land use, which is integrated in the following analyses.

Table 1. Total annual land use and average land use per ton alumina by bauxite mining distinguished by the main deposit type. Note that non-metallurgical bauxite and substitutes (i.e. nepheline, alunite) are excluded.

	total	lateritic bauxites	karst bauxites
annual land use [km^2]	13.9	11.6	2.3
average land use per ton Al_2O_3 [m^2]	0.25	0.27	0.19

2.3 *Future trends in bauxite supply*

Bauxite-quality, as mentioned above, has an important impact on the land use. Bauxite-quality, as it is understood in the context of the present study, can be illustrated by the amount of dry bauxite required to produce a certain amount of alumina (bauxite-to-alumina ratio). This ratio varies between 1.8 to 3.2, with an average value of 2.3 for currently operating bauxite mines worldwide.

The additional integration of quality data from non-operated deposits (exploration or feasibility phase), which represent material flows that can be expected to occur in the next decades, enables to predict probable changes of bauxite-quality in the future. Figure 1 compares bauxite-to-alumina ratios of operating mines with deposits that are currently in a feasibility or exploration status. It can be seen from the model that, on a global scale, bauxite-to-alumina ratios of non-operating deposits are significantly higher compared to those of currently operating mines. This suggests a potential reduction of bauxite-quality in the future (Hausberg et al., 1998).

The thickness and the geometry of the ore body, which also affect the land use, do not show great differences for operated and non-operated deposits on a global scale.

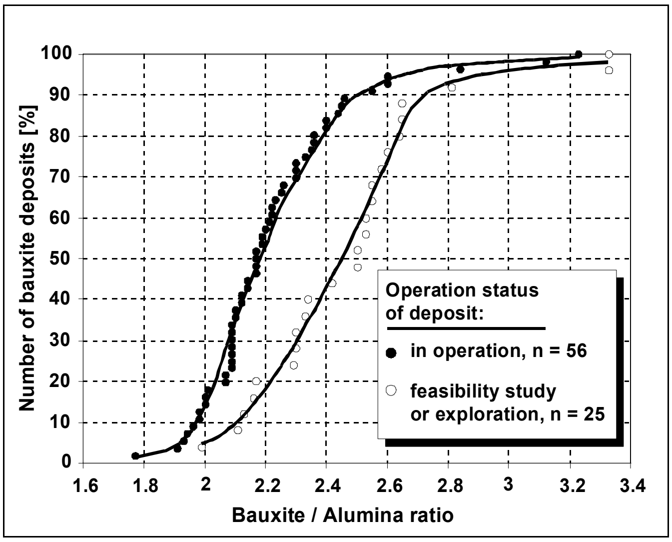

Figure 1. Grade model for bauxite reserves worldwide. Comparison of the Bauxite-to-Alumina ratio for operating and non-operating deposits.

3. ENVIRONMENTAL INFORMATION SYSTEM

For the assessment of environmental impacts which depend on the land use of mining activities not only the geological properties of the deposits but also the environmental properties have to be considered.

Therefore, digital data of different global surveys and research campaigns were organized in 6 environmental categories which are necessary to derive simple parameters for the quantitative characterization of environmental resources and targets which may be influenced by the focused activity (Bauer et al., 1998):

- Land/Ocean ratio
- Population density
- Land Cover
- Soils
- Hydrology
- Morphology

Within these categories the resolution of different data sources varies considerably. For available vector data scales vary between 1:1,000,000 and

1:37,000,000. Raster data resolutions range from cell sizes between one arc second (1" x 1") to one degree (1° x 1°) longitude/latitude. That means cell values represent areas between 1 km² and 10,000 km². In small scales the spatial extent of the operation, including the possible error of the co-ordinates, is small compared to the area which is represented in each cell. If the resolution of the spatial data is higher than the resolution of the point set, areas or lengths are measured within a given selection geometry.

Generally, three basic methods are used to assign quantitative information for a single site from the spatial data sets (see Figure 2).

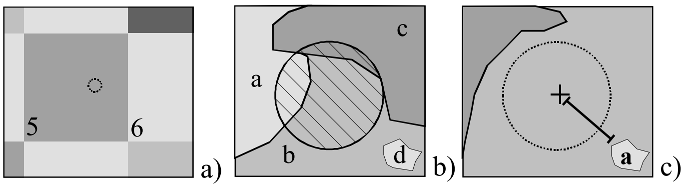

Figure 2. Methods to derive spatial properties; a: identification of a single value, b: calculating areas in a given selection geometry, c: distance measures; circles indicate the precision of the site co-ordinates.

The identification of single values is used for low resolution data sets, e.g. meteorological data in a 1° x 1° resolution. Areas are determined by circles with radii of 10 and 50 km. Distribution patterns are lost. Distance measures are used to integrate the distribution aspect for selected environmental targets.

4. LAND COVER CHARACTERISTICS

To group productive and explored deposits by land cover characteristics within a top down approach the environmental database is merged with the bauxite deposit database.

In contrast to previous panel-based studies (Atkins, 1993) which gathered a high information content for a sub-set of sites this approach includes nearly all sites with a loss of detail. In the scope of a material flow study this approach supports on the one hand grouping of deposits by environmental criteria and on the other hand the visualization of the sensitivity of global inventories towards different measurements of productivity.

According to the given methodologies for deriving environmental data from the information system three examples are chosen to show the application possibilities and limitations for characterizing bauxite supply on global scales. 'Population density', 'Tropical Rain Forest' and 'World Wilderness Areas' will illustrate the different methodologies to derive spatial information for productive and non productive deposits.

4.1 *Population density*

Mining processes have a distinct direct and indirect impact on the population within the vicinity of the site e.g. by the relocation of settlements or the change of land cover. For the given sites population densities were identified and grouped based on data given in (Li, 1996) with a resolution of 1° x 1° (see Figure 3).

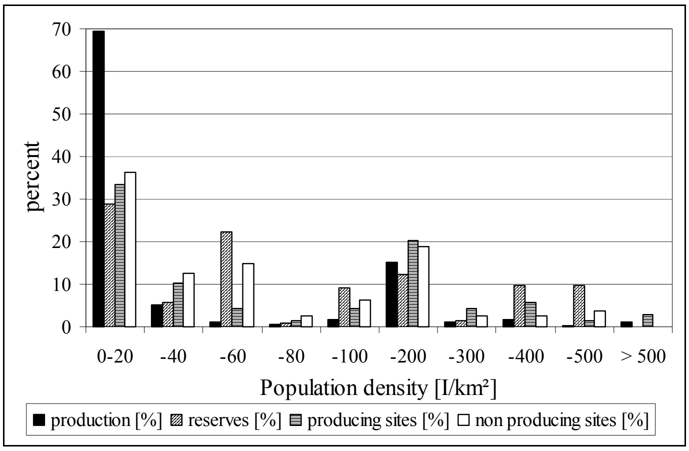

Figure 3. Bauxite deposits and production grouped by population density.

The frequency of sites within each class is given in percent as well as the proportion of the known world production. The non producing deposits are figured by their proportion of the total reserves. It is obvious that one third of the sites, producing nearly 70% of the worlds bauxite is situated in sparsely populated areas. This ratio is inverted considering more densely populated areas. For the non producing sites a shift towards more densely populated areas can be identified.

Based on the mining database the land use which is unavoidable due to deposit characteristics is considered in the analysis. Figure 4 gives a comparison between land use and productivity of dry bauxite.

Two major classes with adverse ratios between production and land use can be identified. In sparsely populated areas lateritic deposits with higher land use are dominant (see Table 1). Karstic bauxites are mined mainly in the Mediterranean, Jamaica and China where population densities are higher.

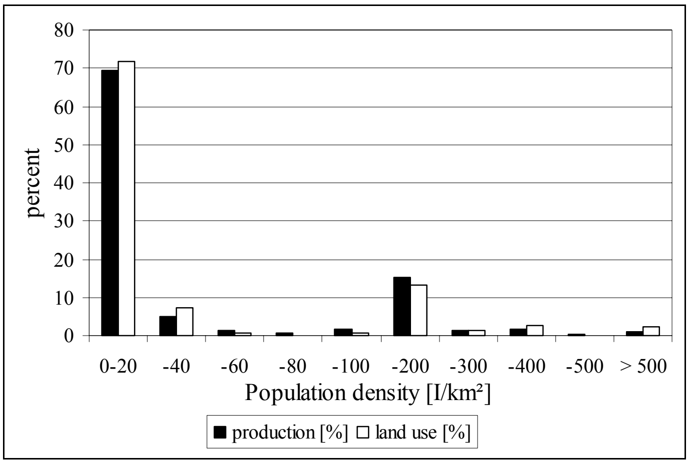

Figure 4. Producing deposits and land use grouped by population density

4.2 *Tropical Rain Forest*

One of the major concerns regarding bauxite mining operations is the disturbance of tropical rain forest probably due to the fact, that the largest recent deposits are situated in the tropics and sub tropics. According to a large scale remote sensing survey in 1993 with a spatial resolution of 1” x 1” global land cover was characterized based on multitemporal image analysis (EROS, 1997). According to the land-ocean ratio the amount of rainforest in the vicinity of each site was determined based on a radius of 10 km. Because of the loss of distribution information by simply deriving areas the figures must be interpreted with care. A high coverage with rain forest indicates a high probability that the deposit is covered with this ecosystem. A low coverage indicates that the major land cover type is different and the disturbance of rain forest seems less probable.

Figure 5 shows present and future deposits grouped by the percent rain forest in the direct vicinity of the site. Production rates and land use is given like in the previous example. This figure indicates, that more than 12% of the current bauxite supply takes place in tropical rainforest at approximately 7-8 % of the known sites. The ratio between production and land use is small. Regarding reserves the interference with tropical rain forest will decline, as far as only 10% are definitely covered by this ecosystem.

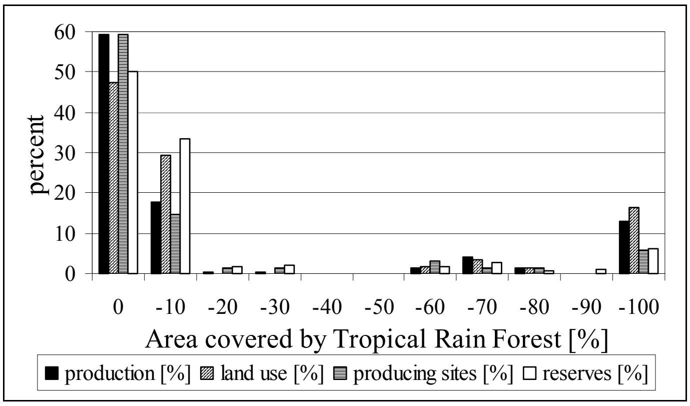

Figure 5. Bauxite deposits and reserves grouped by areas covered with tropical rain forest.

4.3 *World Wilderness Areas*

Another type of environmental target are wilderness areas which are mapped by the Sierra Club and the World Bank integrated by UNEP/GRID. Within this study based on large scale surveys all those areas of the world where no human activity could be recognized so far were mapped and distributed. These so called “wilderness areas” with an spatial extent greater than 400,000 hectares were added to the environmental information system as one particular land cover. For the assessment of a potential interference between mining activities and those wilderness zones the distances between the locations and wilderness areas were determined. The diagram given in Figure 6 shows the producing and non producing deposits grouped by four distance classes. Obviously the main activities and reserves lie outside or at least within a large distance towards these areas.

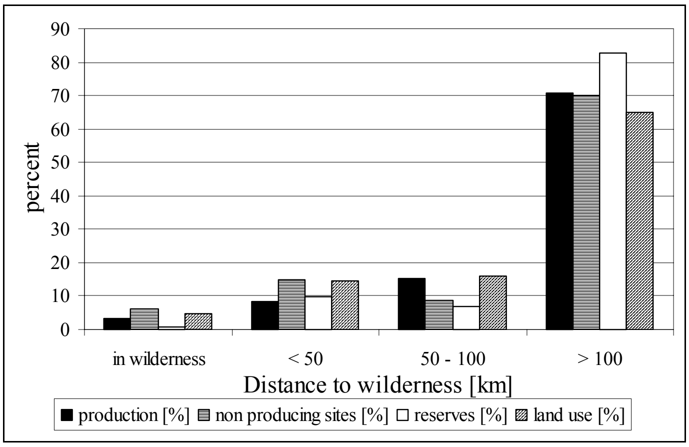

Figure 6. Bauxite deposits grouped by their distance towards world wilderness areas.

5. SITE-SPECIFIC ENVIRONMENTAL ASSESSMENT OF LAND USE

As shown above, the world wide bauxite supply can be characterized by environmental properties in the vicinity of the sites. Furthermore it is possible to assess the environmental impacts of different mining activities with the aid of the databases.

Focusing the alteration of natural functions by the operation the impact of land use can be estimated taking the duration of the activity into account.

During a field study at a lateritic open-pit bauxite-mine in Indonesia several environmental effects which occur during the normal mining process were investigated. These comprise the interruption of groundwater recharge, the soil erosion by wind and water and the interruption from CO_2-absorption by removing the vegetation cover. The land use parameters which are necessary for the calculation were catalogued for areas where mining takes place (pit and tailing ponds) and for areas of the infrastructure (streets, buildings, one small tailing pond, one stockpile etc.) (Figure 7).

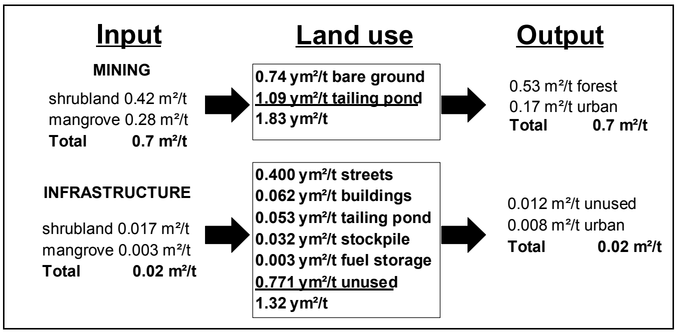

Figure 7. Example of an detailed analysis of land use at a lateritic open-pit bauxite mine in Indonesia.

The amount of land use is expressed taking the duration of use into account (years * square meters per metric ton bauxite [ym²/t]). For the assessment of the main environmental effects, two different areas are distinguished by their land use characteristics. First the land that is affected by erosion by wind and water (1.17 ym²/t), second the land that affect the groundwater recharge and the CO_2-absorption (2.38 ym²/t).

With the data from the environmental information system regarding precipitation, evapotranspiration, wind velocity, ecosystems, soil texture and slope it was possible to estimate the quantities of the identified environmental impacts. The provisional results of the assessment which was done with methods after Choudhury (1988), Wischmeyer & Smith (1978), Woodruff & Siddoway (1965) and Larcher (1994) are presented in Table 2.

Table 2. Example of an detailed environmental impact assessment at a lateritic open-pit bauxite mine in Indonesia.

environmental impact	quantities per ton bauxite
groundwater recharge	- 1500 l
soil erosion by water	13 kg
soil erosion by wind	0.03 kg
CO_2 –absorption	- 7.6 kg

With data from the bauxite supply database and knowledge about the approximate duration of time from surface stripping to rehabilitation, it is possible to estimate several environmental impacts from land use for every activity in the sense of a global study.

6. DISCUSSION AND SUMMARY

The characterization of environmental properties in the vicinity of each bauxite deposit is an useful instrument for the analysis and visualization of environmental aspects. Through the merge of the bauxite supply database in the environmental database, furthermore ore quality, mass calculations and potential future developments can be integrated. Appropriate modification of this methodology enables to analyze other metallic raw material flows as well. The qualitative detection of effects on nature is a first step to quantify environmental impacts. Based on these data, the environmental impact of land use, as an alteration of natural functions and processes during time, can be estimated.

For this estimation the integration of rehabilitation in the analysis is an important aspect. Rehabilitation activities are state of the art at the majority of mining operations. Different strategies for post mining land use, comprising revegetation, afforestation or restoration, depend strongly on the rehabilitation potential. The estimation of this potential in combination with the establishment of measurements for the success of the different approaches is currently performed through several field observations. Without the integration of rehabilitation, a holistic view of environmental aspects of mining activities can not be achieved.

According to uncertainties in the raw data and the low resolution of available environmental data the limited reliability of site-specific results is self-evident. The results may rather be used to characterize majorities and minorities of deposits regarding specific environmental aspects as well to analyze important effects. Additionally it can be shown clearly, that inventories, based on a subset of deposit data, are not representative in a statistical sense. The results are not suited for a stand alone valuation of single deposits or bauxite supply figures. Instead they have to contribute to the interpretation and analysis in the framework of the 'Collaborative Research Center (CRC)', where social and economical aspects are considered as a whole.

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RENATURIERUNG VON BAUXITABBAUGEBIETEN IN AUSTRALIEN*

(RENATURATION OF BAUXITE MINING IN AUSTRALIA)

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ABSTRACT

Opencast mining of bauxite affects relatively large areas. This study focuses on appropriate rehabilitation measures for the mined out land. Beside some socio-economic facts special interest is given to ecological aspects connected with different rehabilitation techniques which are used at the opencast bauxite mine in Weipa (Australia). The findings show that the applied soil replacement techniques have considerable effects on the quality of major pedological parameters. Of the four soil replacement techniques that were analysed, the greatest rehabilitation success was achieved with the so-called *Double Pass* technique, in which the soil is stripped prior to mining exactly according to A- and Bt-horizons and respread in the same sequence after mining. A positive correlation exists between the age of a rehabilitated area and the contents of organic matter, total nitrogen and microbial biomass nitrogen. Based on the results in Weipa and three other bauxite mines (Jamaica, Venezuela, Indonesia) an attempt is made for the development of transferable and holistic rehabilitation strategies.

KEYWORDS
Bauxite mining, rehabilitation, Weipa

* Source: Geografische Rundschau 53, Heft 9, 2001, S. 40-47

Im Zuge der erhöhten Nachfrage nach Aluminium ist die jährliche Gewinnung von Bauxit in den letzten 50 Jahren weltweit um das 15fache von ca. 8 Mio. t auf über 120 Mio. t gestiegen. Neben dem relativ hohen Energiebedarf bei der Aluminiumerzeugung steht vor allem die e-norme Flächeninanspruchnahme infolge der fast ausschließlich im Tagebau betriebenen Bauxitgewinnung im Blickfeld des öffentlichen Interesses. Einer der vordringlichsten Aufgaben der Bergbauunternehmen ist daher die sinnvolle Rehabilitation[1] der ausgeerzten Flächen. Zufriedenstellend zu lösen ist diese Aufgabe nur über detaillierte geoökologische und sozioökonomische Erhebungen vor Ort sowie Laboranalysen von Stoffvorräten und -flüssen, beispielsweise von mineralischen Pflanzennährstoffen und toxischen Schwermineralen. Im Falle der vorliegenden Arbeit wurde dies am nordaustralischen Bauxitgewinnungsstandort Weipa auf Flächen mit nach Zeitpunkt und Art unterschiedlichen Rehabilitationsmaßnahmen exemplarisch durchgeführt. Die Ergebnisse sollen methodische Ansätze zur Entwicklung von nachhaltigen und auf andere Abbaugebiete übertragbaren Rehabilitationsstrategien liefern. Letzteres erscheint zumindest für jene Bauxitbergbaugebiete möglich, die in den feuchten Tropen liegen und damit in zahlreichen klimatischen und edaphischen Merkmalen übereinstimmen. Hierzu gehören rund 90% aller derzeitig wirtschaftlich bedeutsamen Bauxitlagerstätten.

Einführung

Metallische Rohstoffe bilden eine elementare Entwicklungsgrundlage heutiger und kommender Generationen. Sie haben einen erheblichen Anteil an der Gesamtheit anthropogener Stoffströme, die in zunehmendem Umfang die Umwelt irreversibel zu schädigen drohen. Hieraus ergibt sich die Forderung nach einer dem Konzept der Nachhaltigkeit folgenden Umgestaltung und Steuerung dieser Prozesse. Seit Januar 1997 kooperieren neun Institute der RWTH Aachen und das Forschungszentrum Jülich im Sonderforschungsbereich 525 RESSOURCENORIENTIERTE GESAMTBETRACHTUNG VON STOFFSTRÖMEN METALLISCHER ROHSTOFFE der Deutschen Forschungsgemeinschaft mit dem Ziel, eine vollständige Analyse- und Bewertungsmethodik für metallische Rohstoffe zu erarbeiten. Dabei sollen in einer ersten Phase Stoffströme, die mit der Erzeugung von Aluminium verbunden sind, analysiert und Wege zu einer Operationalisierung des Konzepts der Nachhaltigkeit aufgezeigt werden. Im Blickfeld der Untersuchung steht die gesamte Prozesskette der Aluminiumerzeugung, d.h. vom Abbau des Bauxits bis hin zum Recycling des Endproduktes.
In direktem Zusammenhang mit der ressourcen- und umweltschonenden sowie sozial verträglichen Nutzung metallischer Rohstoffe stehen die vielfältigen Aspekte der Rehabilitation der Gewinnungsflächen. Die Abschätzung der damit verbundenen Rekultivierungs- bzw. Renaturierungspotentiale und die Entwicklung geeigneter Rehabilitationsstrategien, unter Einbeziehung sozioökonomischer Gegebenheiten, fallen in das Aufgabenfeld des Teilprojektes Umwelt des SFB. Mehrere Bauxitbergbaustandorte in Nordaustralien (Weipa), Indonesien (Bintan), Venezuela (Los Pijiguaos) und Jamaika werden im Rahmen der Untersuchungen des Teilprojektes Umwelt einer genaueren Analyse unterzogen. Die folgenden Angaben beziehen sich auf Weipa.

Naturraum und Lagerstätte

[1] Umfaßt als Oberbegriff von Rekultivierung und Renaturierung sowohl kulturlandschaftlich als auch naturlandschaftlich orientierte Errichtungen von Bergbaufolgelandschaften.

Eine der größten Bauxitlagerstätten der Erde (jährliche Förderung ca. 12,5 Mio t Rohbauxit) befindet sich in Weipa an der Westküste der Cape York Halbinsel im äußersten Norden von Queensland, Australien (Abb. 1). Dort herrscht ein sommerfeucht-tropisches Klima mit monsunalen Einflüssen. Wie auf dem größten Teil der westlichen Cape York Halbinsel herrschen auch in der Umgebung der Mine halboffene Eukalyptuswälder vor.
Die Böden werden nach der australischen Bodeneinteilung als *bauxitic/lateritic red earths* eingestuft (ISBELL u. MURTHA 1968). Nach der FAO-Klassifikation gehören die meisten zu den Acrisolen, Alisolen und Lixisolen (FAO 1994). Die typischen Profile dieser Böden bestehen aus einem ca. 10 cm mächtigen, durch organische Substanzen dunkel gefärbten A-Horizont und aus einem durchschnittlich 50 cm mächtigen Bt-Horizont. Dieser ist durch einen mit zunehmender Tiefe ansteigenden Anteil an Bauxit-Pisolithen gekennzeichnet. Den C-Horizont bildet die anstehende Bauxitschicht. Die infolge lang anhaltender intensiver chemischer Verwitterung entstandenen Böden sind durch hohe Anteile an sorptionsschwachen Zweischicht (1:1-)Tonmineralen mit geringer Basensättigung und entsprechend niedrigen Gehalten an Nährionen sowie hohen Anteilen an Sesquioxiden gekennzeichnet. Als Konsequenz der hohen Sesquioxidgehalte und der durchweg niedrigen pH-Werte kommt es zum Problem der Phosphatfixierung. Das Problem der Aluminiumtoxicität besteht in Böden mit pH-Werten unter 5.
Das heutige Bauxitprofil ist vermutlich das Ergebnis der seit dem Oligozän ablaufenden Desilifizierung und Ferrallitisierung, wobei das Ausgangsgestein kreidezeitlicher Sandstein bildete (BARDOSSY 1990). Die 10 bis 25 m ü. NN gelegene gibbsitische Plateau-Lagerstätte weist eine durchschnittliche Zusammensetzung von 54 bis 57% Al_2O_3, 4 bis 7% SiO_2, 5 bis 6% Fe_2O_3 und 2 bis 3% TiO_2 auf. Das im Durchschnitt 3,5 m mächtige Erz steht zu 80% in pisolithischer Form an, wobei die einzelnen Pisolithe Durchmesser von 1 bis 16 mm aufweisen. Nach Angaben der den Abbau betreibenden Minengesellschaft COMALCO betragen die *sicheren* (geologisch nachgewiesenen) Erzreserven 210 Mio. t; hinzu kommen 500 Mio. t als *wahrscheinliche* (mit hohem Sicherheitsgrad bestimmte) Reserven sowie weitere 3.600 Mio. t als *mögliche* (vermutete) Reserven. Die o.g. Zahlen unterstreichen die herausragende weltwirtschaftliche Bedeutung der Lagerstätte.
Die geometrische Ausbildung der typischen Plateau-Lagerstätte ermöglicht den Tagebau. Nach Festlegung der Abbauflächen muß zunächst der natürliche *Eucalyptus tetrodonta*-Wald (ca. 250 bis 300 ha/a) mit Bulldozern abgeschoben werden (engl. *stripped*). Daran anschließend wird der anstehende Oberboden (0,5 bis 0,6 m) mit Hilfe von Erdhobeln (engl. *scrapers*) gelöst (Abb. 2 und Abb. 3) und soweit vorhanden auf bereits abgebaute Lagerstättenteile aufgetragen, ansonsten vorübergehend aufgehaldet. Etwa 60% des so freigelegten Wertminerals werden mittels Reißhaken mit einer Eindringtiefe von 1 m aus dem Gebirgsverband gelöst, bevor es mit Hilfe von Radladern auf 150 t SLKW (Schwerlastkraftwagen) geladen wird (Abb. 4).

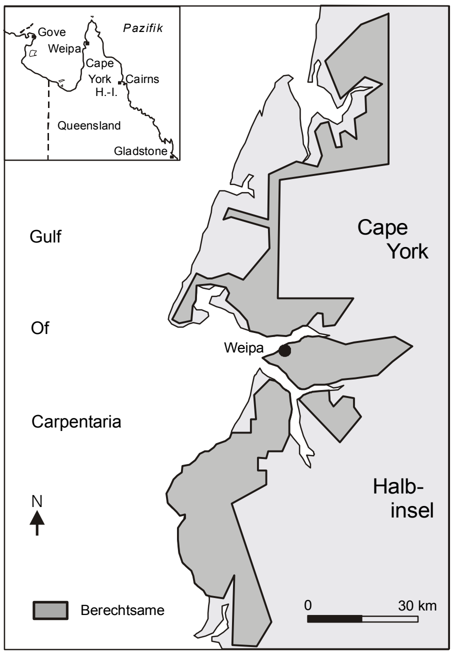

Abb. 1: Lage des Bauxittagebaus Weipa.

Abb. 2: Abtragen des Bodens mit Erdhobeln (engl. scrapers) im Tandembetrieb.

Abb. 3: Für den Bauxitabbau vorbereitete Fläche; ca. 60 cm Boden ist im *Dual Strip*- Verfahren (s.u.) abgetragen worden.

Abb. 4: Bauxitabbau und Beladen der 150 t SLKW.

Sozioökonomische Rahmenbedingungen

Die Township Weipa befindet sich innerhalb Australiens in einer äußerst peripheren Lage (Abb. 1). Die Cape York Region ist eine der isoliertesten und am dünnsten besiedelten Räume von Queensland. Die Township gliedert sich in einen nördlichen Siedlungsteil mit zentralen Verwaltungs- und Freizeiteinrichtungen und in die südliche Aborigine-Siedlung Napranum.
Im nördlichen Siedlungsteil leben etwa 2400 Einwohner, die fast ausschließlich für Comalco tätig sind. Nach Aussehen und Funktion entspricht er auch Jahrzehnte nach seiner Gründung dem Bild einer klassischen *company town*. Dies belegen die infrastrukturellen und bevölkerungsstatistischen Kenndaten (AUSTRALIAN BUREAU OF STATISTICS; DAMES AND MOORE 1997):

- Die Hälfte der erwerbstätigen Bevölkerung arbeitet unmittelbar in der Bauxitmine, die andere Hälfte ist im Dienstleistungsbereich, d.h. vor allem in öffentlichen Einrichtungen tätig.
- Die Fluktuation ist hoch. Rund 17% der Bevölkerung werden im Laufe eines Jahres "ausgetauscht".
- Die durchschnittliche Aufenthaltsdauer der Menschen beträgt 6 Jahre.
- Der Anteil der Frauen ist mit 41,5% an der Gesamtbevölkerung vergleichsweise gering.
- Nur wenige ältere, d.h. aus dem Erwerbsleben ausgeschiedene Personen bleiben auf Dauer ansässig.
- Aborigines leben kaum in diesem Teil der Bergbaustadt (4,3% der hier ansässigen Bevölkerung).

Im südlichen Siedlungsteil Napranum leben rund 800 Aborigines und Torres Strait Islanders. Die infrastrukturelle Austattung ist deutlich schlechter und der soziale Abstand zu der weißen Bevölkerung im nördlichen Weipa erheblich. Die Einwohner von Napranum verdienen weitaus weniger als die Minenarbeiter im nördlichen Teil der Township. Rund 15% der Haushalte haben ein Einkommen von weniger als 20 000 AUS $ (im nördlichen Weipa sind es hingegen lediglich 3%) (DAMES AND MOORE 1997). Zwar sind nach der Erwerbsstatistik 95,2% der indigenen Bevölkerung im Bereich der verschiedenen *community services* (Post, Gesundheitswesen u.a.) tätig, dennoch ist die Mehrzahl im Grunde von der staatlichen Fürsorge abhängig. Viele Aborigines ergänzen einen Teil ihres Lebensunterhaltes durch Fischfang.
Bevor Comalco 1957 die Abbaugenehmigung für Bauxite auf der westlichen Cape York Halbinsel erhielt, nutzten die Aborigines das Land für Jagd- und Sammelzwecke. Ihre Rechte

wurden insofern gewahrt, als sie weiterhin Zugang zum Land behielten, das für den Erzabbau vorgesehen ist oder nach Auserzung bereits renaturiert wurde.

Renaturierungsmaßnahmen der Minengesellschaft auf den ausgeerzten Flächen

Die gesetzliche Grundlage für die Rehabilitationsaktivitäten bildet der COMMONWEALTH ALUMINIUM CORPORATION AGREEMENT ACT von 1957. Dieser fordert, daß die sanierten Flächen keine unnatürlichen Hangneigungen aufweisen dürfen und daß der Eingriff in das natürliche Entwässerungsnetz zu minimieren ist.
Die anfänglich forcierten weide- und forstwirtschaftlichen Rekultivierungen mit dem Ziel, eine wirtschaftliche Basis für die Grundversorgung der ansässigen Bevölkerung nach Beendigung des Bergbaus zu schaffen, wurden wegen mangelnder Weideleistung bzw. unsicherer Holzerträge sowie der extremen Marktferne schon ab 1974 nicht weiter geführt. Seitdem wird die Errichtung eines sich selbsttragenden Ökosystems (”objective of rehabilitation is the reestablishment of a stable self sustaining ecosystem” COMALCO 1997) angestrebt. Dies soll über eine Rückführung der Abbauflächen in einen naturnahen Zustand erreicht werden, also eine Renaturierung im Sinne der deutschen Definition DIN 4047.
Bis 1996 wurden 6290 ha (das sind ca. 80% der gesamten Tagebaufläche) rekultiviert bzw. renaturiert. Davon entfielen 75% auf naturnahe und 25% auf bereits vor 1974 rekultivierte Flächen (14,5% Weideland, 5,9% Aufforstungen und 4,6% Sonstige) (COMALCO 1997).
Für die Renaturierung (engl. *revegetation, restoration*) verwendet man in der Regel Saatmischungen aus den einheimischen Gattungen *Eucalyptus, Acacia*, *Dodonea*, *Grevillea* und *Melaleuca*. Es wird eine Bestandesdichte von 1500 Stämmen pro Hektar, wie sie auch im Durchschnitt im natürlichen Eukalyptuswald besteht, angestrebt. Der Saatmischung sind meist 100 kg Superphosphat pro Hektar beigemengt.

Eigene Bodenanalysen auf renaturierten Flächen – Methoden

Im Rahmen der geoökologischen Geländearbeiten des Teilprojekts Umwelt (GÖK) in Weipa wurden Bodenproben genommen, die im bodenchemischen Labor der University of Queensland vorrangig auf ihren Kohlenstoff- und Stickstoffgehalt hin untersucht wurden. Es standen folgende Parameter als Bewertungskriterien der Regenerationsfähigkeit des Ökosystems, insbesondere des Bodens, im Mittelpunkt der Untersuchung:

- Organischer Kohlenstoff: Bestimmung indirekt mittels CNS Autoanalyser; C-org. > 98% C ges.. Der Gehalt an organischem Kohlenstoff gibt Aufschluß über den Gehalt an organischer Substanz im Boden (0,5 bis 0,58 g C entsprechen 1 g org. Substanz – SCHULTZ 1995). Die organische Bodensubstanz ist insbesondere in den feuchten Tropen von herausragender ökologischer Bedeutung und zwar durch ihren Beitrag zur
  - Nährstoffnachlieferung, insbesondere von N
  - Kationenaustauschkapazität
  - Aggregatstabilität
- Gesamtstickstoff: Bestimmung direkt mittels CNS Autoanalyser. Stickstoff ist oftmals, besonders in den Tropen, limitierender Faktor für das Pflanzenwachstum. Der Gesamtstickstoffgehalt im Boden ist ein Richtmaß dafür, welche Mengen des (hauptsächlich) organisch gebundenen Stickstoffs während einer bestimmten Zeitspanne mineralisiert und somit in pflanzenverfügbare Form überführt werden können.
- Mikrobieller Biomasse-Stickstoff: Bestimmung photometrisch über anaeroben Brutversuch nach AMATO und LADD 1988. Bei der Messung des mikrobiellen Biomasse-N wird

fast ausschließilch der N-Anteil erfaßt, der in Bakterien und Pilzen vorliegt. Man ermittelt also den ”aktiven Pool" im Stickstoffkreislauf. Dieser Parameter ist ein brauchbares Maß für die mikrobielle Aktivität im Boden.

- Nitrat: Bestimmung mittels Extraktion mit KCl, photometrisch. Nitrat stellt die wichtigste Form anorganischen Stickstoffs dar. Die Messung von Nitrat gibt Aufschluß darüber, wieviel Stickstoff direkt über die Bodenlösung pflanzenverfügbar ist. Allerdings ist Nitrat sehr leicht wasserlöslich und dementsprechend schnell auswaschbar. Daher ist der Nitratgehalt im Boden starken zeitlichen Schwankungen unterworfen.

Einfluß der Bodenumbettungstechnik auf die Renaturierung

Schon früh erkannte man den entscheidenden Einfluß der verschiedenen Bodenumbettungsverfahren auf den Erfolg der Renaturierungsmaßnahmen (DAHL und FOSTER 1988, 1989). Einen genaueren Nachweis erbrachte ein aufwendiger Feldversuch (engl. s*oil replacement trial*), den die University of Queensland und COMALCO ab 1990 gemeinsam durchführten. Dabei wurden auf einer gut sechs Hektar großen ausgeerzten Fläche die folgenden vier Bodenumbettungsverfahren getestet:

- *Double Pass* (DP) bedeutet, daß der Boden exakt getrennt nach A- und B-Horizont abgetragen und in gleicher Abfolge wie zuvor wieder aufgetragen wird.
- Bei der *Dual Strip* Technik (DS) wird der Boden in zwei gleichmächtigen Schichten von ca. 30 cm umgebettet, unter Beachtung der ursprünglichen Schichtenabfolge.
- Mit *Stockpiled* (ST) ist das Auftragen von zuvor auf Halde gelagertem Boden ohne jede Trennung nach Bodenschicht gemeint.
- *Subsoil only* (SU) bedeutet, daß praktisch nur Material aus dem Bt-Horizont aufgetragen wird, da der A-Horizont bereits vor der Bodenumbettung im Zuge der Rodung entfernt wurde.

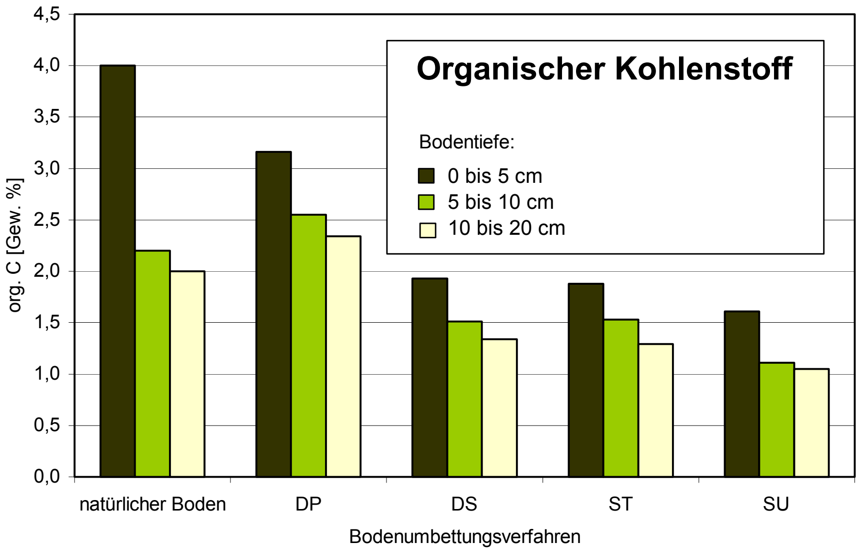

Abb. 5: Organischer Kohlenstoff in Abhängigkeit von Bodenumbettungstechnik und Bodentiefe nach 7 Jahren.

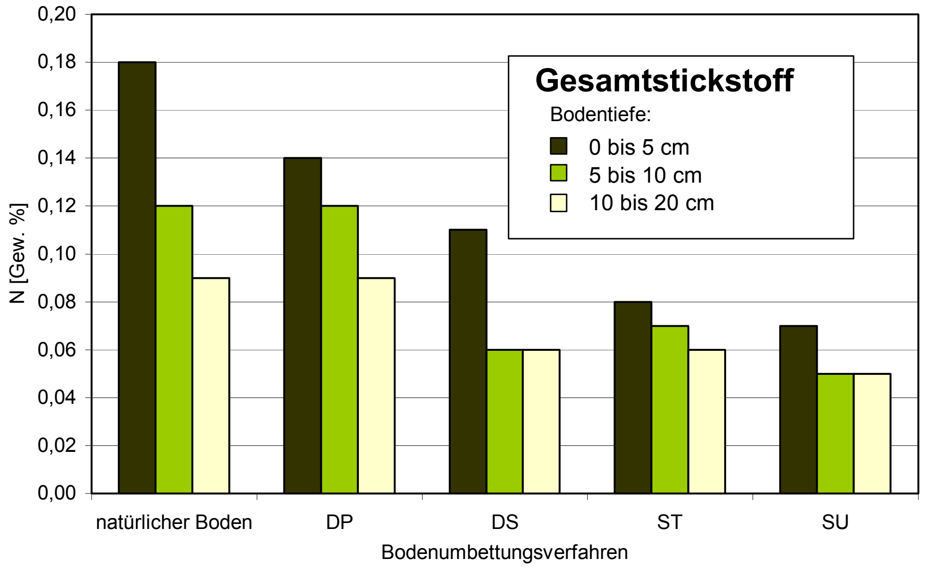

Abb. 6: Gesamtstickstoff in Abhängigkeit von Bodenumbettungstechnik und Bodentiefe nach 7 Jahren.

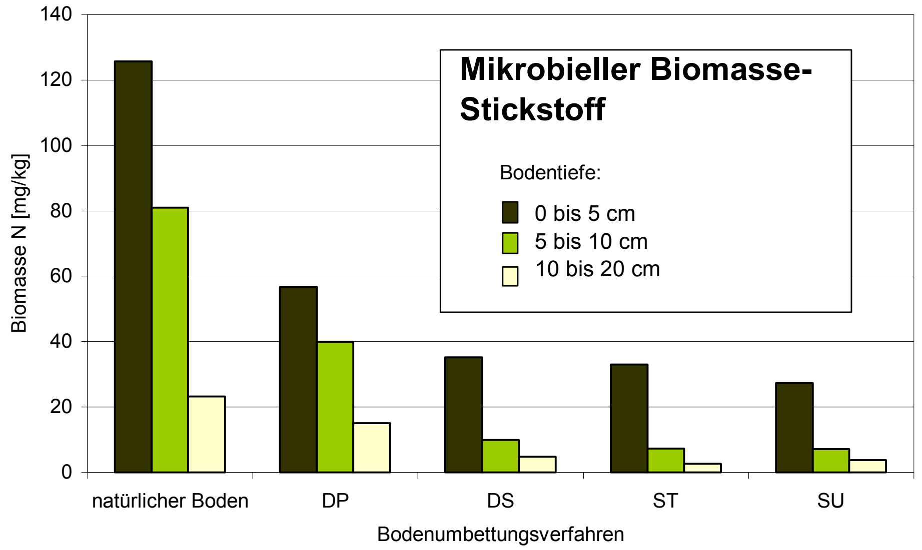

Abb. 7: Mikrobieller Biomassestickstoff in Abhängigkeit von Bodenumbettungstechnik und Bodentiefe.

Die Diagramme (Abb. 5 bis 8) zeigen die auf der Versuchsfläche und einer benachbarten natürlichen Waldfläche ermittelten Analyseergebnisse. Aufällig ist, daß die per Double Pass-Technik umgebetteten Böden für alle Untersuchungsparameter die günstigsten Werte aufweisen. So sind die Gehalte an organischem Kohlenstoff, Gesamtstickstoff und mikrobiellem Biomassestickstoff signifikant ($p<0,05$) höher als in den Böden der übrigen Verfahren (Hahn et. al. 1999). Selbst nach sieben Jahren ist der Einfluß der Bodenumbettungstechnik auf die untersuchten Parameter noch deutlich ablesbar. Eine Ausnahme bildet der Parameter Nitrat, der allerdings aus schon genannten Gründen nur begrenzt aussagekräftig ist.

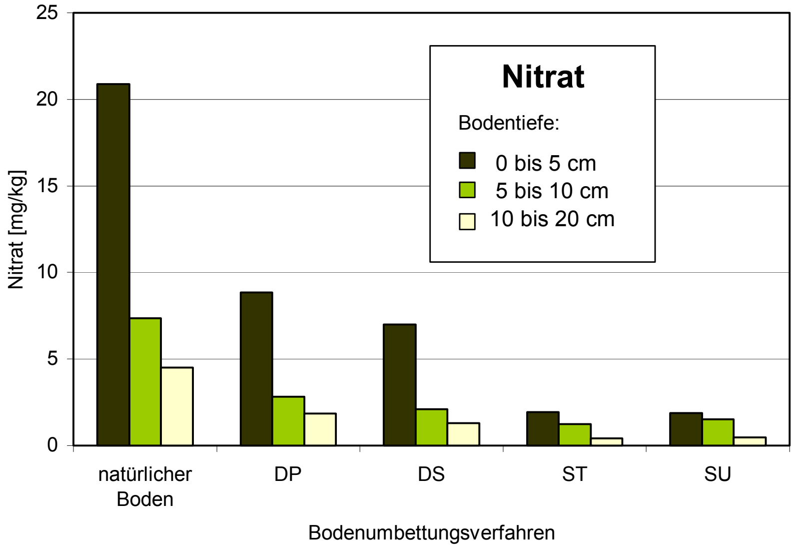

Abb. 8: Nitrat in Abhängigkeit von Bodenumbettungstechnik und Bodentiefe nach 7 Jahren.

Nach SCHWENKE (1996) spielt der Gehalt an organischer Substanz im Boden eine Schlüsselrolle für die angestrebte Stabilisierung des renaturierten Ökosystems in Weipa. Nach den an der University of Queensland gewonnenen Erfahrungswerten sind mindestens 1,5% organischer Substanz in den obersten 0 bis 5 cm Bodenschicht für eine erfolgversprechende Renaturierung nötig. Dieser Mindestgehalt wird nur bei der *Double Pass*-Technik schon in wenigen Jahren erreicht. Entsprechend ist diese Umbettungstechnik zu favorisieren. Bei ihr bleiben sowohl die ursprüngliche Menge als auch die ursprüngliche Zusammensetzung und Verteilung der organischen Bodensubstanz weitestgehend erhalten.
Allerdings ist dieses Verfahren besonders zeit- und kostenaufwendig. Daher wird derzeitig das wesentlich einfachere *Dual Strip*-Verfahren weit häufiger angewendet. Bei dieser Technik wird zwar der vormalige Oberboden wieder oberflächlich aufgetragen. Berücksichtigt man aber die natürliche Horizontmächtigkeiten (im Mittel 10 cm A-Horizont und 50 cm Bt-Horizont), so wird deutlich, daß bei dieser Technik der A-Horizont mit ca. 20 cm Bt-Horizont sozusagen verdünnt wird.
Weniger nachteilig als erwartet wirkt sich die Haldenlagerung des abgetragenenen Bodens auf die untersuchten Parameter aus. Die von VISSER et. al. (1984) an anderem Ort in langjährigen Feldversuchen und Laboruntersuchungen nachgewiesene deutliche Abnahme der organischen Substanz und mikrobiellen Aktivität in auf Halde gelagerten Böden konnte hier nur in geringem Maße beobachtet werden.
Die *Subsoil only*-Umbettungstechnik wurde nur testhalber ausgeführt. Die Analyseergebnisse zeigen hier erwartungsgemäß, abgesehen vom Parameter Nitrat, die ungünstigsten Werte.
Die verschiedenen Auswirkungen der genannten Umbettungstechniken bleiben auch viele Jahre nach der Umbettung noch erkennbar (siehe nächstes Kapitel, Abb. 9).

Einfluß des Umbettungsalters auf die Renaturierung

Art und Stand der Rehabilitation ausgeerzter Flächen sind nicht nur von der Bodenumbettungstechnik, sondern auch vom Alter der jeweils getroffenen Maßnahmen abhängig.
In der Abb. 9 sind die zeitlichen Veränderungen ausgewählter Bodenparameter auf zwischen 2-20 Jahre alten Renaturierungsflächen dargestellt.

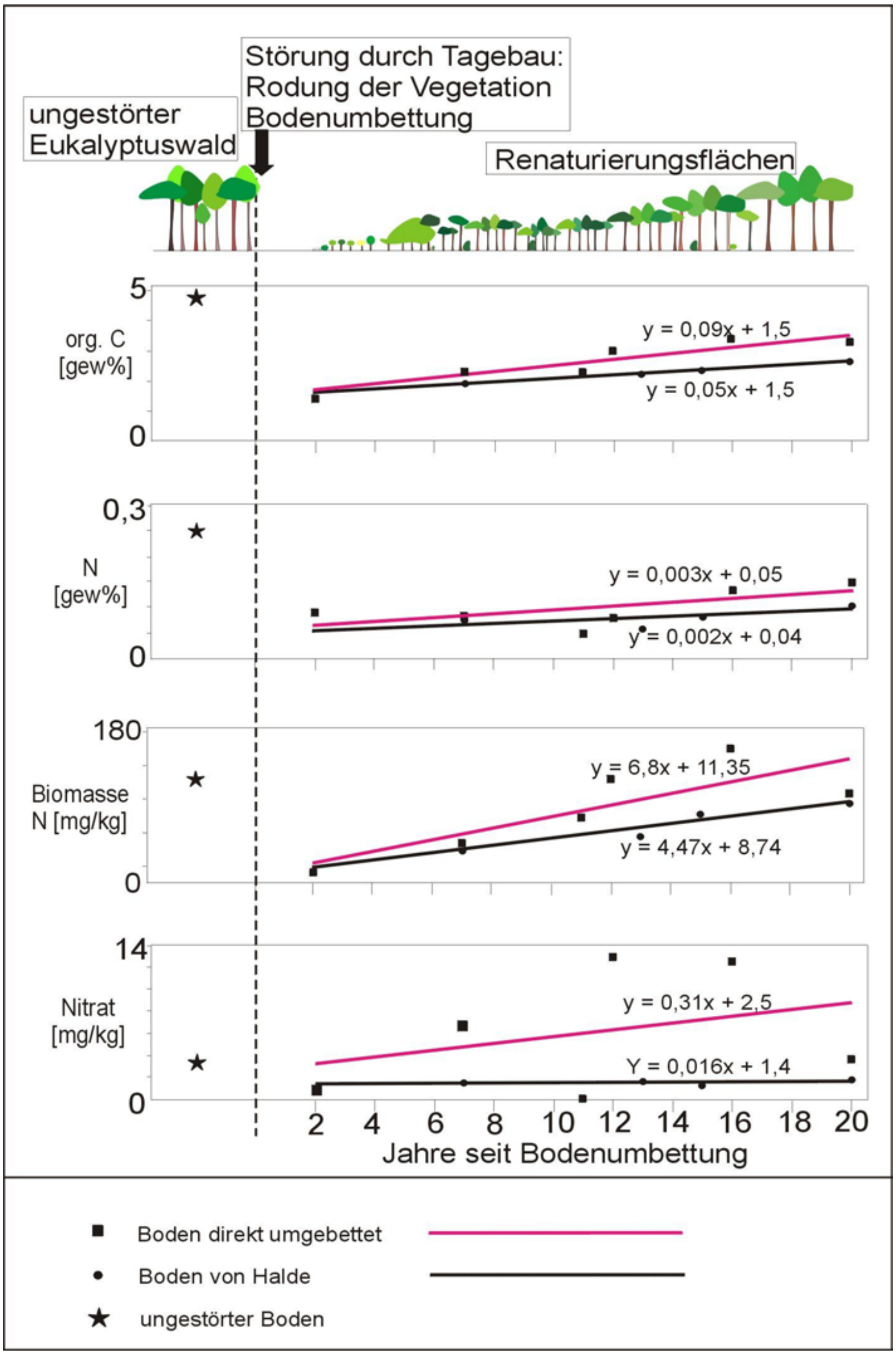

Abb. 9: Veränderung bodenkundlicher Untersuchungsparameter mit zunehmendem Alter der Renaturierungsflächen; zum Vergleich Gehalte des ungestörten Bodens.

Zu den Anfangsproblemen aller Renaturierungsflächen gehört, daß mit der Entfernung der Savannenvegetation vor dem Bauxitabbau auch die Streunachlieferung abrupt endet. Die Folge sind rasche Rückgänge der toten organischen Bodensubstanz und beträchtliche Verluste an mineralischen Pflanzennährstoffen. Zu deren Ausgleich erfolgten nach der Umbettung in allen Verfahren Düngerzugaben, die jeweils in Verbindung mit den Einsaaten vorgenommen wurden.

Mit Fortschreiten der Regeneration und damit steigender Biomasse wie auch steigender pflanzlicher Abfälle erhöht sich die organische Substanz im Boden wieder. Dies drückt sich in

einer Zunahme des Gehaltes an Gesamtstickstoff und an mikrobiellem Biomassestickstoff aus.
Berechnet man die C/N-Verhältnisse in den unterschiedlich alten Renaturierungsböden, so ergibt sich das in der Abb. 10 dargestellte Diagramm. Man erkennt deutlich eine Abnahme des C/N-Verhältnisses auf den älteren Flächen. Ein enges C/N-Verhältnis fördert die mikrobielle Aktivität im Boden und spricht für einen höheren Zersetzungsgrad der organischen Substanz und somit für eine einsetzende Stabilisierung des komplexen Systems Boden-Pflanze auf den renaturierten Flächen. Die Kenngröße C/N-Verhältnis stellt einen integralen Parameter mit hohem ökologischen Aussagewert dar und kann deshalb als Leitparameter mit Indikatorfunktion für eine Beurteilung des Renaturierungserfolges herangezogen werden.

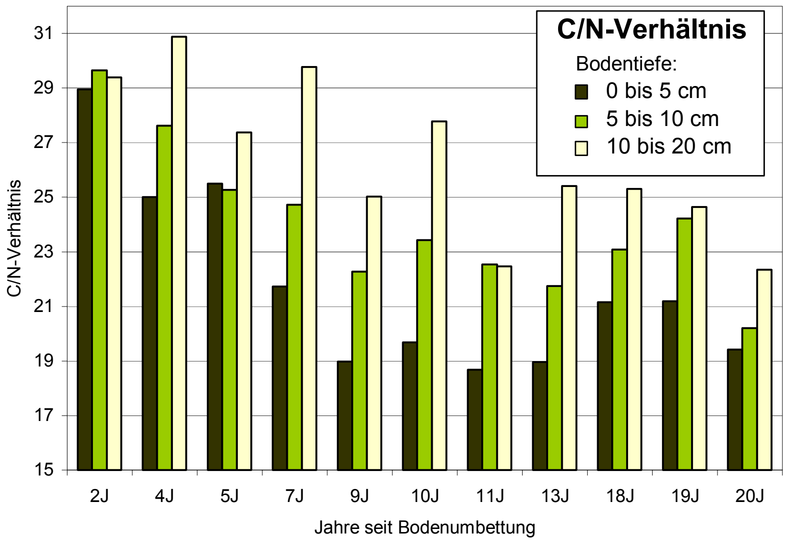

Abb. 10:C/N-Verhältnisse von renaturierten Böden in Abhängigkeit vom Alter und Bodentiefe.

Bewertung der bisherigen Renaturierungsmaßnahmen

Für den Standort Weipa ist zusammenfassend festzuhalten, daß eine vollständige Wiederherstellung des ursprünglichen Ökosystems ist in absehbarer Zeit nicht erreichbar ist. Die Gründe hierfür liegen hauptsächlich darin, daß sich der natürliche *Eucalyptus tetrodonta*-Wald über einen sehr langen Zeitraum entwickelt hat und in enger Beziehung zu dem lateritischen Bauxitprofil steht. Durch die Entfernung der Bauxitschicht kann sich die neue Vegtationsdecke nur über der unmittelbar darunter anschließenden *Ironstone*-Schicht entwickeln. Dies aber bedeutet, daß die bodenphysikalischen und -chemischen Substrateigenschaften grundlegend anders geworden sind. Das Renaturierungsziel muß sich daher auf die Schaffung von neuen Ökosystemen richten, die im Einklang mit den veränderten Standortbedingungen stehen und daher ebenfalls selbstragend sind. Nach ihren Strukturen und Funktionen können sie sich auffällig von denen der ursprünglichen Wälder unterscheiden.

Methodische Ansätze zur Entwicklung von überregional anwendbaren Rehabilitationsstrategien

Die ermittelten ökologischen Parameter haben sich als relevant für ein kontinuierliches Monitoring der renaturierten Flächen erwiesen. Zur Zeit wird in Zusammenarbeit mit der University of Queensland und COMALCO eine Methode entwickelt, die bewertende Aussagen über den Erfolg oder Mißerfolg der bisher angewandten Renaturierungsmaßnahmen erlaubt.

Grundsätzlich erfordern die vielfältigen Probleme sowohl auf ökologischer als auch auf ökonomischer Seite in allen Abbauregionen einen inhaltlich und methodisch breit gefächerten und standortübergreifenden Untersuchungsansatz zur Entwicklung geeigneter Rekultivierungs- und Renaturierungsstrategien. Dazu ist in einem ersten Schritt eine detaillierte Bestandsaufnahme aller Parameter durchzuführen, die das Rehabilitationspotential bedingen (können). Einflußfaktoren, die in direktem Zusammenhang mit den bergbaulichen Aktivitäten stehen, sind z.B. die Beseitigung der bestehenden Vegetation, die Umbettung des Oberbodens oder der eigentliche Bauxitabbau. Von den standort-vorgegebenen Faktoren sind Klima, natürliche Vegetation und Böden sowie die sozioökonomischen Gegebenheiten wie Infrastruktur, demographische Merkmale oder gesetzliche Vorgaben zu erfassen. Daran anschließend können dann anhand der gewonnenen Basisdaten die Möglichkeiten für eine geeignete Nutzung (z.B. in Gestalt von Forsten, Ackerland, Weideland oder Siedlungs- und Erholungsflächen) abgeschätzt werden und daraus die (ökologisch und ökonomisch) am besten geeignete Folgenutzung oder Renaturierung abgeleitet werden.

Für die praxisnahe Planung ist dieses Schema je nach konkret vorliegender Fragestellung und nach örtlichen Gegebenheiten mehr oder weniger umfassend oder stark vereinfacht anzuwenden (Abb. 11).

So erfordert beispielsweise die geplante Einrichtung von intensiv nutzbarem Ackerland – eventuell nur für bestimmte Feldfrüchte – wesentlich weiterreichende bodenkundliche und biologische Voruntersuchungen als dies bei der Schaffung von nur extensiv nutzbarem Weideland erforderlich ist.

Die Frage, in wie weit eine Fläche, die durch den Bergbau in Anspruch genommen worden ist, überhaupt für eine Nutzung geeignet ist, wird vorrangig nach den ökologischen Rahmenbedingungen zu beantworten sein. Daneben sind selbstverständlich technische und finanzielle Aspekte zu beachten. Aber auch sozioökonomische Hemmnisse können eine agrar- oder forstwirtschaftliche Folgenutzung schon zu Beginn einer Planung ausschließen. Ein Beispiel für diesen Fall ist der Bauxittagebau in Los Pijiguaos (Venezuela), wo sich in der unbewohnten Region die Frage nach einer kommerziellen Nutzung momentan nicht stellt.

Läßt sich keine geeignete Folgenutzung ermitteln, ist es aus Gründen der Umwelt- und Ressourcenschonung sinnvoll, die Rückführung des bergbaulich gestörten Geländes in den Zustand anzustreben, wie er in mehr oder weniger ähnlicher Weise vor dem bergbaulichen Eingriff bestand. Das heißt geotechnische und biologische Maßnahmen haben die *Renaturierung* zum Ziel.

In den meisten Fällen jedoch ist die ausgeerzte Fläche agrar- oder forstwirtschaftlich nutzbar. Hier muß zunächst geklärt werden, ob nur eine oder mehrere Nutzungsarten möglich sind und ob überhaupt ein Nutzungsbedarf besteht. Insbesondere in Gebieten mit starkem Bevölkerungsdruck und Flächenknappheit, wie beispielsweise in den weltwirtschaftlich bedeutenden bauxitfördernden Ländern Jamaika und Indonesien, kommt diesem Aspekt zentrale Bedeutung zu.

Erfahrungen in Weipa haben gezeigt, daß eine forstwirtschaftliche Nutzung der Flächen u.a. mit Edelhölzern (z.B. Teakholzanpflanzungen) zwar möglich, jedoch wirtschaftlich nicht immer erfolgreich umsetzbar ist (s.o.). Hier besteht die sinnvolle Alternative in einer Renaturierung. Der Weg der Renaturierung, der in Weipa eingeschlagen wurde, muß dabei keinesfalls einen geringeren Planungs- und Arbeitsaufwand nach sich ziehen, als dies bei einer Aufforstung der Fall wäre.

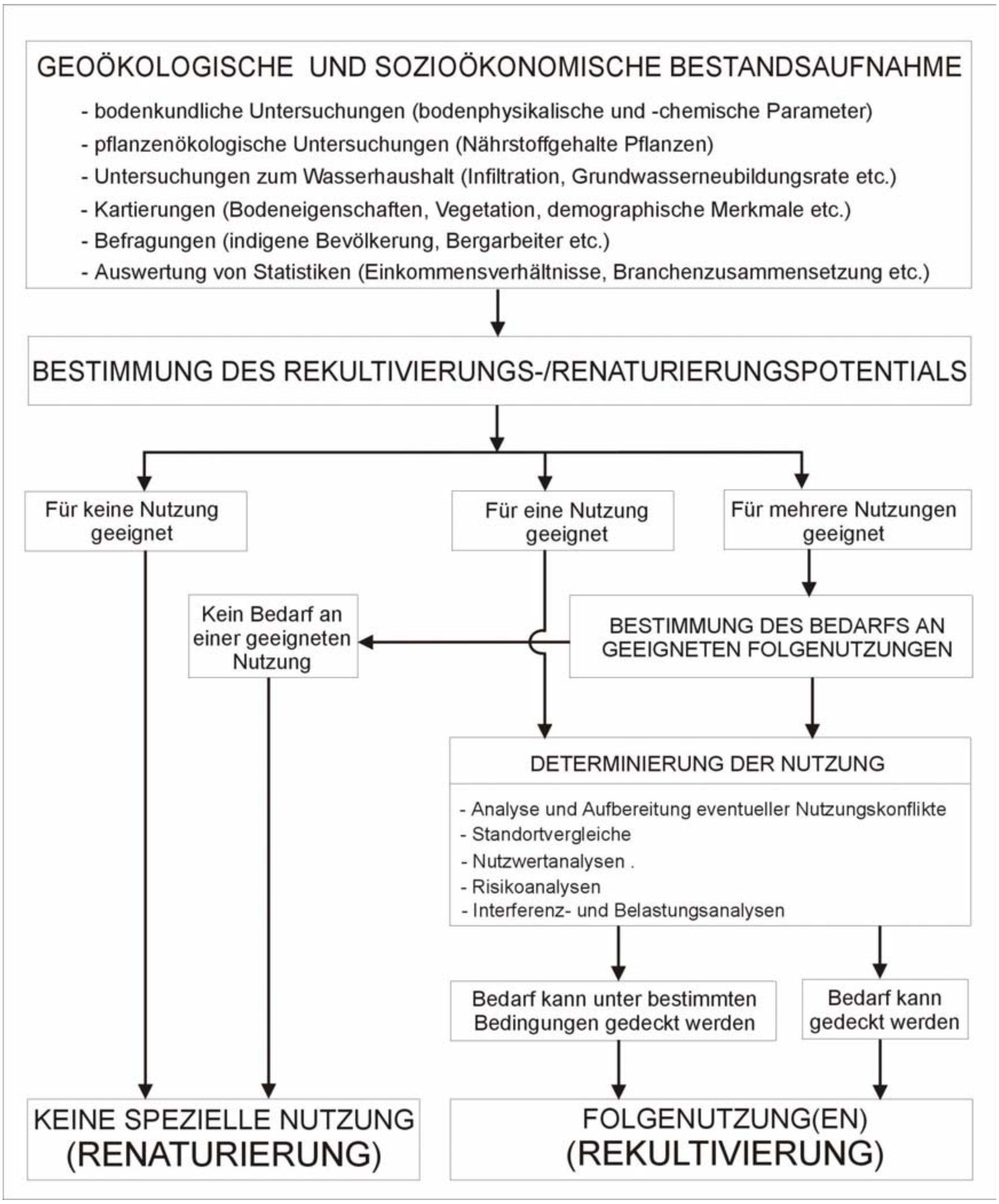

Abb. 11: Beispiel für eine Planungsorganisation von Folgenutzungen in Abbaugebieten (in Anlehnung an LESER 1991, stark verändert).

Ein anderes Bild zeigen die großflächigen Bauxitabbaugebiete in Jamaika. Dort ist, im Unterschied zu Weipa, die agrarisch nutzbare Landfläche eine äußerst knappe Ressource. Bei der Entwicklung nachhaltiger Rekultivierungsstrategien finden daher sozioökonomische Aspekte stärkere Beachtung als ökologische. Entsprechend zielt die Rehabilitation auf eine die kleinbäuerlichen Traditionen berücksichtigende, jedoch stärker (markt-)wirtschaftlich orientierte Form der Folgenutzung.

Sobald das Rehabilitationsziel bestimmt ist, muß über geeignete Instrumentarien wie Standortvergleiche, Nutzwert- und Risikoanalysen ermittelt werden, wie dieses Ziel bestmöglich zu erreichen ist.

Unabhängig davon, ob eine weidewirtschaftliche oder ackerbauliche Folgenutzung oder aber Renaturierung angestrebt wird, sind die Gefahren der Bodenerosion zu beachten. Dies gilt in besonderem Maße für die stärker reliefierten Gebiete an den Bauxitgewinnungsstandorten in Jamaika und Venezuela. In Los Pijiguaos wird dem Erosionsproblem dadurch begegnet, daß unmittelbar nach Auftrag des Oberbodens auf die ausgeerzten Flächen schnellwüchsige Grasarten (*Brachiaria decumbens* und *Brachiaria humidicola*) ausgesät werden. In extrem flachen Lagerstätten (z.B. Weipa) bereiten dagegen die Wiederherstellung eines stabilen Nährstoffkreislaufs und die Schaffung ausreichender Bestandesdichten einheimischer Gehölzarten auf den renaturierten Flächen größere Probleme.

Fazit

Die erläuterten methodischen Ansätze ermöglichen es, überregional anwendbare Strategien zur Rehabilitation von Gewinnungsflächen zu entwickeln, die sowohl naturräumliche Voraussetzungen als auch gesellschaftliche Erfordernisse berücksichtigen. Die methodischen Ansätze treffen nicht nur auf die Wiederherstellung von Bauxitabbauflächen zu. Auch für die Gewinnungsstandorte anderer metallischer Rohstoffe, die hauptsächlich im Tagebau gewonnen werden, können die entwickelten methodischen Ansätze eine geeignete Grundlage zur Entwicklung von Rekultivierungs- und Renaturierungsstrategien bilden sowie gleichzeitig Hilfestellung zur Bewertung von Potentialen für eine nachhaltige Folgenutzung bereitstellen.

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BAUXITGEWINNUNG IN DEN TROPEN: METHODISCHE ANSÄTZE ZUR BEURTEILUNG VON REKULTIVIERUNGS- UND RENATURIERUNGSPOTENTIALEN*

(Bauxite mining in the tropics: Methodological evaluation of recultivation and renaturation potentials)

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ABSTRACT

The article presents methodological approaches to the evaluation of rehabilitation potentials at selected bauxite mine sites in the Tropics. Among the geographical and mine-technical characteristics of a mine site the socio-economic conditions are of great importance for above mentioned approach. By the example of the bauxite mine site in Weipa (Australia) the most important geoecological and socio-economical parameters for the evaluation are specified.

KEYWORDS

Bauxite mining, rehabilitation, rehabilitation strategies, socio-economic conditions, geoecology

* Source: Aachener Geographische Arbeiten, Band 36, 2002, S. 91 - 117

1. Einführung

Metallische Rohstoffe stellen neben den energetischen Rohstoffen eine wesentliche Entwicklungsgrundlage heutiger und kommender Generationen dar. Sie haben einen erheblichen Anteil an der Gesamtheit anthropogener Stoffströme, die in zunehmendem Umfang die Umwelt irreversibel zu schädigen drohen. Hieraus erwächst die Forderung nach einer dem Konzept der Nachhaltigkeit folgenden Umgestaltung und Steuerung dieser Prozesse. Die Entwicklung geeigneter Strategien und Maßnahmen im Sinne der Agenda 21 setzt dabei die ganzheitliche Betrachtung von Stoffströmen, das heißt von der Gewinnung bis zur Entsorgung, voraus. Seit Januar 1997 kooperieren neun Institute der RWTH Aachen und das Forschungszentrum Jülich im Sonderforschungsbereich 525 "Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe" der Deutschen Forschungsgemeinschaft, um eine vollständige Analyse- und Bewertungsmethodik für metallische Rohstoffe zu erarbeiten. Dabei sollen in einer ersten Phase Stoffströme, die mit der Erzeugung von Aluminium verbunden sind, analysiert und Wege zu einer Operationalisierung des Konzepts der *sustainable development* aufgezeigt werden. Zentrales Element der Untersuchung ist die gesamte Prozesskette der Aluminiumerzeugung, d.h. vom Abbau des Bauxits bis hin zum Recycling des Endproduktes. Im engen Zusammenhang mit der ressourcen- und umweltschonenden sowie sozial verträglichen Nutzung mineralischer Rohstoffe stehen die vielfältigen Aspekte der Rekultivierung oder Renaturierung der Gewinnungsflächen. Die Abschätzung der damit verbundenen Rekultivierungs- bzw. Renaturierungspotentiale und die Entwicklung geeigneter Strategien unter Einbeziehung sozioökonomischer Gegebenheiten fallen in das Aufgabenfeld des Teilprojektes "Umwelt" des SFB.

2. Rekultivierung – Renaturierung - Rehabilitation

Die Beschäftigung mit methodischen Aspekten der Analyse des Rekultivierungs- und Renaturierungspotentials erfordert eine eindeutige Klärung der Begriffe Rekultivierung und Renaturierung, die bisher im deutschsprachigen Raum in wenig konsistenter Weise angewendet werden. Auch die englische Fachliteratur erschwert durch die zum Teil uneinheitliche Verwendung einer Vielzahl von Termini wie "recultivation", "restoration", "reclamation", "rehabilitation", "regeneration" oder "revegetation" eine klare begriffliche Differenzierung. In Anlehnung an KLÖTZLI (1991) und die DIN-Norm 4047 (1985) soll im folgenden unter *Rekultivierung* die wirtschaftliche Wiedererschließung eines Raumes nach bergbaulichen Eingriffen verstanden werden. *Renaturierung* bezeichnet hingegen die Rückführung von Ökosystemen in einen naturnahen Zustand (s.a. PFLUG 1998).

Als Oberbegriff für Rekultivierungen und Renaturierungen dient im folgenden der Begriff (Landschafts-)Rehabilitation, um auf einem höheren sprachlichen Integrationsniveau sowohl die kulturlandschaftlich als auch naturlandschaftlich orientierte Errichtung von Bergbaufolgelandschaften zusammenzufassen. Der Begriff Rekultivierungspotential bezeichnet demnach das vorwiegend *kulturlandschaftliche*, der Terminus Renaturierungspotential das hauptsächlich *naturlandschaftliche* Leistungsvermögen eines Raumes mit deren Hilfe eine Entwicklung eingeleitet werden soll, die den Nutzungsansprüchen der Gesellschaft oder einer ökologisch orientierten Planung entspricht.

3. Die nachhaltig orientierte (Wieder-)Herstellung von Bergbaufolgelandschaften

Die Herstellung von Metallen wie Aluminium oder Kupfer erfordert bei der Gewinnung neben dem Ausbringen des eigentlichen Bauxiterzes, große Massenströme an Abraum oder Nebengestein. Damit ist ein erheblicher Eingriff sowohl in die Natur- als auch in die Kulturlandschaft verbunden. Die Aufgabe, vormals für die Rohstoffgewinnung oder für die Rohstofflagerung genutzte Flächen zu rekultivieren oder zu renaturieren, ist in den meisten der Bauxit fördernden Ländern mittlerweile gesetzlich verankert, so daß auch die beteiligten Bergbauunternehmen diesem Problem zunehmende Aufmerksamkeit schenken müssen. Die damit verbundenen Problemfelder sind sehr vielfältig und umfassen ökologische und sozioökonomische Aspekte des Abbaus gleichermaßen. Insbesondere im Hinblick auf das sozioökonomische Umfeld, die Ressourcenschonung und die Wirtschaftlichkeit kommt der Frage große Bedeutung zu, inwieweit während der Bergbauzeit und für die Zeit nach der Gewinnungsphase Lebens- und Arbeitsmöglichkeiten entstehen bzw. von der dort ansässigen Bevölkerung angenommen werden. Das Ziel der Aufarbeitung bergbaulicher Eingriffe ist es, eine den jeweiligen ökologischen Gegebenheiten angepaßte Regeneration von Pflanzen- und Tierwelt in die Wege zu leiten oder eine erneute, den örtlichen sozioökonomischen Traditionen oder finanziellen Möglichkeiten entsprechende Landnutzung (wieder-) herzustellen (Finanzierungsantrag des SFB 525 1996, S. 235).

Für die Beurteilung des Rehabilitationspotentials und die Entwicklung angepaßter Strategien ist der Rückgriff auf die klassische komplexgeographische Analyse regionaler Systemzusammenhänge geeignet (BASTIAN 1992, HARTMANN 1992, LESER 1991, u.a.), d.h. die Darstellung und Strukturierung der den Abbauraum beherrschenden physischen und gesellschaftlichen Prozesse und Faktoren. Dieser integrierende Zugang kann maßgeblich zum Verständnis regionaler Systemfunktionalität und -dynamik beitragen, auf das die Beurteilung von landschaftsgerechten Rehabilitationspotentialen zu gründen hat.

Die vielgestaltigen Wechselbeziehungen, die bei der Untersuchung von Rehabilitationsmaßnahmen zu berücksichtigen sind, verdeutlicht das nachfolgende Modell zur Mensch-Umwelt-Beziehung einer Region (Abb. 1). Kennzeichnend für den Raum sind danach drei miteinander verknüpfte Systembereiche: Das natürliche System, das sozioökonomische System und die Land(Folge-)nutzung. Die Art und Intensität der Folgenutzung sind dabei abhängig von den jeweiligen Einzelfaktoren des physischen und anthropogenen Rahmens und entsprechen regional sehr unterschiedlichen Ansprüchen. Umgekehrt kann die Art der Folgenutzung wiederum entscheidenden Einfluß auf die beiden anderen Systeme nehmen. Nicht zu vernachlässigen sind zudem externe Steuerungsgrößen, sowohl auf physischer Seite, z.B. Bodenerosion oder kleinräumige Klimaveränderungen, als auch auf sozioökonomischer Seite, z.B. schwankende Weltmarktpreise, gesellschaftlicher Wertewandel. Es handelt sich also nicht um ein geschlossenes System, auch wenn aus methodischen Gründen eine Grenze der regionalen Betrachtung gezogen wird. Trotz der damit einhergehenden Unschärfe bietet dieses Modell aufgrund seines stark raumbezogenen Charakters einen geeigneten methodischen Rahmen für die Bearbeitung der o.a. Fragestellung. Denn die Rehabilitation einer vom Bergbau beeinträchtigten Landschaft kann nicht nur auf der Basis eines Einzelfaktors erfolgen, z.B. im Hinblick auf die mineralische Nährstoffversorgung des Bodens. Um eine dauerhafte Entwicklung einzuleiten, die den regionalen Verhältnissen gerecht wird, sind die verschiedensten Bedingungen und Einflüsse auf den betroffenen Raum in Rechnung zu ziehen. So können z.B. bei gleichen physischen Bedingungen zweier Bergbauregionen durchaus unterschiedliche Landnutzungen aufgrund uneinheitlicher sozioökonomischer Verhältnisse erwachsen.

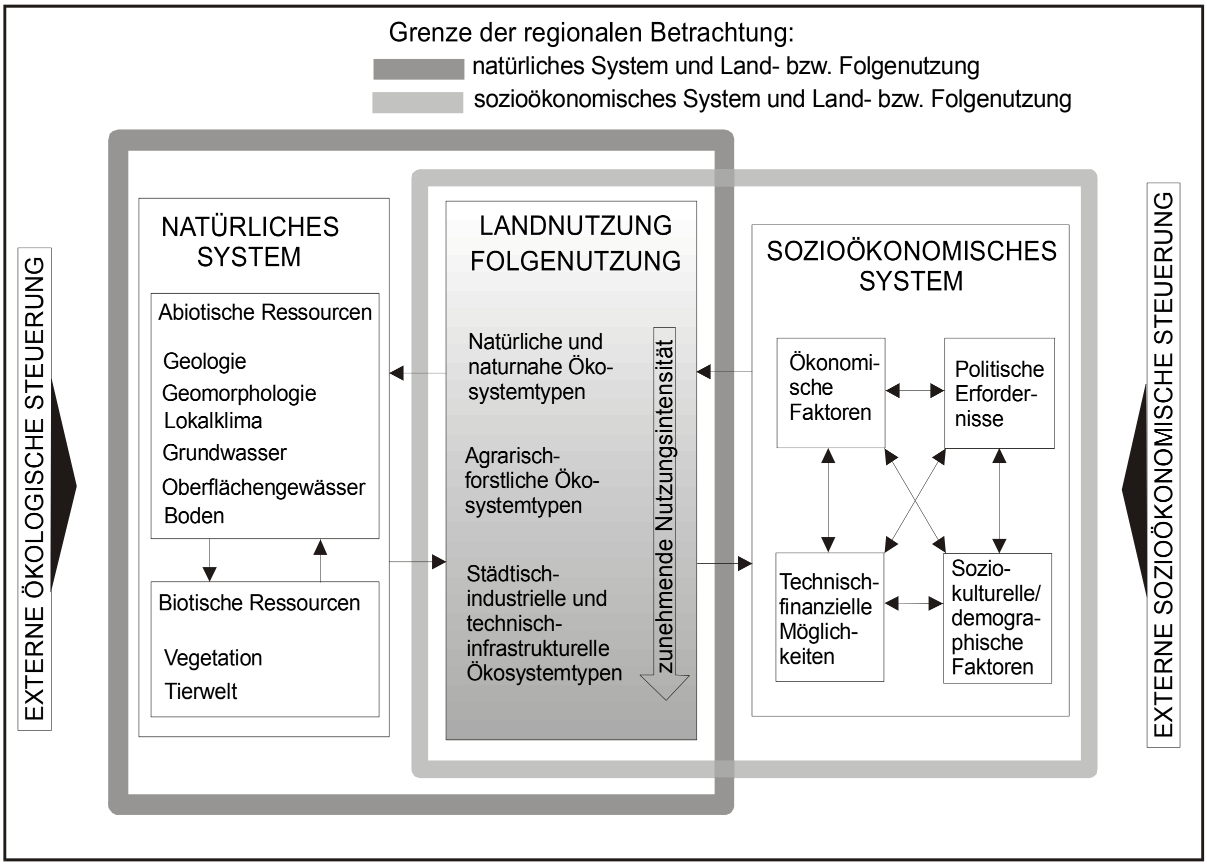

Abbildung 1: Schema eines regionalen ökologisch-ökonomischen Systems (Nach MESSERLI 1978; verändert).

Um eine geeignete Rehabilitationsstrategie für ausgeerzte Flächen zu ermitteln, reicht es also nicht aus, den Blick nur auf die Verhältnisse vor Beginn des Abbaus zu richten. Zumeist handelt es sich um Standorte, die bereits seit mehreren Jahrzehnten in Betrieb sind. Somit ist grundsätzlich davon auszugehen, daß mittlerweile ein sozioökonomischer Wandel stattgefunden hat, der die Einrichtung von "Nutzungen", wie sie dort einst vor Beginn des Bergbaus vorherrschten, unsinnig erscheinen lassen kann. Die Komplexität der mit einer nachhaltig orientierten Landschaftsrehabilitation verbundenen Probleme veranschaulichen regionale Fallanalysen aus mehreren Untersuchungsräumen, in denen Rekultivierungs- oder Renaturierungsmaßnahmen infolge von Bauxitabbau notwendig sind.

4. Untersuchungsräume

Entsprechend den Entstehungsbedingungen des Bauxits – feuchttropisches Klima mit saisonalem Wechsel von Regen- und Trockenzeit - befinden sich die weltweit bedeutendsten Lagerstätten überwiegend in tropischen und subtropischen Räumen (Abb. 2). Allein auf die Staaten Australien, Guinea, Jamaika und Brasilien entfallen fast 70% der Weltbauxitförderung. Das zumeist lateritische Verwitterungsprodukt liegt oberflächennah und kann daher im Tagebau gefördert werden. Eine bedeutsame Ausnahme unter den o.g. Ländern mit ausschließlich lateritischen Bauxiten bildet Jamaika, wo sich die größten Karstbauxitreserven der Erde befinden. Diese werden allerdings auch im Tagebau gefördert.

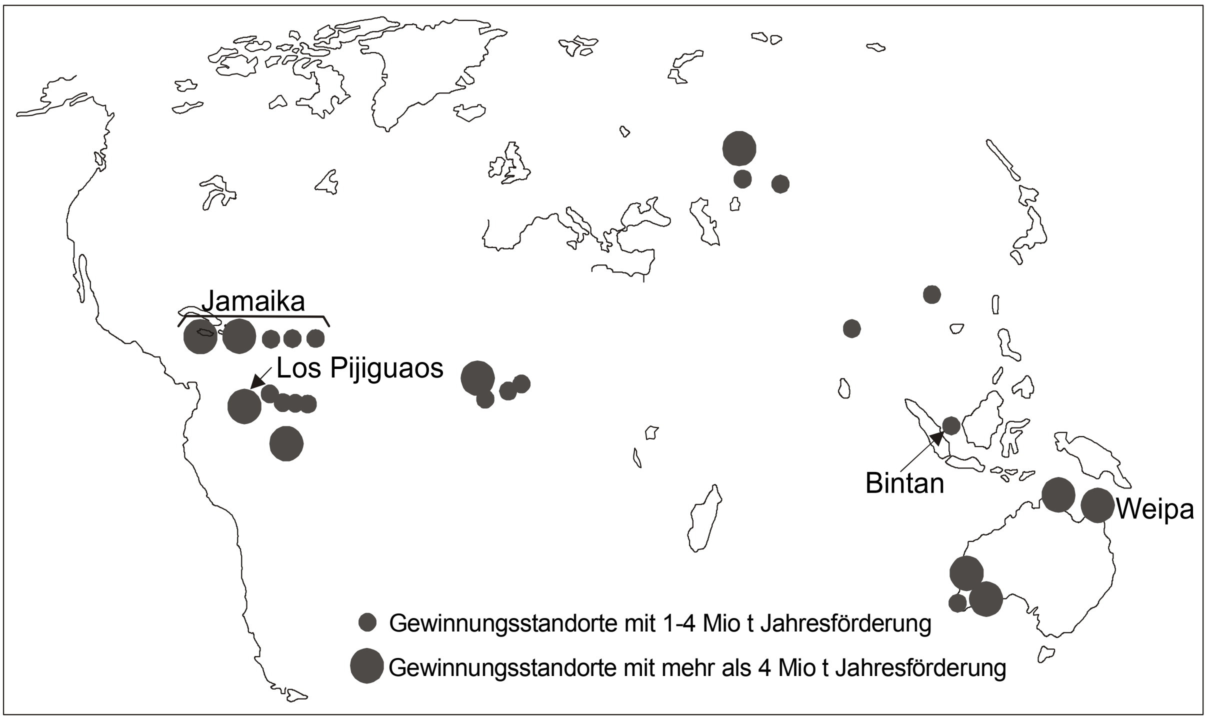

Abbildung 2: Geographische Lage der Bauxit-Gewinnungsstandorte
mit mindestens 1 Mio. t Jahresförderung.

Unter feuchtheißen Klimabedingungen entstehen als Ergebnis der intensiven chemischen Verwitterung vorwiegend sorptionsschwache Zweischicht Tonminerale (meist Kaolinit). Kennzeichnend für die meisten Böden ist der Prozeß der Desilifizierung, das heißt die Verarmung an Silizium und der Ferralitisierung mit der Folge der residualen Anreicherung von Al- und Fe- Oxiden sowie der späteren verstärkten Wegführung der Alkali- und Erdalkali-Ionen. Darauf gründet sich unter anderem das oft relativ niedrige natürliche Produktionspotential vieler tropischer Böden. Charakteristisch für viele Bauxitabbaugebiete ist eine savannen- oder waldähnliche Vegetation, die allerdings sowohl von der Artenzusammensetzung als auch von den Strukturmerkmalen her sehr unterschiedlich ausgebildet ist. Die wenig fruchtbaren Böden sind ein Grund dafür, daß häufig nur eine extensive Landnutzung in diesen Räumen stattfindet.

Im Rahmen der Untersuchung werden mehrere Bergbaustandorte in Nordaustralien (Weipa), Indonesien (Bintan), Venezuela (Los Pijiguaos) und Jamaika einer genaueren Analyse unterzogen, die durch unterschiedliche Naturraummerkmale gekennzeichnet sind (Tab.1). Im folgenden wird beispielhaft der Untersuchungsstandort Weipa vorgestellt, der bereits Gegenstand umfangreicher Untersuchungen und Erhebungen im Rahmen von Geländekampagnen war.

Tabelle 1: Übersicht über geoökologisch relevante Naturraummerkmale in den einzelnen Untersuchungsräumen.

Standort	Klima	Böden	Vegetation	Relief/Gewässer
Weipa 12°38` S 141°54` E	Sommerfeucht tropisch	Acrisole (FAO-UNESCO 1988) bauxitic-lateritic red earths (Isbell 1968)	Eukalyptus-Savannenwald "Eucalyptus woodland"	Schwemmfächer tertiären Ursprungs aberodiertem Material (2 – 20 m ü. NN)
Los Pijiguaos 6°22` N 66°52` W	Übergangsraum zwischen Sommerfeucht tropischen und Immerfeucht tropischen Klima	Ferralsole (FAO-UNESCO 1988)	Halb-immergrüner Wald "Bosque Humedo Premontano", z.T. Trockenwald "Bosque Seco Tropical"	Stark fluvial zerschnittenes Plateau (600 – 700 m ü. NN)
Bintan 0°50` N 104°12` E	Immerfeucht tropisch	Ferralsole (FAO-UNESCO 1988)	Sekundärwald mit inselhaften Relikten von immergrünem Tieflandsregenwald	Hügelige Insel, Abbauflächen (5 – 80 m ü. NN)
Jamaika 18°15` N 77°30` W	Immerfeucht-tropisch; mit orographisch bedingten Abweichungen in der Niederschlags-verteilung	Nitisole (FAO-UNESCO 1988) in der Umgebung der Bauxitlagerstätten	Sekundäre Buschvegetation mit wenigen Relikten tropischen Regenwaldes	Hügeliges Kalksteinplateau ca. 500 m ü. NN, z.T. mit typischen Karstformen und sog. "bauxite pockets"

5. Der Bergbaustandort Weipa, North Queensland

Der von der *Comalco Pty. Ltd.* betriebene Tagebau *Weipa* mit einer Berechtsame von 2590 km² und einer jährlichen Förderung von etwa 14,5 Mt Rohbauxit befindet sich innerhalb Australiens in einer äußerst peripheren Lage (Abb. 3). Die Cape York Region ist eine der isoliertesten und am dünnsten besiedelten Räume Queenslands. Außer Weipa (2400 E. 1998) existieren mit Napranum und Mapoon, die ausschließlich von Aborigines bewohnt werden, nur noch zwei weitere Orte in der Nähe der Bergbauregion. Zur nächsten größeren Stadt, dem rund 850 km entfernten Cairns, besteht lediglich eine in der Trockenzeit befahrbare “Schotterpiste”. Eine Eisenbahnlinie existiert nicht. Die Versorgung der im Bergbau tätigen Bevölkerung erfolgt daher fast ausschließlich über den Seeweg bzw. mit dem Flugzeug. Der namengebende Ort Weipa entstand als Missionsstation Ende des vorigen Jahrhunderts. Erst 1966 erfolgte in Verbindung mit der Erschließung der Abbauflächen und dem Aufbau von Verladeeinrichtungen an der Küste durch die Firma *Comalco* der Ausbau zur Kleinstadt.

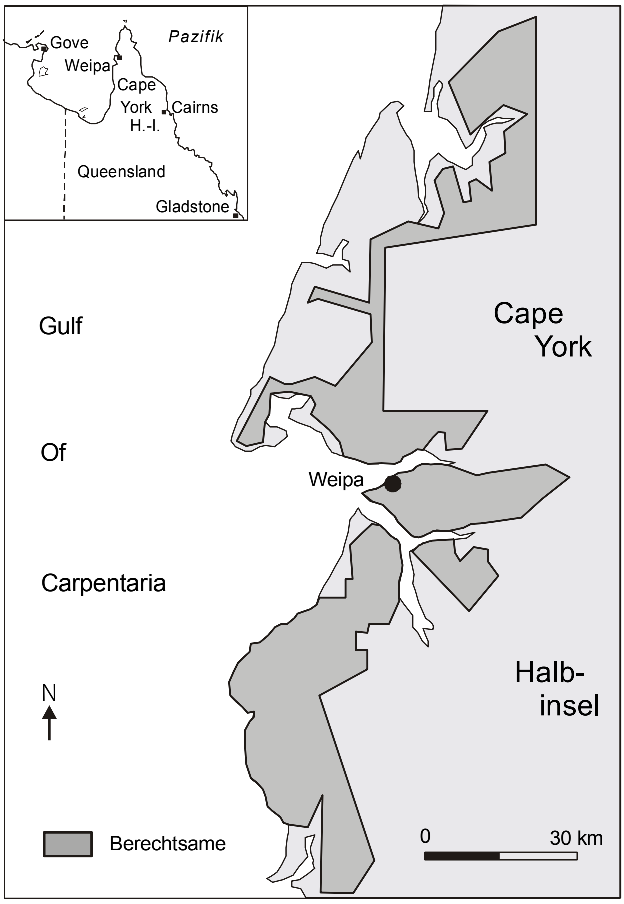

Abbildung 3: Lage des Tagebaus Weipa.

5.1 Die ökologischen (physisch-geographischen) Voraussetzungen

Das sommerfeucht-tropische Klima mit monsunalen Einflüssen bedingt eine jährliche Niederschlagsmenge von durchschnittlich 1890 mm, wovon ca. 96% in den Sommermonaten zwischen November und April fallen. Der relativ ausgeglichene jährliche Temperaturgang weist Maxima von 30°C im Juli und 35°C im November auf. Die niedrigsten Monatsmittel liegen bei 19°C im Winter und bei 24°C in den Sommermonaten. (DEPARTMENT OF PRIMARY INDUSTRIES, 1995)

In der Umgebung von Weipa dominieren nach dem Bodenklassifikationssystem der FAO-UNESCO (1988) Acrisole und Alisole, die nach ISBELL (1968) auch als "bauxitic/lateritic red earths" bezeichnet werden. Das typische Profil dieser Böden besteht aus einem ca. 10 cm mächtigen, durch organische Substanzen dunkel gefärbten A-Horizont und aus einem durchschnittlich 50 cm mächtigen B-Horizont. Im Gegensatz zum lehmigen A-Horizont ist der B-Horizont kiesiger und enthält mit zunehmender Tiefe einen ansteigenden Anteil an abbauwürdigen Bauxit-Pisolithen. Die durch intensive chemische Verwitterung gekennzeichneten Böden sind arm an austauschbaren Nährionen. Verschlechtert wird die natürliche Bodenfruchtbarkeit zudem durch die hohen Anteile an sorptionsschwachen Zweischicht Tonmineralen und Sesquioxiden. Bei pH-Werten zwischen 5,2 und 6,2 ist die Gefahr der Aluminiumtoxizität für Pflanzen nicht gegeben. Besonders hervorzuheben ist das Problem der Phosphatfixierung infolge des sesquioxidreichen und sauren Bodens.

Wie der größte Teil der westlichen Cape York Halbinsel ist auch die natürliche Vegetation in der Umgebung von Weipa durch relativ einförmige, halboffene und etwa 25 - 30 m hohe Eukalyptuswälder gekennzeichnet. Neben den vorherrschenden Baumarten *Eukalyptus tetrodonta* (Darwin stringy bark) und *E. polycarpa* (long-fruited bloodwood) finden sich noch Arten wie *E. nesophila* (Melville Island bloodwood), *E. dichromophloia* (gum-topped bloodwood) und *Erythrophloem chlorostachys* (Cooktown Ironwood). Weitere wichtige Gehölze sind *Acacia rothii*, *Grevillea parallela*, *Parinari nonda* und *Planchonia careya*. Im Unterwuchs dominieren die beiden tropischen Gräser *Sorghum pulmosum* (native sorghum) und *Heteropogon triticeus* (giant spear grass).

5.2 Die sozioökonomischen Rahmenbedingungen

Über die Hälfte der Bevölkerung der Cape York Bevölkerung sind Aborigines oder Torres Strait Islanders, obwohl diese Gruppen innerhalb von Gesamtqueensland nur knapp 2% der Gesamtbevölkerung stellen. Die indigenen Gruppen sind dabei nicht gleichmäßig verteilt, sondern konzentrieren sich auf einige Aborigines- bzw. Torres Strait Islanders-Siedlungen. Dies zeigt bereits die demographische Sondersituation des Abbaugebietes, die durch weitere demographische Strukturen betont wird (Abb. 4). So leben beispielsweise mehr Männer als Frauen in der Cape York Region - eine unmittelbare Folge der Bergbauwirtschaft, in der weitaus mehr Männer als Frauen Beschäftigung finden.

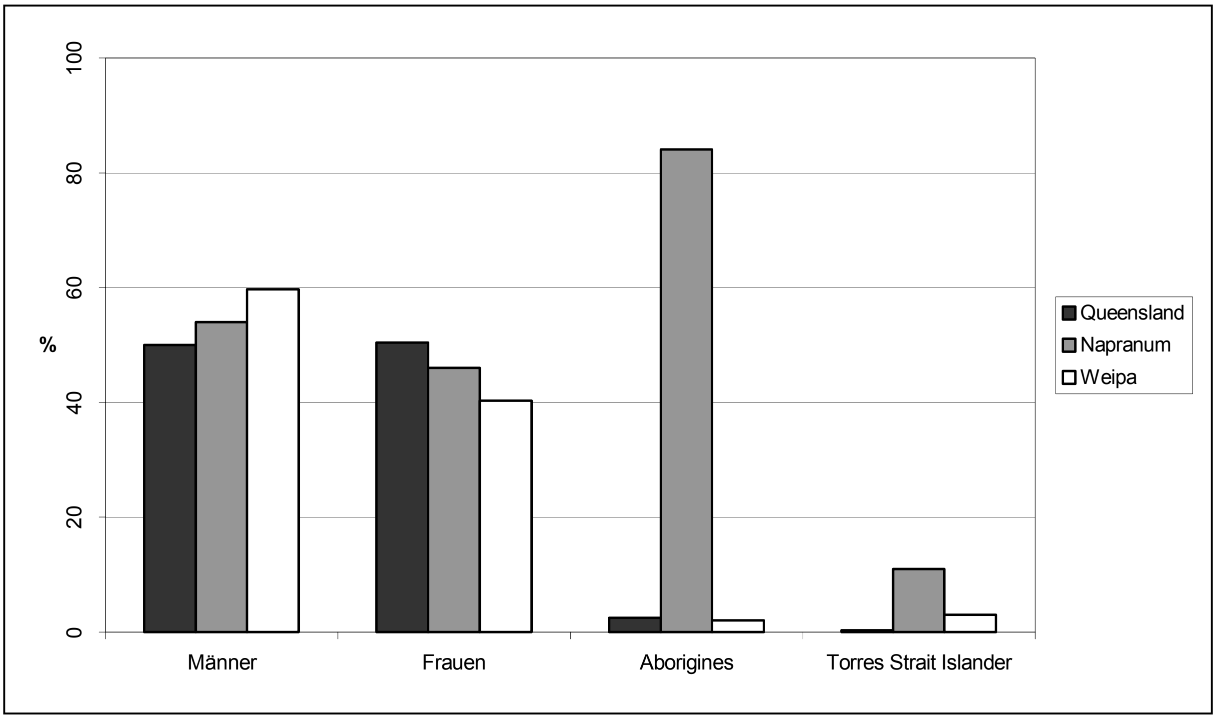

Abbildung 4: Demographische Merkmale von Weipa und Napranum im Vergleich zu Queensland

Die hohe Fluktuation der Bewohner und der geringe Anteil älterer Menschen und Frauen an der Gesamtbevölkerung unterstreichen den *company town* –Charakter Weipas. Zudem besteht eine räumliche Trennung zwischen den von Aborigines und Torres Straits Islander bewohnten Bereichen und den Nicht-Aborigenes europäischen Ursprung, die ausschließlich im Hauptort Weipa-North wohnen. Die Aborigines leben hingegen im rund 12 Kilometer entfernten Ortsteil Napranum (Weipa-South). Bevor Comalco 1957 die Abbaugenehmigung erhielt, nutzten sie das Land zu Sammel- und Jagdzwecken.

Mehr als die Hälfte der Erwerbstätigen ist unmittelbar beim Bergbauunternehmen beschäftigt. Darüber arbeitet ein großer Anteil der Erwerbstätigen im tertiären Sektor, insbesondere in öffentlichen Einrichtungen. Bei den Minenarbeitern handelt sich fast ausschließlich um weiße Australier. Obschon sich viele Aborigenes und Torres Strait Islanders wegen der Mine in Napranum angesiedelt haben, konnte aufgrund mangelnder Qualifikation nur ein kleiner Teil von ihnen dort Arbeit finden.

Der tiefe gesellschaftliche Graben, der nicht nur die *township* Weipa, sondern ganz Australien durchzieht, zeigt sich deutlich in den Einkommensverhältnissen (Abb. 5). Die Aborigines in Napranum verdienen weitaus weniger als die Minenarbeiter in Weipa-North. Rund 15% der Haushalte in Napranum haben ein Einkommen von weniger als 20 000$ im Jahr, in Weipa-North hingegen sind es lediglich 3%. Die durchschnittliche Haushaltsgröße ist dabei mit 6,8 Personen zudem noch größer als in Weipa-North, wo die Haushalte lediglich 3,9 Personen umfassen. (DAMES & MOORE 1997)

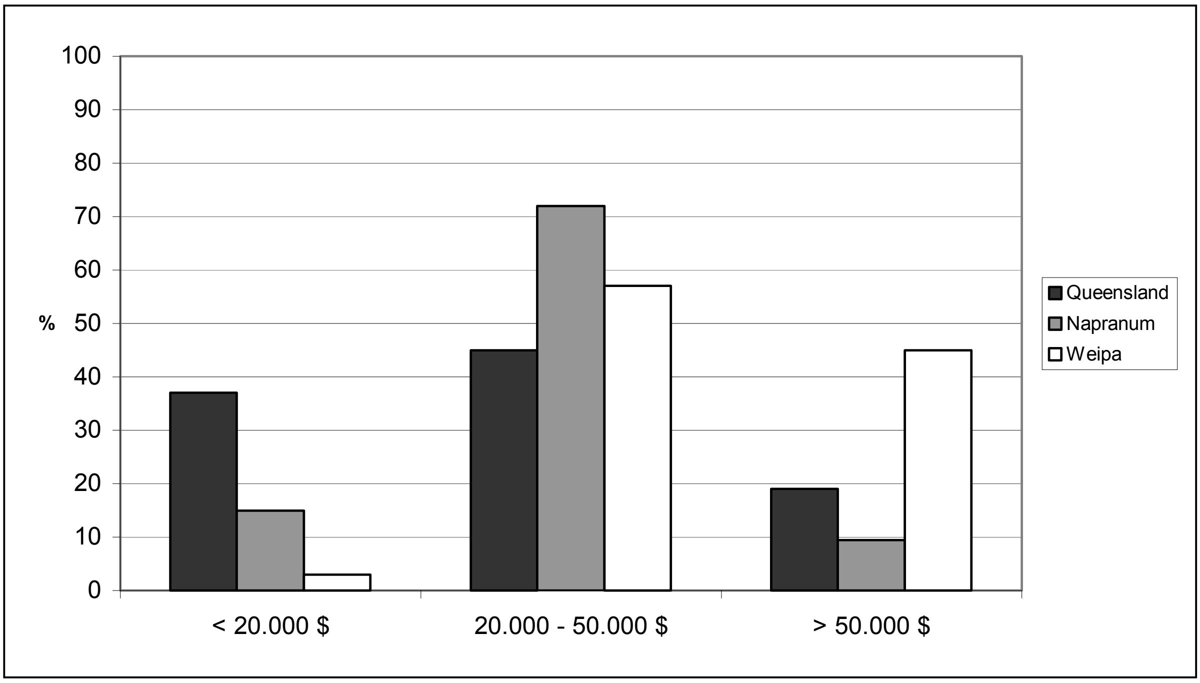

Abbildung 5: Einkommensverhältnisse (pro Kopf-Einkommen in Austr. $)

Dennoch sind Bergbaustandorte für arbeitssuchende Aborigenes attraktiv, denn bezogen auf Queensland sind die Einkommensverhältnisse in Napranum vergleichsweise günstig. Auf Staats-bene beträgt der Anteil der Haushalte mit weniger als 20 000$/a sogar 36,1%. Auch die Arbeitslosenrate ist in Weipa-North bzw. Napranum deutlich niedriger als in Gesamt-queensland. Zurückzuführen ist dies jedoch nicht auf eine örtliche florierende Wirtschafts-struktur. Eine entscheidende Rolle spielen hier die *Community Development Employment Projects*, die von den einheimischen Gruppen verwaltet werden, und die zahlreichen Aborigi-nes und Torres Strait Islander eine Arbeitsgelegenheit geben. Innerhalb des Ortes Napranums stellen die Community Development Employment Projects rund 95% der Arbeits-möglichkeiten für die Aborigenes. Gefördert werden diese Arbeitsbeschaffungsprogramme u.a. vom Bergbauunternehmen. Landwirtschaft wird nur in äußerst geringem Umfang betrie-ben, ein Teil der Aborigenes bestreitet sein Einkommen auf traditionelle Weise mit Fischfang in den küstennahen Gewässern. Die Mehrzahl der Aborigenes sind jedoch abgängig von der staatlichen Fürsorge.

5.3 Versuche zur nutzungsorientierten Wiederherstellung von Abbauflächen

Bereits 1966 begannen die ersten Rekultivierungsarbeiten mit dem erklärten Ziel eine lebensfähige wirtschaftliche Basis für die Grundversorgung der dort ansässigen Bevölkerung nach Beendigung des Bergbaus zu schaffen. Anfängliche Versuche, Weideflächen zur Rindfleischproduktion einzurichten, wurden wegen mangelndem Lebendgewichtszuwachses schnell wieder aufgegeben. Die hauptsächlich aus Eukalyptus- und Akazienarten bestehende natürliche Gehölzvegetation hat aufgrund des hohen Termitenbefalls keinen kommerziellen Wert. Ebenso wurden schon 1976 Aufforstungen mit Nutzholzarten wie *Khaya senegalensis* (African mahogany), *Tectonia grandis* (teak), *Pinus caribbea* (Caribbean pine), *Swietenia macrophylla* (Honduras mahogany) und *Araucaria cunninghamii* (hoop pine) wegen der zu stark schwankenden Holzerträge und der sehr großen Marktferne aufgegeben. Verschiedene Marktfrüchte (cash crops) wie Mangos, Limonen oder Kokosnüsse und andere Früchte wurden im Laufe der Zeit getestet, wobei nur die beiden Baumfrüchte *Anarcardium occidentale* (cashew) und *Azadirachta indica* (neem) erfolgversprechende Ergebnisse lieferten. Die genannten und wenig profitablen Folgenutzungen führten dazu, daß man auf den abgebauten Flächen schon früh zur Renaturierung übergegangen ist, das heißt die Rückführung in einen naturnahen Zustand. Ziel ist es, ein sich selbst aufrechterhaltendes Ökosystem zu schaffen, dessen Struktur und Funktion nicht unbedingt mit der des ursprünglichen Waldes übereinstimmen muß: “The objective is the reestablishment of a stable and self-sustaining ecosystem” (MULLIGAN u. DAHL 1996).

Bis 1996 wurden 6290 ha (ca. 80%) der gesamten Tagebaufläche rekultiviert bzw. renaturiert, wovon 75 % der Fläche mit einheimischen Gehölzen bepflanzt wurden. Auf die restliche Fläche entfallen 14,5 % Weideland, 5,9 % Aufforstungen und 4,6 % sonstige Flächen (Abb. 6) (Comalco, 1997).

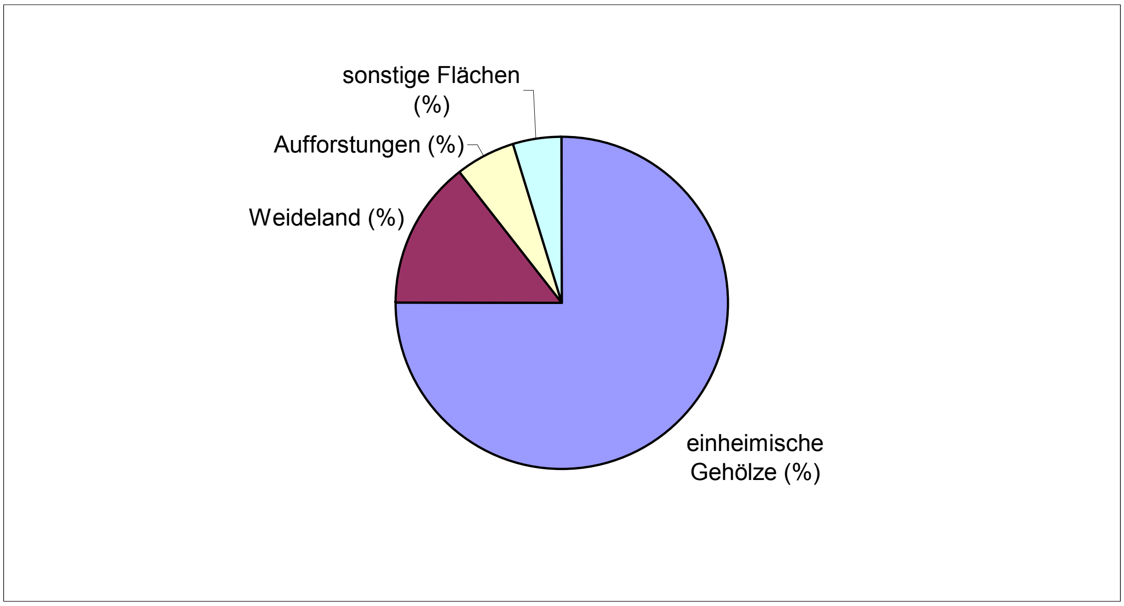

Abbildung 6: Prozentuale Anteile der rekultivierten und renaturierten Flächen im Tagebau Weipa (Stand: 1997)

Die gegenwärtige Zielsetzung erscheint wesentlich bescheidener, trägt jedoch dem faktisch nicht vorhandenen Nutzungsdruck in dieser peripheren Region Rechnung. Bei einer realistischen Potentialeinschätzung dürfen solche ökonomischen Faktoren nicht außer Acht gelassen werden. Zudem haben die bisherigen geoökologischen Untersuchungen gezeigt gemacht, wie schwierig schon die Errichtung eines stabilen und naturnahen Stoffkreislaufes ist, der schließlich die Grundlage für eine später erfolgende Errichtung eines Agrar- oder Forst-Ökosystems bilden könnte.

Die völlige wirtschaftliche Abhängigkeit vom Bergbau und die schwierige ethnisch-demographische Situation Weipas können hier nur angedeutet werden. Sie weisen jedoch auf die entscheidenden Hemmnisse hin, wie problematisch es sein wird, sich selbst tragende Alternativen auf dem Arbeitplatzsektor zur entwickeln und eine nachhaltige, durch geeignete Rekultivierungsmaßnahmen gestützte Folgenutzung einzuleiten. Außer der Marktferne ist ein anderer Faktor von Bedeutung: Eine wichtige Rolle bei der Entwicklung von nutzungsorientierten Zielsetzungen bei der Aufbereitung der Abbauflächen spielt im Fall Weipa vor allem die rechtliche Situation. In zunehmendem Umfang erheben die Aborigines Anspruch auf das Land, das sie vor dem Bergbau ausschließlich für ihre Zwecke nutzen konnten. Eine Entscheidung für eine bestimmte Nutzung bzw. Rekultivierungsstrategie kann infolgedessen nur in Abstimmung mit den Vorstellungen der Aborigenes getroffen werden. Eine Planung, die sich nur nach westlich geprägten Entwicklungsmaßstäben und Lebensstilen richtet, wird auf geringe Akzeptanz stoßen.

5.4 Die Renaturierung in Weipa

Die gesetzliche Grundlage für die anfänglichen Rekultivierungs- und späteren Renaturierungsaktivitäten bildet der "Commonwealth Aluminium Corporation Agreement Act" von 1957, welcher im wesentlichen fordert, daß die renaturierten Flächen keine unnatürlichen Hangneigungen aufweisen dürfen und daß der Eingriff in das natürliche Entwässerungsnetz zu minimieren ist. Daher müssen bereits beim Abtrag des wesentliche Aspekte der Renaturierung beachtet werden. Wie später anhand eigener Erhebungen kurz dargelegt wird, spielt die angewandte Technik der Bodenumbettung eine entscheidende Rolle für den Renaturierungserfolg. Zwischen April und Dezember während der Trockenzeit wird die kulturfähige Schicht mit zwei "scrapern" (Erdhobel), die hintereinander im Tandembetrieb arbeiten, gelöst und zumeist auf angrenzenden, ausgeerzten Flächen wieder aufgetragen (Abb. 6). Durch dieses besondere Verfahren kann der durchschnittlich 60 cm mächtige Mutterboden in zwei gleich mächtigen Schichten abgetragen und in der gleichen Abfolge wieder aufgebracht werden (Abb. 7).

Nicht immer kann der abgetragene Boden sofort wieder auf bereits abgebaute Flächen aufgetragen werden. In diesem Fall muß der Boden auf Halde gelegt werden und kann erst zu einem späteren Zeitpunkt auf eventuell weit entfernt liegende Flächen wieder aufgebracht werden. Da durch die Abbauaktivitäten die Minenoberfläche zum Teil sehr verfestigt ist, wird unmittelbar vor dem Aufbringen des Bodens der Untergrund in 3 m Abständen aufgebrochen, um eine bessere Durchwurzelbarkeit zu ermöglichen.

In den letzten Jahrzehnten ist es durch Forschung und ständige Erfolgskontrolle gelungen, geeignete Saatmischungen zusammenzustellen, die es ermöglichen, trotz der extremen Umweltbedingungen wie Wechsel von Trockenheit und Überflutung, unfruchtbare Böden, Feuer und Termiten eine der ursprünglichen Vegetation ähnliche Vegetationsbedeckung (wieder)herzustellen. In der Regel verwendet man für die meisten Flächen eine bewährte Standardsaatmischung mit den vorherrschenden einheimischen Gattungen.

Abbildung 7: Abtragen des Bodens mit “openbowl-scrapern” im Tandembetrieb.

Abbildung 8: Frisch für den Bauxitabbau vorbereitete Fläche
ist ca. 60 cm Boden abgetragen worden

Trotz der manchmal bis zu 40 in der Standardsaatmischung enthaltenen Arten, wird die Zusammenstellung der Mischung ständig neu überdacht, da sich häufig erst nach längerer Zeit herausstellt, welche Arten sich durchsetzen. Nicht zuletzt hängt die Auswahl der Arten auch davon ab, wie leicht bzw. schwierig das Saatgut zu erhalten ist. Seit 1982 wird der größte Teil des Saatgutes von Einheimischen aus den nahegelegenen Aboriginal Communities gesammelt und anschließend nach Gewicht an Comalco verkauft. Allein die Kosten für das sehr zeitaufwendige Sammeln der Samen können bis zu 15% der gesamten Renaturierungskosten betragen (COMALCO, 1997). Um eine dem natürlichen Eukalyptuswald vergleichbare Bestandesdichte zu gewährleisten, werden die Samen in vitro auf ihre Keimungsfähigkeit hin geprüft. Die Resultate dieser zum Teil recht aufwendigen Tests bestimmen wieviel an Samen von jeder Art in die Saatmischung kommen,. Nach Einsetzen der ersten heftigen Regenfälle beginnt die Saat- und Pflügesaison. Das Pflügen verringert die Konkurrenz der durch den Regen in den Boden gebrachten Grassamen und verbessert gleichzeitig die physikalischen Eigenschaften des Keimungssubstrates. Direkt im Anschluß wird ausgesät, wobei der Saatmischung in der Regel 100 kg Superphosphat pro Hektar beigemengt sind. Um eine geschlossene Vegetationsdecke auf den renaturierten Flächen sicher zustellen, werden im Februar Setzlinge mit der Hand ausgepflanzt. (COMALCO, 1997).

5.5 Für das Renaturierungspotential relevante geoökologische Kennwerte

Die vorhergehenden Ausführungen verdeutlichen die Komplexität der geotechnischen Maßnahmen und biologischen Vorarbeiten, die mit der Renaturierung der ausgeerzten Flächen einhergehen. Im Rahmen der Geländeuntersuchungen wurden bodenkundliche und pflanzenökologische Analysen zur Beurteilung der Regenerationsfähigkeit des Ökosystems anhand zahlreicher Parameter durchgeführt. Am Beispiel der beiden ausgewählten Kenngrößen organische Substanz und Gesamtstickstoffgehalt im Boden soll an dieser Stelle kurz auf die Bedeutung der Bodenumbettungstechnik für den Renaturierungserfolg eingegangen werden (Abb. 8 und Abb. 9). Die beiden o.g. Parameter eignen sich wegen ihres integralen Charakters mit hohem ökologischen Aussagewert besonders zur Kennzeichnung des ökologischen Renaturierungs-potentials.

Der Gehalt an organischer Substanz im Boden (0,5-0,58 g org. C = 1 g organische Substanz) ist einer der Schlüsselfaktoren für die Schaffung eines funktionierenden Ökosystems, denn er beeinflußt nicht nur bodenphysikalische und bodenchemische Prozesse, sondern ist auch für die mikrobielle Aktivität im Boden und den Versorgungszustand mit Nährelementen von entscheidender Bedeutung. Der prozentuale Anteil von Gesamt-Stickstoff im Boden ist ein Maß dafür, wieviel Sticktsoff unter bestimmten Bedingungen zu pflanzenverfügbaren Stickstoff-formen (Nitrat, Ammonium) mineralisiert werden kann.

Im Zuge von Geländearbeiten, die in Weipa von Oktober 1997 bis Januar 1998 stattfanden, wurden Bodenproben gesammelt und im bodenchemischen Labor der University of Queensland vorrangig auf ihren Kohlenstoff- und Stickstoffgehalt hin untersucht. Um den Einfluß der verschiedenen Bodenumbettungsverfahren zu ermitteln, wurde ein Teil der Proben auf einer Versuchsfläche (Soil Replacement Trial) der University of Queensland genommen. Diese etwa 6,4 ha große Fläche wurde 1990 angelegt, 1991 bepflanzt und teilweise gepflügt. Auf der Versuchsfläche wurden verschiedene Renaturierungstechniken getestet:

Bei den im folgenden verwandten Abkürzungen handelt es sich um feststehende Begriffe, die nicht ohne weiteres ins Deutsche übersetzt werden können.

- Mit stripping time (A, B, C) ist der Zeitpunkt der Bodenumbettung gemeint: A = May , B = September, C = December
- Double Pass (DP) bedeutet, daß der Boden exakt getrennt nach A- und B-Horizont ab- und wieder aufgetragen wird.
- Bei der Dual strip Technik (DS) wird der Boden in zwei gleichmächtigen Schichten von ca. 30 cm umgebettet.
- Subsoil only (SU) bedeutet, daß kein Oberboden auf getragen wird.
- Mit stockpiled (ST) ist das Auftragen von zuvor auf Halde gelagertem Boden gemeint.

Die als ”Dual Strip” bezeichnete Technik wird am häufigsten angewendet und erlaubt es die obere Bodenschicht, die eine erheblich höhere mikrobielle Aktivität aufweist und reicher an Nährelementen sowie organischer Substanz ist, wieder oberflächlich aufzubringen. Berücksichtigt man allerdings die natürliche Horizontmächtigkeit (im Mittel 10 cm A-Horizont und 50 cm B-Horizont so wird deutlich, daß bei dieser Technik der A-Horizont mit ca. 20 cm B-Horizont “verdünnt” wird. Das nahezu streng horizontbezogene Bodenumbettungsverfahren ”Double Pass” hat sich als sehr zeit- und kostenintensiv erwiesen.

Der Gehalt an organischer Bodensubstanz und der Stickstoffgehalt in den drei angegebenen Bodentiefen stehen in enger Abhängigkeit zu den angewandten Bodenumbettungsverfahren. Die Abbildungen und zeigen die ausgewerteten Analyseergebnisse, die auf der Versuchsfläche und auf einer benachbarten natürlichen Waldfläche (native) ermittelt wurden. Bei einem Vergleich zwischen natürlicher Waldfläche und den renaturierten Flächen, ergeben sich sowohl beim organischen Kohlenstoff als auch beim Gesamt-Stickstoff signifikante Unterschiede ($p<0,05$) zu den Umbettungsverfahren DS, SU und ST. Nur mit der “Double Pass”-Technik werden ähnliche Werte wie sie im natürlichen Ökosystem auftreten erreicht. (HAHN et. al. 1999)

Ausgehend von einem an der University of Queensland empirisch gewonnenen Schwellenwert für eine erfolgreiche Renaturierung von mindestens 1,5% organischem Kohlenstoff in den obersten 0-5 cm Bodenschicht ist deutlich zu erkennen, daß mit der ”Double Pass”-Technik zu allen Zeiten die für das Pflanzenwachstum günstigsten Gehalte an organischer Substanz erzielt werden. Auch beim Gesamtstickstoff sind die höchsten prozentualen Anteile bei der ”Double Pass”-Technik zu beobachten. Auffällig sind die durchweg niedrigen Werte beim “Subsoil only”. Offensichtlich ist eine horizontbezogene Umbettung des Oberbodens eine grundlegende Voraussetzung für eine ausreichende Versorgung des Bodens mit organischer Substanz und mit Stickstoff. Ein Einfluß des Zeitpunktes des Bodenabtrags läßt sich aus den bisher gewonnenen Daten nicht ohne weiteres ableiten, wenngleich erwähnt werden sollte, daß sich der Zeitpunkt der Bodenabtragung beispielsweise auf den Gehalt an unerwünschten Grassamen auswirkt (FOSTER u. DAHL, 1990). Die relativ niedrigen Stickstoff-Werte im September sind dadurch zu erklären, daß in der Trockenzeit das Gefüge des umgelagerten Bodens stark gestört wird, so daß hier bei allen Techniken die ungünstigsten Werte für das Pflanzenwachstum auftreten.

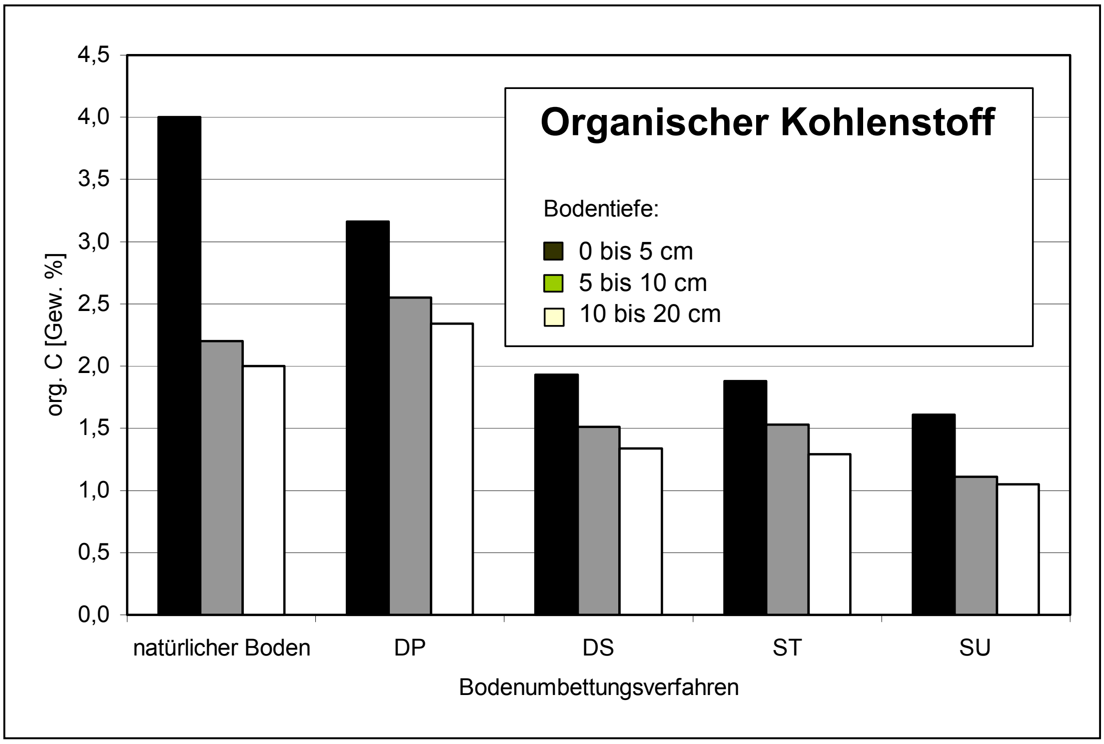

Abbildung 9: Organischer Kohlenstoff in Abhängigkeit von Bodenumbettungstechnik und Bodentiefe

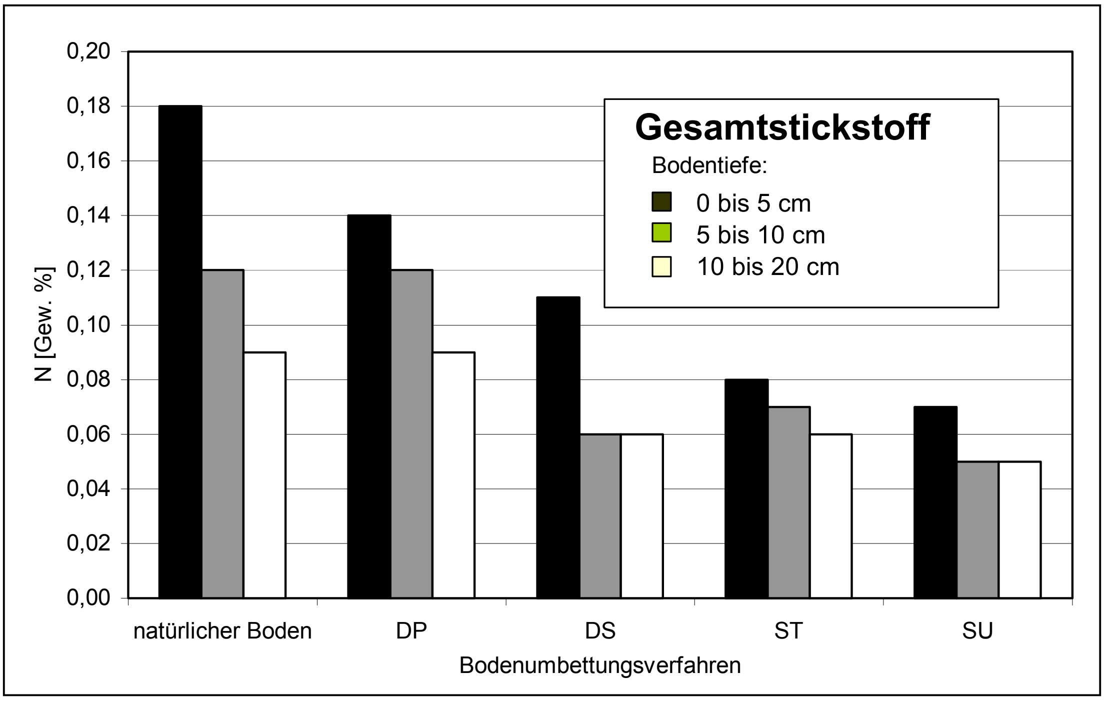

Abbildung 10: Gesamtstickstoff in Abhängigkeit von Bodenumbettungstechnik und Bodentiefe

6. Methodische Ansätze zur Potentialabschätzung und Strategieentwicklung

Die vielfältigengen Probleme sowohl auf ökologischer als auch auf ökonomischer Seite in allen Abbauregionen erfordern einen inhaltlich und methodisch breit gefächerten und standortübergreifenden Untersuchungsansatz zur Entwicklung geeigneter Rekultivierungs- und Renaturierungsstrategien (Abb. 11). Dazu ist in einem ersten Schritt eine detaillierte Bestandsaufnahme aller Parameter durchzuführen, die das Rehabilitationspotential bedingen (können). Einflußfaktoren, die in direktem Zusammenhang mit den bergbaulichen Aktivitäten stehen, sind z.B. die Beseitigung der bestehenden Vegetation, der Abtrag des Oberbodens oder der eigentliche Bauxitabbau. Ferner werden die ökologischen Faktoren wie Klima, natürliche Vegetation oder unbeeinflußte Böden sowie die sozioökonomischen Gegebenheiten wie bestehende Infrastruktur, demographische Merkmale oder gesetzliche Vorgaben erfaßt. Daran anschließend wird anhand der gewonnenen Basisdaten unter Berücksichtigung von eventuellen Nutzungskonflikten und Standortalternativen eine Abschätzung der Möglichkeiten für eine bestimmte Nutzung (z.B. Aufforstung, Weideland oder Siedlungs- und Erholungsflächen) vorgenommen, um eine optimale Landnutzung zu ermitteln Das Ziel dieser allgemeinen methodischen Vorgehensweise ist, die am besten angepaßte Folgenutzung (einschließlich der Möglichkeit einer Renaturierung) aufzuzeigen.

Für die praxisnahe Planung ist dieses Schema zu konkretisieren (Abb. 12). Die Grundlage der Folgenutzungsplanung bildet die Aufnahme der örtlichen ökologischen und ökonomischen Gegebenheiten, wobei der Detaillierungsgrad abhängig von der jeweiligen Fragestellung ist. So erfordert beispielsweise die geplante Einrichtung von intensiv nutzbarem Ackerland - eventuell nur für bestimmte Feldfrüchte - wesentlich weiterreichende bodenkundliche und biologische Voruntersuchungen als dies bei der Schaffung von nur extensiv nutzbarem Weideland erforderlich ist.

Die Frage, in wie weit eine Fläche, die durch den Bauxitbergbau in Anspruch genommen worden ist, überhaupt für eine Nutzung geeignet ist, wird vorrangig durch die ökologischen Rahmenbedingungen bestimmt. Ausschlaggebend sind dabei technische und finanzielle Aspekte. Aber auch gravierende sozioökonomische Hemmnisse können eine agrarische oder forstwirtschaftliche Folgenutzung schon zu Beginn einer Planung ausschließen. Ein Beispiel für diesen Fall ist der Bauxittagebau in Los Pijiguaos (Venezuela), wo sich in der unbewohnten Region die Frage nach einer kommerziellen Nutzung momentan nicht stellt.

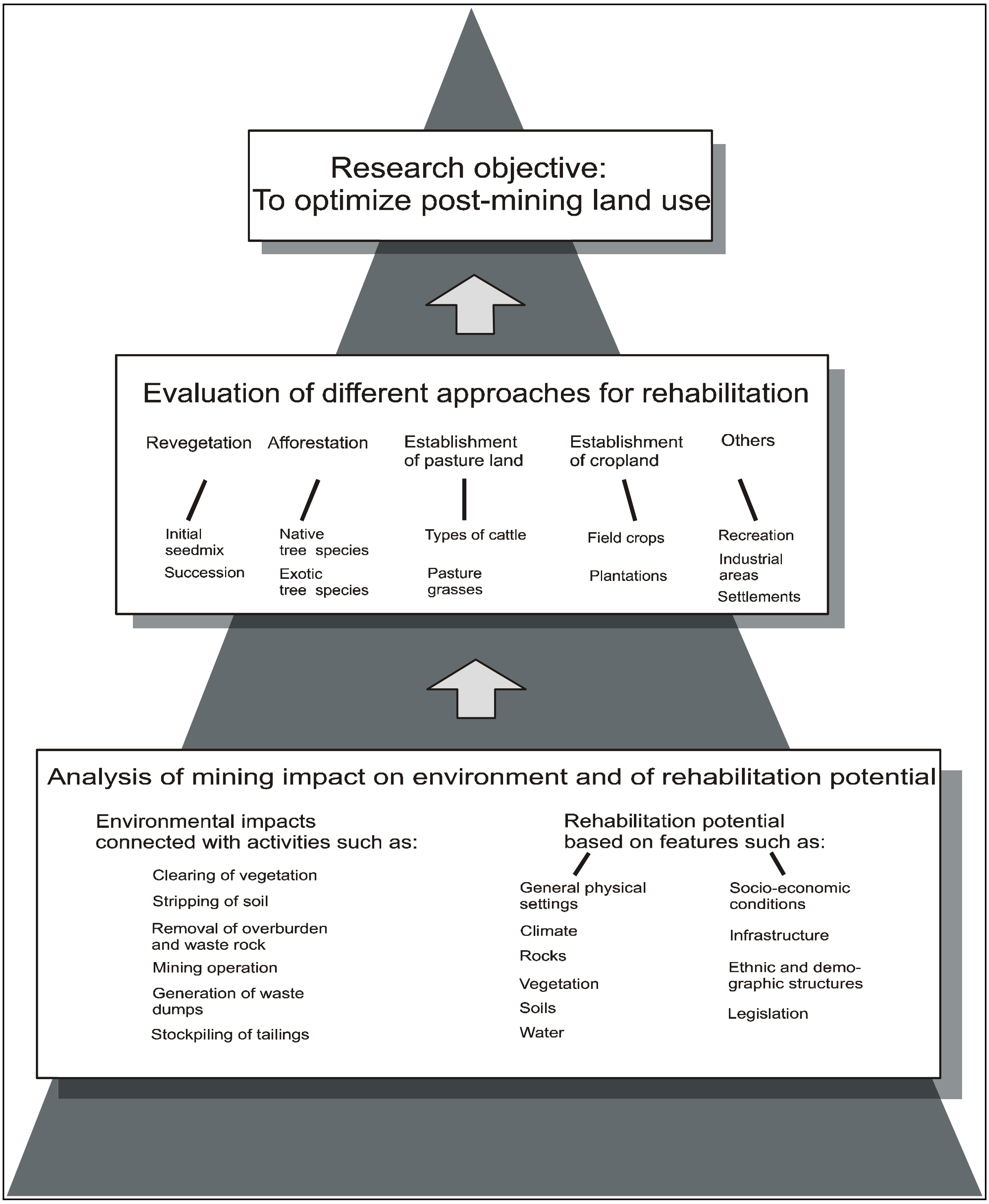

Abbildung 11: Allgemeines Schema zur methodischen Vorgehensweise bei der Analyse des landschaftlichen Rehabilitationspotentials (eigener Entwurf)

Läßt sich keine geeignete Folgenutzung ermitteln, ist es aus Gründen der Umwelt- und Ressourcenschonung sinnvoll, die Rückführung des Ökosystems in den Zustand anzustreben, wie er vor dem bergbaulichen Eingriff bestand. Das heißt geotechnische und biologische Maßnahmen haben die *Renaturierung* zum Ziel. In den meisten Fällen jedoch ist die ausgeerzte Fläche z.B. agrar- oder forstwirtschaftlich nutzbar. Hier muß zunächst geklärt werden ob nur eine oder mehrere Nutzungen möglich sind und ob überhaupt ein Bedarf besteht. Insbesondere in Gebieten mit starkem Bevölkerungsdruck und Flächenknappheit wie beispielsweise Indonesien und Jamaika kommt diesem Problem zentrale Bedeutung zu. Untersuchungen in Weipa haben gezeigt, daß eine forstwirtschaftliche Nutzung der Flächen u.a. mit Edelhölzern (z.B. Teakholzanpflanzungen) zwar möglich, jedoch wirtschaftlich nicht erfolgreich umsetzbar ist. Hier besteht die sinnvolle Alternative in einer Renaturierung. Der Weg der Renaturierung, der hier eingeschlagen wurde, zieht dabei keinesfalls einen geringeren Planungs- und Arbeitsaufwand nach als dies bei einer Rekultivierung der Fall wäre.

Ein anderes Bild zeigen hingegen die Bauxitgewinnungsstandorte in Jamaika. Im Unterschied zu Weipa ist in Jamaika die agrarisch nutzbare Landfläche eine äußerst knappe Ressource. Daher stehen hier bei der Bewertung des Rekultivierungspotentials und der Entwicklung nachhaltiger Rekultivierungsstrategien sozioökonomische Faktoren viel stärker im Vordergrund als ökologische. Entscheidendes Kriterium für eine erfolgreiche Rekultivierung in Jamaika ist eine den kleinbäuerlichen Traditionen entsprechende und (markt-)wirtschaftlich orientierte Form der Folgenutzung. Unabhängig davon, ob eine weidewirtschaftliche oder ackerbauliche Folgenutzung angestrebt wird, ist in Jamaika das primäre Rekultivierungsziel der Schutz des Bodens vor Erosion. (Kölfen 1999)

In stark reliefiertem Gelände kommt dem Erosionsschutz grundsätzlich eine übergeordnete Bedeutung zu, da eine stabile Landoberfläche die Voraussetzung für alle Formen der Folgenutzung und der Renaturierung bildet. Um z.B. die stark erosionsgefährdeten Hänge in der Bauxitmine in Los Pijiguaos (s. Tab.1) zu schützen, werden unmittelbar nach Auftrag des Oberbodens auf die ausgeerzten Flächen schnellwüchsige Grasarten (*Brachiaria decumbens* und *Brachiaria humidicola*) ausgesät. In extrem flachen Lagerstätten (Weipa) hingegen bereitet beispielsweise die Wiederherstellung eines stabilen Nährstoffkreislaufs oder die Schaffung ausreichender Bestandesdichten einheimischer Gehölze auf den renaturierten Flächen größere Probleme.

Nachdem der Bedarf geklärt ist, muß die Form und Intensität der Folgenutzung über geeignete Instrumentarien, wie Standortvergleiche, Nutzwert- oder Risikoanalysen festgelegt werden.

Am Ende der Planungsorganisation steht entweder eine *Renaturierung* oder *Rekultivierung* der zuvor bergbaulich genutzten Fläche. Das erläuterte Schema ermöglicht es, überregional anwendbare Strategien zur Landschaftsrehabilitation zu entwickeln, die sowohl naturräumliche Voraussetzungen als auch gesellschaftliche Erfordernisse berücksichtigen.

Ausgehend von einer Analyse der agrarökologischen und sozioökonomischen Rahmenbedingungen gilt es weiter aufzuzeigen, welche Möglichkeiten bestehen, in Anspruch genommene Flächen nach bzw. bereits während der bergbaulichen Tätigkeit in eine landschaftsgerechte Regionalentwicklung einzubinden.

7. Fazit

Jeder Bauxitbergbaustandort besitzt naturräumliche, sozioökonomische und bergbautechnische Besonderheiten, denen bei der Analyse des Rehabilitationspotentials und der Entwicklung angepaßter Rehabilitationstrategien vor Ort Rechnung getragen werden muß. Die hier vorgestellten integrativ-holistischen Ansätze zur Strategieentwicklung (Abb.11 und Abb. 12) implizieren eine umfassende Analyse und Beurteilung von Gewinnungsstandorten, indem eine den örtlichen Verhältnissen angepaßte Gewichtung der einzelnen Untersuchungsschritte, z.B. hinsichtlich der Erosionsgefährdung, erfolgt.

In den überwiegenden Fällen stellt der Bauxit-Bergbau den mit Abstand wichtigsten Wirtschaftsfaktor der betroffenen Region dar. Alle wirtschaftlich relevanten Tätigkeiten haben sich auf den Bergbau eingespielt. Das Hauptproblem - nicht nur im Fall von Weipa, sondern generell in peripheren Bergbauregionen - liegt nun darin, einen sich selbst tragenden Entwicklungsstand zu erreichen, der auch nach Beendigung des Abbaus eine ökonomische und ökologisch nachhaltige Grundlage besitzt. Dadurch wird das Spektrum potentieller Rehabilitationsstrategien eingeschränkt, selbst wenn es aus ökologischer Sicht mehrere Alternativen geben mag.

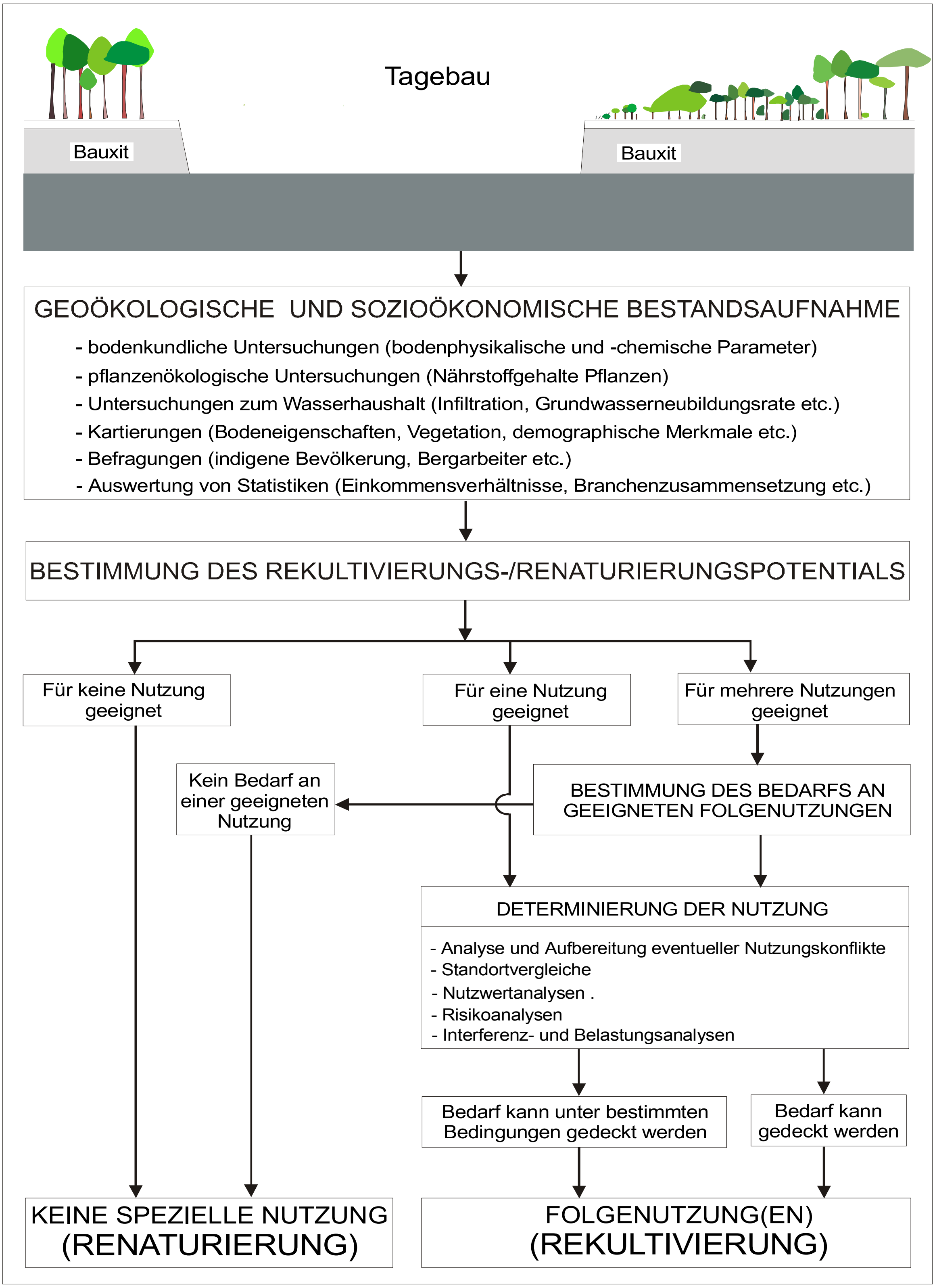

Abbildung 12: Beispiel für eine Planungsorganisation von Nutzungen in (Bauxit-) Bergbaufolgelandschaften

(in Anlehnung an Leser 1991, stark verändert).

Zusammenfassend lassen sich zur Beurteilung von Potentialen und Strategien für eine nachhaltig orientierte Landschaftsrehabilitation zwei Forderungen erheben:

1. Bei der Beurteilung des Rehabilitationspotentials und der Entwicklung nachhaltiger Rehabilitationsstrategien müssen sowohl die standortspezifischen ökologischen als auch die örtlichen sozioökonomischen Merkmale erfaßt und in die Analyse integriert werden.
2. Entscheidend bei der methodischen Vorgehensweise ist die Identifizierung der Faktoren (ökologische oder sozioökonomische), die bei der Analyse von vorrangiger Bedeutung sind. Das heißt jede Fallanalyse erfordert andere Gewichtungen der Merkmal- oder Faktorenkombinationen der einzelnen Parameter.

Dies trifft nicht nur auf die Wiederherstellung von Bauxitabbauflächen zu. Auch bei der Beurteilung anderer Gewinnungsstandorte von Bodenschätzen, die hauptsächlich im Tagebau gewonnen werden, könnten die entwickelten methodischen Ansätze eine geeignete Grundlage zur Analyse von Rekultivierungs- und Renaturierungspotentialen bilden und gleichzeitig Hilfestellung zur Entwicklung von Strategien für eine nachhaltige Folgenutzung bereitstellen.

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TOWARDS GENERIC CHARACTERISATION FACTORS FOR LAND USE AND WATER CONSUMPTION*

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ABSTRACT
Many potential environmental impacts considered in LCA and raw material flow studies vary considerably depending on the affected environment on both local and regional scales. Particularly metals being generally associated with large concentration processes at single sites, are covered insufficiently in generic inventories impact assessments. Thus an environmental information system (EIS) has been developed based on a geographic information system to analyse and quantify distinct environmental properties in the vicinity of any producing site considered.

The EIS was developed in the framework of a collaborative research programme aiming at the resource orientated analysis of metallic raw material flows. Firstly aluminium was taken as case study. The spatial database covers all present production sites of bauxite extraction, alumina refining and aluminium smelting. Environmental data for each location were derived from global digital survey data covering land cover, soils, morphology, climate, topography and population density.

The main application of this database is the characterisation of environmental safeguard objects which may be affected by the activity of concern. In combination with the technical inventory, it is possible to estimate site-specific in- and outputs such as land use, water consumption or emissions. Land use is weighted by the amount of dry substance not accumulated due to the activity. Water consumption is weighted with a site specific scarcity factor whereas emissions of acidifying substances are weighted by critical loads exceedance ratios.

The weighted impact scores can be interpreted on any desired aggregation level ranging from sites to technologies to countries or even global average values. Specific short term challenges can be inferred from scenarios. These weighting factors were developed for specific patterns of the primary aluminium production. Present research efforts focus on copper specific aspects.

KEYWORDS
LCIA, land use, water consumption, bauxite mining, alumina refining

* Source: Proceedings of Life Cycle Assessment of Metals - Issues and Research Directions, SETAC USA, Pensacola

1 Introduction

Many potential environmental impacts considered in LCIA (*Life Cycle Impact Assessment*) vary considerably depending on the affected environment on both local and regional scales. Particularly metals, generally associated with large concentration processes at single sites, are covered insufficiently in generic inventories and impact assessments.

In order to provide generic characterisation factors which encompass the individual situation at each location an environmental information system SARIS (Site-Specific Natural Resource Information System) has been developed based on a Geographical Information System (GIS). This system was developed in the framework of a collaborative research programme aiming at the resource orientated analysis of metallic raw material flows. Case studies are based on aluminium and copper.

2 Methodology

Each metal has a particular spatial distribution pattern due to the different resources required in the production process. Especially the primary production of a metal (mining, refining, smelting) is characterised by a specific pattern due to the ore resource distribution. This distribution pattern pre-defines environmental mechanisms. LCA as a tool is not designed for any spatial differentiation but several approaches where developed to overcome this elementary disadvantage. According to the necessary additional data collection in the inventory the approaches can be divided into two categories.

One approach is based on a further differentiation of impact categories according to different environmental issues or endpoints. Examples of additional categories for land use are discussed in [1]. Different aspects of water use and consumption are discussed given in [2].

The other approach replaces current characterisation factors by spatially weighted factors which comprise the sensitivity of different environments. This has been revealed for the emission of acidifying substances [3] or in a broader approach [4].

The first approach is appropriate, if the inventory modelling allows a more detailed data collection, which may be difficult with regard to global assessments. The second approach is suitable, if the spatial extent of the system is well defined and appropriate regional weighting factors exist.

In order to develop site specific generic characterisation factors for the production of metals a GIS is used to structure the information for a spatially differentiated environmental impact assessment in a spatio-temporal database. At present, the major categories of the database are land cover, soils, climate, water, morphology and population density. For each data source separate routines and models were developed to derive characteristic parameters for any location with importance for the primary production. The sites themselves are integrated by their co-ordinates, their capacity and important technological specifications.

Due to the obtainable precision of location data and the small scale of the environmental data between 1:1.000.000 and 1° x 1° longitude/latitude no direct environmental interventions can be modelled. Taking the land cover characteristics data as an example it is impossible, to determine, which ecosystem in particular is affected by a single activity. Therefore parameters are estimated as average values for an unit circle with a radius of 50 km. This radius is an operational choice to encounter major properties in the site vicinity. The derived parameters can be further classified, combined and aggregated. Spatial data, site information and classification tables are the core elements of SARIS. Potential screening applications are discussed in the following for the two impact categories “land use” and “water consumption”.

3 Land Use

Land use is a major issue regarding to the production of metals. Mining and, in many cases, solid waste disposal cause a short or long term occupation of land. As an important impact category in LCIA, land use is linked to several impacts on life support functions being generally supplied by land. Following [1], the temporal occupation is quantified in annual square meters per ton of ore [am²/t]. By introducing the duration, small, but long lasting occupations do have a similar dimension like large, but short term occupations. Rehabilitation measurements are taken indirectly into account.

To estimate the size of a mining enterprise, mining areas are calculated based on ore body geometry and thickness of overburden. Land use for infrastructure is estimated by a correlation function which was developed based on data gathered during several field studies. The duration of mining is estimated based on own research within the collaborative research programme and literature [5].

As far as no direct environmental damage mechanism is defined for land use, each is counted the same way in the inventory. To reflect different environmental properties at the different locations two operational parameters are chosen based on the land cover data in SARIS: the naturalness and the net primary production of natural ecosystems (NPP).

The “naturalness” is determined as the ratio of natural ecosystems and the available area in the defined unit circle. Thus it characterises the degree of man-made alterations of land cover characteristics at a single location. This ratio ranges from 0 – 1 with 1 indicating an undisturbed ecosystem. The naturalness itself is linked neither to a particular safeguard object nor an environmental damage mechanism. Therefore, it is related to the second operational parameter “net primary production” (NPP) in order to distinguish different natural ecosystems by an important service function. Its unit is kg of dry weight (DW) per m² per year. Figure 1 reveals a map of currently known bauxite mines worldwide, their annual bauxite production and different levels of NPP worldwide, taken from [6].

By using SARIS the factors to represent a site can be condensed within a single diagram which allows a preliminary assessment of the source strength on the one hand side and of the environmental conditions on the other hand. Figure 2 contains all bauxite mining sites, their cumulative contribution to the total land use in percentage and their “naturalness”. Three sites (Gongxian (China), Ichiniso (Ghana) and Weipa (Australia)) are identified as examples. One can infer that approximately 30% of the annual land use takes place in areas, where the “naturalness” is rather low. 50% of land use takes place in regions which are altered up to only 20%. In figure 3 the estimates of the NPP for the natural ecosystems in the site vicinity are given. According to [7] NPP rates greater than 1 [kg/m² .y] are reached only in forest ecosystems. The highest NPP rates are reached in tropical rain forest with 2.2 [kg/m² .y]. For bauxite mining 50% of land use occurs at sites, where high NPP-rates characterise the natural ecosystems. To reflect the different degrees of man made alterations this NPP is weighted by the “naturalness”. The result is given in figure 4. High NPP rates are indicated for about 20% of the annual land use. For more than 40% of the annual land use NPP rates are low. Taking Weipa in Australia as an example, the high “naturalness” and medium NPP result in a relatively high value whereas Ichiniso in Ghana with high NPP rates but a low degree of “naturalness” is characterised by a rather low overall NPP-rate.

Based on these data, sites can be distinguished according to the size of the intervention and the properties of the environment. This distinction can be a first step to identify relevant impact mechanisms which should be considered in the impact assessment. The given example suggests, that high productive ecosystems are affected at few bauxite mines with a share of 20% of the land use worldwide.

4 Water consumption

Water consumption is addressed by a LCIA-category named “extraction of abiotic resources from the natural environment”. Freshwater (except fossil ground water) is a renewable resource being limited in quality and availability on both local and regional scales and varying considerably from site to site. Compared to other abiotic resources freshwater can be a flow or fund resource. The exceptional case of using fossil groundwater is considered as depletion of a stock. Depleting a flow resource results in the reduction of the regeneration rate. Depleting a fund means to overexploit regeneration rates [1]. Owens [2] suggests five different "use categories" distinguishing in-situ use (e.g. transportation) and ex-situ use (e.g. consumption) of waters and different consumption patterns reflecting whether the water is returned to the local ecosystem or not. Effects on quality, which are caused by airborne pollutants or waste water are modelled in other, more appropriate categories within the LCIA framework.

Considerable water consumption during primary aluminium production is related to the refining process. Cooling waters and the final moisture content of the residues (red mud) are consumption in the stricter definition framework. The average consumption in the refining process can be estimated with 1 m^3/t alumina. The final moisture content of red mud depends on the processed bauxite as well as the disposal technology. It varies between 30% to 50% and 0,2 to 0,8 m^3/t alumina [8]. It is not possible to determine the freshwater source within the technical inventory and the location information base. In some cases sea water and waste water from other industries are used, which is not considered in this methodology.

For a global assessment on a site level the water availability is characterised by the environmental data of SARIS. A commonly used parameter to quantify the water availability in a given catchments is the difference between the monthly precipitation and evapotranspiration. This difference is an estimate for the surface and subsurface runoff of freshwater. This amount can be used to quantify the annual renewable freshwater resources at a given location. The map in figure 5 reveals all alumina refineries scaled by their capacity and runoff-values derived from SARIS. For each site the specific situation has been characterised. Figure 6 shows all alumina refineries and their contribution to the installed capacity worldwide. The capacity is used as an indication for the amount of water consumption. Runoff values can be grouped in arid (< 60 mm/a), humid (60 – 600 mm/a) and tropical (> 600 mm) regions. Nearly 80% of the alumina capacities are located in humid areas.

Especially freshwater is a resource with competitive uses. Commonly, regions are characterised by the water availability per capita and year to determine whether water is scarce or abundant. This availability is defined as the ratio of the population density and the renewable freshwater. In figure 7 the same sites are plotted versus the water availability per capita. In scientific literature availabilities below 1000 [$m^3/c \times a$] are classified as high water stress in a particular region [9].

The difference between the data points of each diagram indicates, that even if water is seriously short at a couple of sites, the scarcity is restricted to six operations only.

5 Discussion

Within the interpretation of such site-specific parameters several restrictions have to be considered. At first, precision and accuracy of the background data is oftentimes low. Therefore aggregates should be considered as potentials as in the LCIA-categories. Only differences in magnitudes should be considered and discussed rather qualitatively than quantitatively.

The impact categories considered are usually modelled as input categories without being linked to specific endpoints. By opposing interventions with single property parameters other aspects are disregarded. Land use is interlinked with a variety of environmental impacts also during mining operations which can not be adequately covered by small set of parameters. The net primary production of natural ecosystems as indicator is especially meaningful for bauxite mining which is mainly bound to tropical and sub-tropical regions. The deposit distribution pattern of other ores may require the definition of alternative indicators. Water consumption as a competitive use is in many cases treated within the econosphere and not the ecosphere which has to be recognised in the interpretation.

The strength and advantage of this approach is the repeatable and comparable characterisation of all sites within a given system. The system and its functionalities support the distinction of major and minor issues on a first screening level. Representative sites can be identified and studied in more detail. In practice the outlined procedure does not require an intensive inventory analysis, it rather may be used to define the level of detail for the different elementary flows.

6 Conclusion

The distribution pattern of large industrial sites pre-determines local and regional environmental impacts. By using spatial environmental data and location coordinates it is possible to characterise this pattern and to predict probable environmental mechanisms. By this generic approach no additional inventory data has to be collected within this first screening level.
By this procedure it is possible to discuss not only fallback strategies like general reduction plans but also to identify urgent needs for further action considering the conditions on site.
Within the ongoing development process of a worldwide applicable LCIA this approach provides background information about problems which can be associated with the use of a particular raw material world-wide. Representative examples for a more detailed analysis can be chosen based on the comparative assessment.

7 Literature

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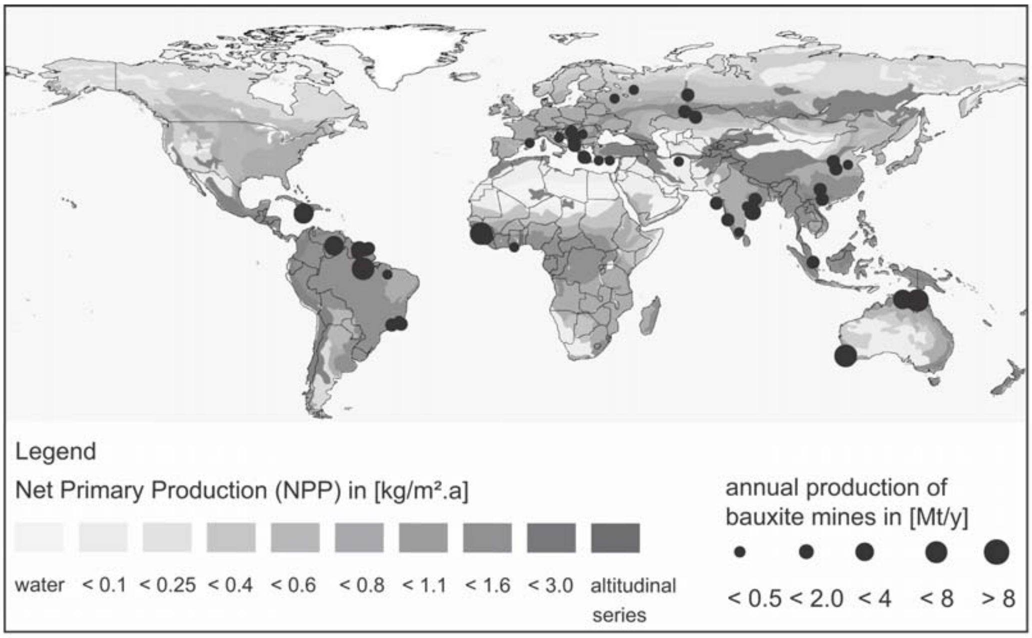

Fig. 1: Worldwide bauxite mining and net primary production

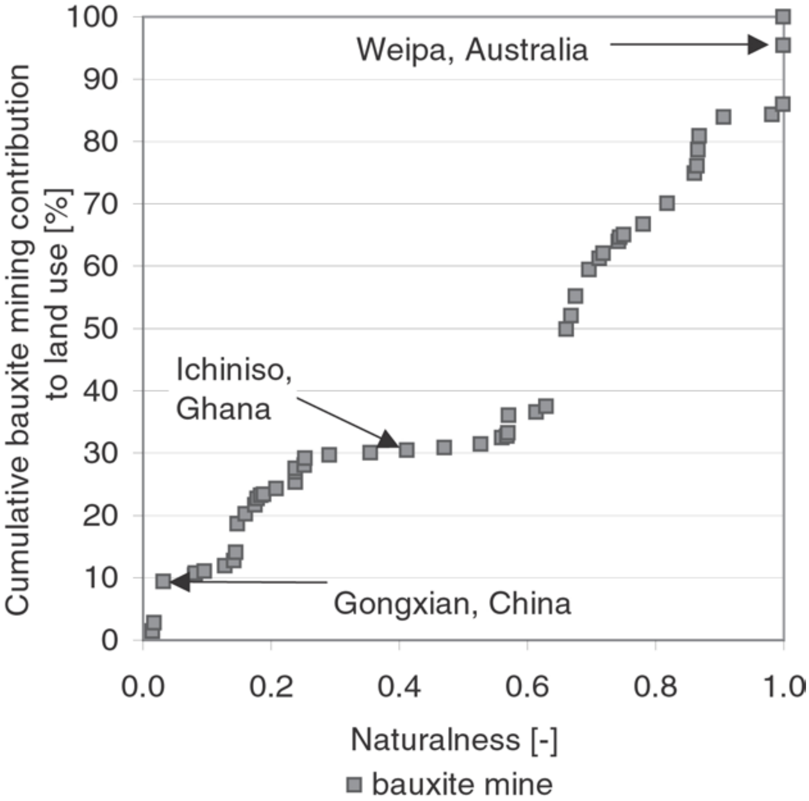

Fig. 2: Bauxite mining, land use and naturalness

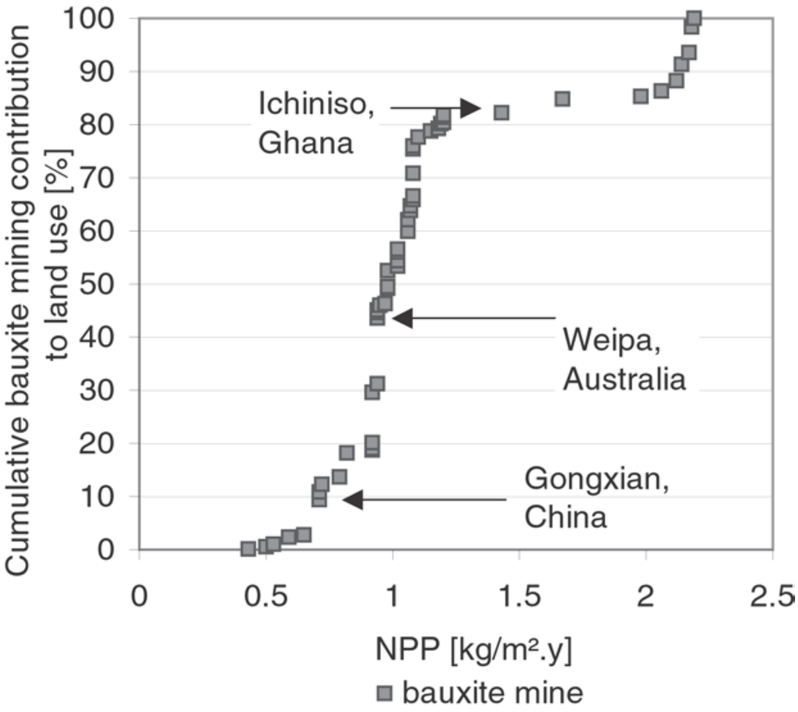

Fig. 3: Bauxite mining, land use and net primary production

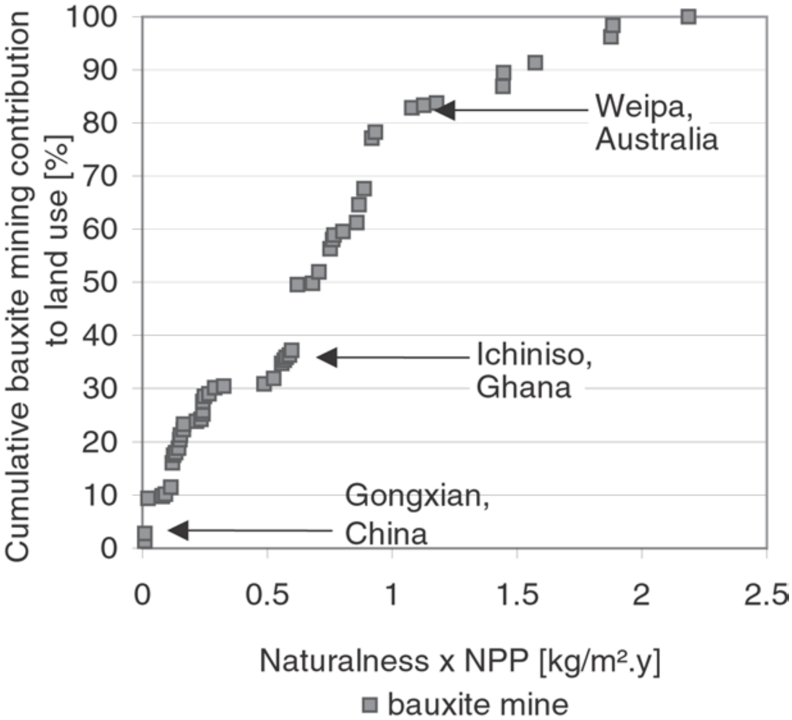

Fig. 4: Bauxite mining, land use and weighted NPP

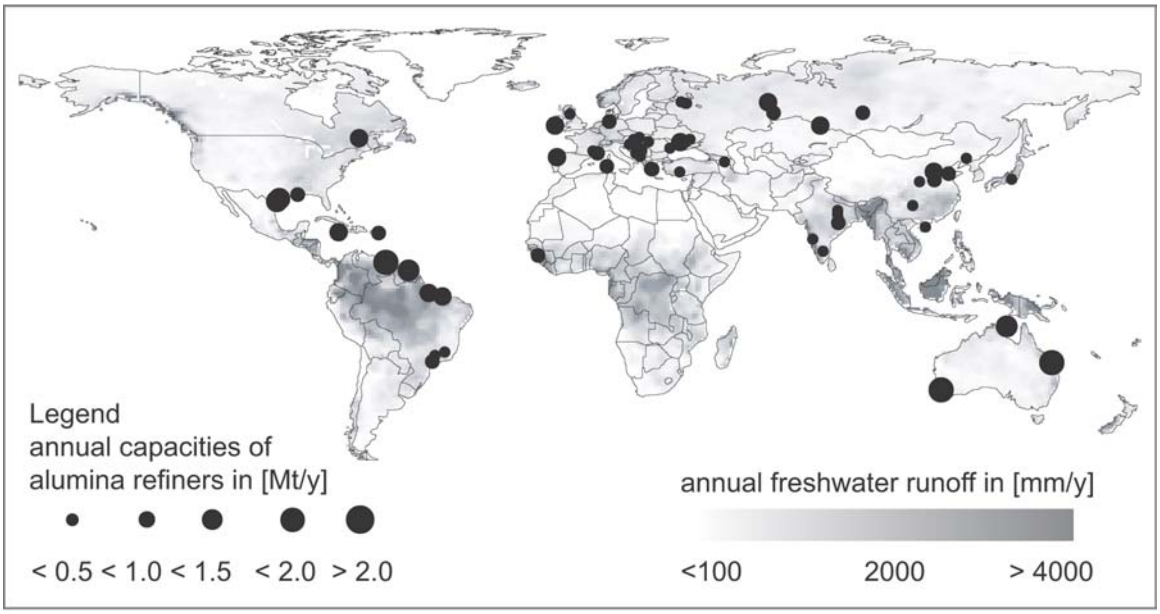

Fig. 5: Worldwide alumina refining and annual freshwater availability

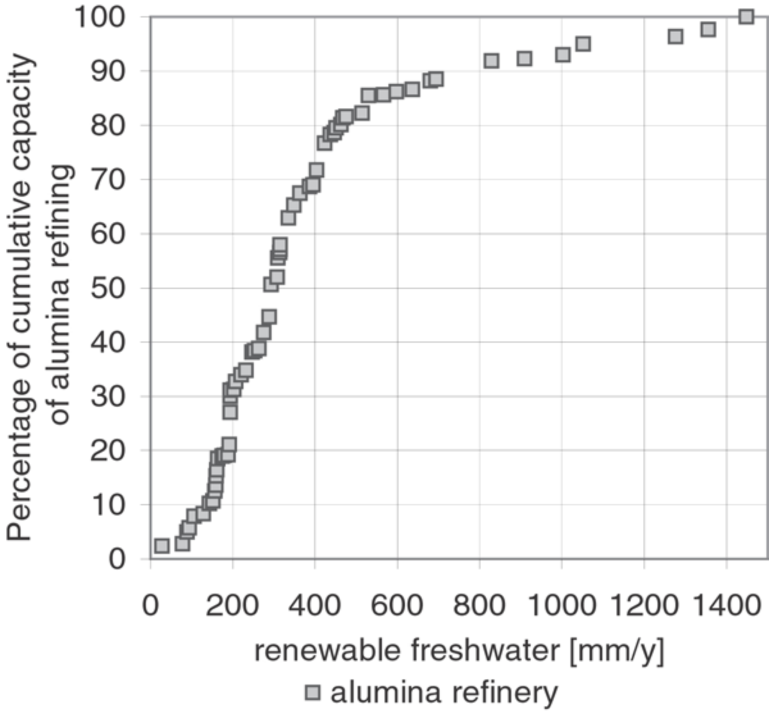

Fig. 6: Alumina refining and renewable freshwater

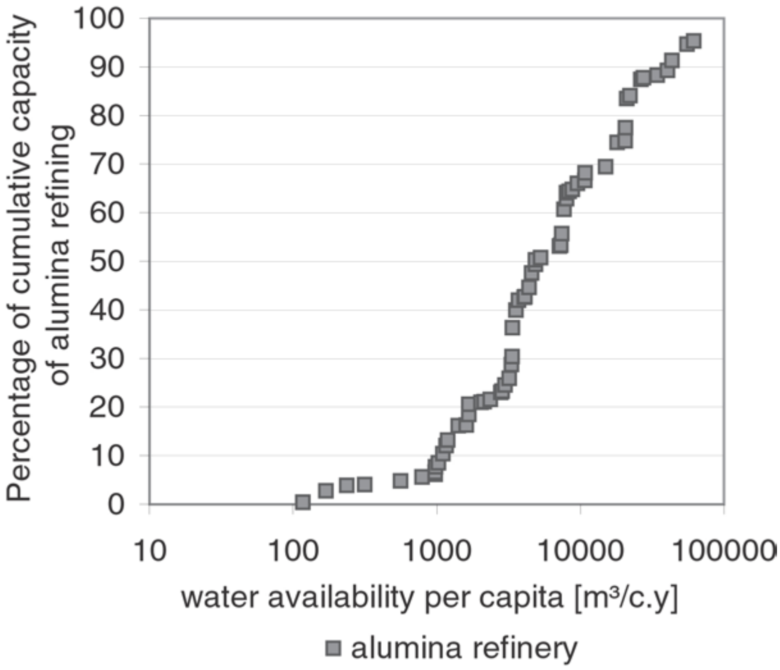

Fig. 7: Alumina refining and water availability per capita

SPECIFICATION OF FIELDS OF ACTION FOR A RESOURCE ORIENTATED, SUSTAINABLE DESIGN OF MATERIAL FLOWS OF METALLIC RAW MATERIALS WITH THE AID OF A GEOGRAPHICAL INFORMATION SYSTEM

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ABSTRACT[1]

Basic element of a resource orientated raw material flow management is the analysis of environmental impacts along the production chain. Many potential environmental impacts considered in raw material flow analyses are simplified disregarding the source strength of the intervention or the carrying capacity of the surrounding environment. The derived results therefore are only partially sufficient to develop targets and strategies for the management of global metallic raw material flows.

Here Geographical Information Systems (GIS) offer the possibility to provide spatial information for the raw material flow analysis. In order to oppose potential environmental impacts with local interventions the environmental information system SARIS (Site Specific Natural Resources Information System) has been developed.

SARIS contains relevant global digital survey data covering land cover, soils, morphology, climate, topography and population density. For each customized methodologies are available to display site specific parameters in tabular form or in a digital atlas. The application of this system is demonstrated taking the primary production of aluminum as example. Thus locations of bauxite mining, alumina refining and aluminum electrolysis are included in the spatial database.

For selected areas of activity options are specified with a harmonized procedure to identify conflict areas and potential impacts are quantified. Within the broader framework of raw material flow management this information is used to specify strategic options for a sustainable design of metallic raw material flows based on comparable and representative information on global scales.

KEYWORDS

Environmental impacts, site-specific parameters, land use, water consumption, acidification, GIS

[1] Summary of Ph.D. thesis: Präzisierung von Handlungsfeldern für eine ressourcenorientierte, nachhaltige Gestaltung von Stoffströmen metallischer Rohstoffe mit Hilfe eines Geografischen Informationssystems

SITE SPECIFIC ENVIRONMENTAL IMPACTS IN GLOBAL MATERIAL FLOW SCENARIOS*

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ABSTRACT

The mining, processing and refining of metallic raw materials and the utilisation of metals is a complex global network of producers and consumers. Facing the needs of future generations the resource oriented analysis and subsequently the design of raw material flows is a present challenge. Within the analysis of such systems environmental impacts play an essential role in decision making and management. Considering the current practice of life cycle assessment the environmental impact of material flows is normally figured as site independent. Contradicting many impacts can only be interpreted considering local environmental properties and socio-economic conditions.

To enable a site specific impact assessment global environmental data where structured in a geographic information system. Those processes, which are connected to large mass and energy flows at a single location where also collected within the system. For aluminium, which is taken as an example, this is bauxite mining, alumina refining and the aluminium electrolysis. Based on the capabilities of this system indicators where developed and measured to describe the environmental performance on local scales. Special emphasis of current research is put on land use and water use which are particularly dependent on site specific conditions. Within the interpretation of the results different aggregation levels allow comparisons of single sites, countries and technologies related to a world average. By a “what if”-scenario, based on technical variations within the near future challenges and potentials with regard to site specific conditions are identified and discussed.

KEYWORDS

Land use, water consumption, scenarios, alumina refining, bauxite mining

* Source: Proceedings European Metallurgical Conference EMC 2001, S. 321-332

Introduction

Production and use of metals initiate direct and induced anthropogenic material and energy flows. There is growing evidence of further need to study and disseminate the positive and negative effects associated with processing and supplying metals. Engineers, economists and natural scientists from the Aachen University of Technology and the Forschungszentrum Jülich co-operate in the Collaborative Research Centre (CRC) 525 „Resource-Orientated Analysis of Metallic Raw Material Flows“. Taking up the concept of sustainability this research programme aims at the development of options for a resource-sensitive use of metallic raw materials. Decision support relies on a broad information background to derive efficiency measures not only for technological enhancements but also for the integration of stakeholders. To support this process a scientific instrument has been developed to integrate information on complex metal flow systems. Besides the description of the present situation, scenarios show possible future developments and their effects within the three dimensions of sustainability: economy, environment and society.

Existing methods to describe physical flows and technological systems, such as process chain analysis or Life Cycle Assessment (LCA), often show a lack of integration of site specific conditions, which can have a large influence on environmental, but also social or economical impacts. In particular processes which initiate large mass- and energy flows at a single location require a detailed analysis. In a first step the mass flow of aluminium was chosen as an example. Therefore bauxite mining, alumina refining and the electrolyses were analysed as site dependent large scale operations. This paper presents the integration of the results within the operational framework of the global material flow analysis.

Site specific environmental impact assessment

Complex metallic raw material flows on global scale as well as linked environmental impacts can not be seized consistently and sufficiently neither with a single method nor an isolated set of indicators. Large mass and energy flows at single sites, small scale recycling procedures or the production of supplementary products require an integrative framework which allows the detailed analysis of relevant system components, but also, with regard to sustainability, a holistic view on the entire system.

Within the CRC 525 environmental issues are considered particularly important beyond consequences on capital or resources availability. For environmental impacts several methodologies have been developed in the last decades. Each of which suits for a particular objective in different spatial scales and time frames.

The general and commonly applied methodological framework for assessing environmental impacts along a production system is the Life Cycle Assessment (LCA) according to the ISO 14040 standards [1]. Within a LCA the inventory analysis, as standardised procedure, is in some cases efficient to detect targets for further activities or to support decision making. The inventory analysis is followed by the impact assessment (LCIA) during which different in- and outputs are aggregated by using equivalence factors. These characterise the contribution of a single flow to one environmental damage mechanism, called environmental category. The result is given as an impact potential. For each category an impact score (N) is calculated by the general equation (1) [2] with:

$$N_j = \sum_i M_{ij} * Q_i \qquad \text{(eq. 1)}$$

N = indicator score

M = environmental intervention in category *j*

Q = characterisation factor for intervention *i*

A prominent example is the acidification potential which describes the amount of H^+ Ions released by an emission into water or air. The acidification potential of nitrogen oxides and sulphuric acid (interventions) is expressed in SO_2-equivalences (characterisation factor). The strength of this approach is, that it allows the aggregation of a multitude of emitted substances to a clearly organised set of potential impacts along a product system.

In the present LCIA-methodology, no essential distinction is made where the intervention takes place. Regional properties or sensitivities which have an influence on the effects are gathered by global or national averaging of natural conditions [3]. Only during the final interpretation and valuation this restriction may be recognised.

To reflect environmental properties for single locations or countries within the global material flow the environmental impact assessment has been extended. This extension requires two additional terms:

- The source strength to recognise different plant sizes and to allow a weighted aggregation for the environmental interventions.
- The site or country specific characterisation factor to weight the specific impact potentials.

The general equation (1) is therefore embedded within equation (2).

$$N_{jk} = \frac{\sum_{l=1}^{n_k} \left(\sum_{i=1}^{m_j} M_{ji} * Q_i \right) * Q_l * A_l}{\sum_{l=1}^{n_k} A_l} \qquad \text{eq(2)}$$

A = strength of environmental intervention at location *l*

k = elements for aggregation

n = number of locations for the element k

m = number of substances/interventions within category j

This allows the characterisation of a single location and the aggregation of the mass- and energy flows related to capacity. Latter is an operational figure for the source strength to derive country profiles or global reference values.

To derive site specific characterisation factors it is necessary to collect and manage a number of environmental data. A Geographical Information System (GIS) is used to order the information for the regionalised environmental impact assessment in a spatio-temporal database.

At present the major categories of the database are land cover, soils, climate, water, morphology and population density. For each data source separate routines and models were developed to derive characteristic parameters for any location with importance for the primary production as element of the main process chain. These parameters are stored in the information system of the CRC 525 [4]. The sites themselves are to be captured by their co-ordinates and integrated into this system with their capacity and important technological specifications.

Due to the obtainable precision of location data and the small scale of the spatial data between 1:1.000.000 and 1° x 1° longitude/latitude most parameters are estimated as average values for an unit circle with a radius of 50 km. To suit for the equations of the described methodology, a subset of the estimated parameters has to be classified, combined and aggregated to characterisation factors. This is done by separate tables within the relational database.

By separating the raw parameter base from the combination rules and the location database the integration of new sites, accomplishing geo-data and the refining of characterisation factors can be done independently.

Material flow analysis

The superimposed model for the integrated characterisation of mass and energy flows within the CRC 525 is the process chain. Due to the nature of the system, different groups of processes have to be distinguished: The main process chain encloses all those processes which main commodity is the studied metal (mining, ore processing, smelting, alloy production, casting and manufacturing processes as well as processing of scraps).

Supporting processes (production of auxiliary materials) are modelled in the supplementary process chain. Energy as an important input for several modules is additionally modelled in a separate chain to depict different energy supply situations.

For each group different levels of detail and different spatial scales are appropriate. Within the primary production of the main process chain, large mass and energy flows occur at a single site or plant. Therefore sites are recognised. The secondary production is differentiated according to the specific materials in the recycling system of a country. The supplementary chain is modelled in technological categories and is assigned to a country. The allocation of a process within a process group has to be carefully adjusted to the metal considered. An example is the disposal of tailings within the primary production which does not fit in the commodity rule but which is strictly related to a single location. The energy for the main and supplementary process chain is modelled using the supply situation of a country. In cases, where this is an insufficient estimation of the supply situation, energy supply is modelled for a single site.

This grouped process chain is used to develop scenarios allowing the analysis of technical improvements for the entire material flow. Within a definite time frame, reliable estimations for the reference development are opposed to technical and structural variations [5]. As each process is available with its distinct in- and outputs, it is possible to quantify the effects which technical improvements may have.

Application

In the first working phase of the CRC 525 aluminium was chosen as an example to implement and refine the proposed framework. Within the ongoing programme copper is also analysed which allows a broader application of data and methodologies.

The primary production within the main process chain of aluminium includes bauxite mining, alumina refining, aluminium electrolysis, anode production and red mud disposal. Alloy production, casting of formates and the first and second manufacturing levels complete the main process chain. The supplementary process chain contains, among others, the production of aluminium fluoride, anode pre-requisites and caustic soda. The energy supply is related to countries except for the electrolysis, for which the so called “contract mix” is used. For the site specific analysis 378 sites have been collected covering nearly 100 % of the known bauxite reserves under operation or under exploration, the alumina refineries and the aluminium smelters.

Regarding resources, two important natural resources beyond minerals are affected by the primary production of metals: land and freshwater. Both resources are restricted as safeguard objects in availability and quality at any location. The corresponding category in LCIA is land use and resource depletion of abiotic fund and flow resources. Quality issues are indirectly addressed by other impact categories like acidification, eutrification or ecotoxicity. Within the following sections land use and water consumption are explained in more detail, representing other categories requiring spatial differentiation also.

Land use

Land use is a major issue within the production of metals. Mining and, in some cases, solid waste disposal cause a short or long term occupation of land. As an important impact category in LCIA, land use is linked to several impacts on biodiversity and other life support functions being generally supplied by land. Following Lindeijer [6], the temporal occupation is quantified in [am^2/t]. By introducing the duration, small, but long lasting occupations do have the same score as large, but short term occupations. Rehabilitation measurements are taken indirectly into account.

To estimate the size of a mining enterprise, mining areas are calculated based on ore body geometry and thickness of overburden. Land use for infrastructure is estimated by a correlation function which was developed based on data gathered by several field studies [7]. The duration of mining is estimated based on own research within the programme and publications. In cases, where reclamation is probable, two years are assumed as occupation period. In cases when no reclamation measurements seem to be probable, 10 years are applied. For the duration of infrastructure production figures and reserves are considered.

As far as no direct environmental damage mechanism is defined for land use, each is counted the same way in the inventory. To reflect different environmental properties, five additional characterisation factors are established based on a detailed cause and effect analysis. These factors are soil erosion by wind and water, the reduction of groundwater recharge, the naturalness and the net primary productivity of biomass [8]. The naturalness and the net primary productivity are used as characterisation factors not only for mining but also for subsequent land uses in the process chain and are explained in more detail below.

Based on remote sensing data provided in the information system the ratio of natural ecosystems and agricultural land or urban areas is determined for each location. This ratio is called naturalness characterising the degree of man-made alterations of land cover characteristics at a single location. It ranges from 0 – 1 with 1 indicating a undisturbed ecosystem. The naturalness itself is linked neither to a particular safeguard object nor an environmental damage mechanism. Therefore it is related to the net primary productivity (NPP) in order to distinguish different natural ecosystems by an important service function. Its unit is kg of dry substance (DS) which is not accumulated due to degradation. Both values can be further aggregated to an ecosystem indicator indicating the importance of a natural ecosystem and its NPP at an individual site. Figure 1 reveals a map with the global distribution of bauxite mines and the net primary productivity [9].

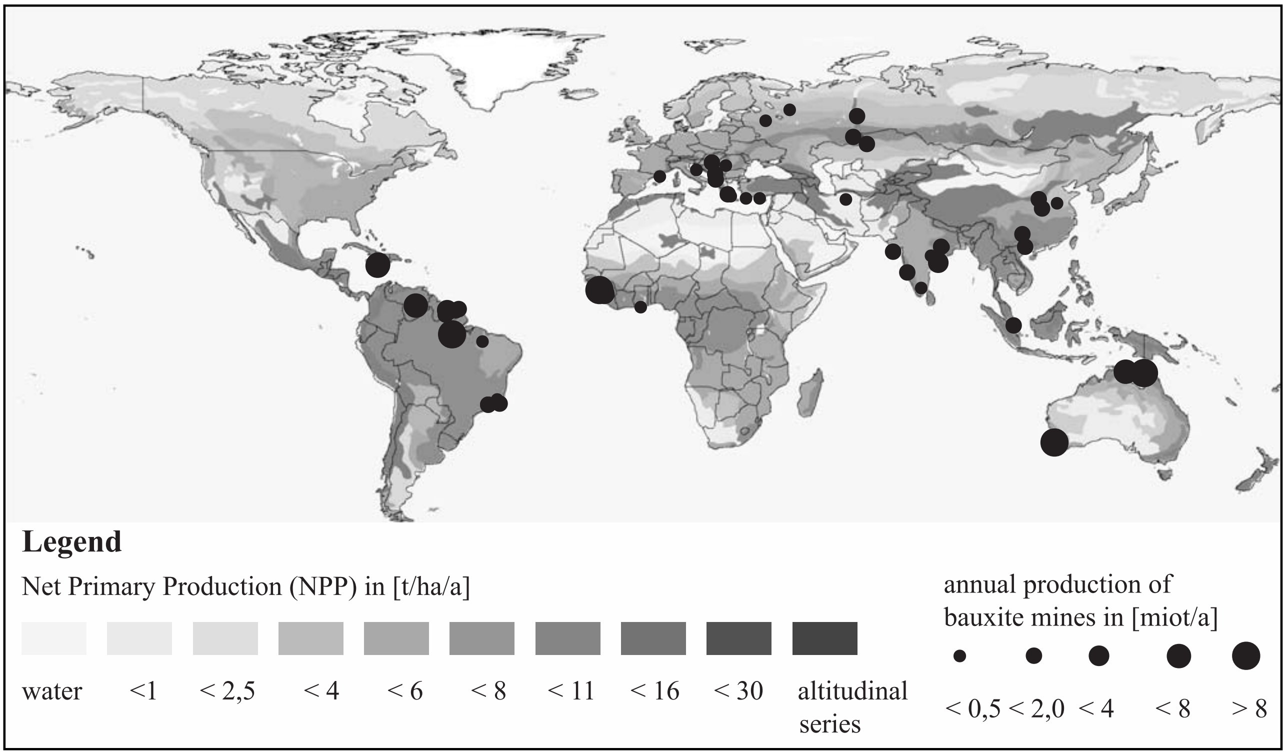

Figure 1: Global distribution of bauxite mines and net primary productivity.

The indicators are calculated for all operations. Two cases are distinguished. In the first case the reference situation is characterised based on reliable estimations of the duration. In the second case the minimum duration for mining is assumed for all locations as maximum potential to reduce land use. In figure 2 the indicator scores for the global assessment are given for both cases.

Except the naturalness, which is a dimensionless site indicator remaining unchanged by the activity, land use can be reduced significantly assuming best practice in land management. This would be additionally beneficient for the NPP. The small change in the ecosystems indicator implies a larger naturalness at sites short-term occupation prevails.

Not only global averages are important within the framework of the CRC 525. In the scenario analysis, different supply chains and upstream variations are taken into consideration. One scenario covers the packaging sector in Germany claiming about 20% of the annual primary aluminium consumption in the reference year 1997 [5]. Considering the direct and indirect imports of bauxite one can follow the material flow upstream and analyse the indicators of this particular sector. In figure 3 the indicator scores are shown similarly to figure 2 aggregated by the share each supplying bauxite mine had in the reference year. The total of 19 mines was identified. Main exporting countries where Jamaica, Guinea, Australia, Former Soviet Union, Guyana and Brazil.

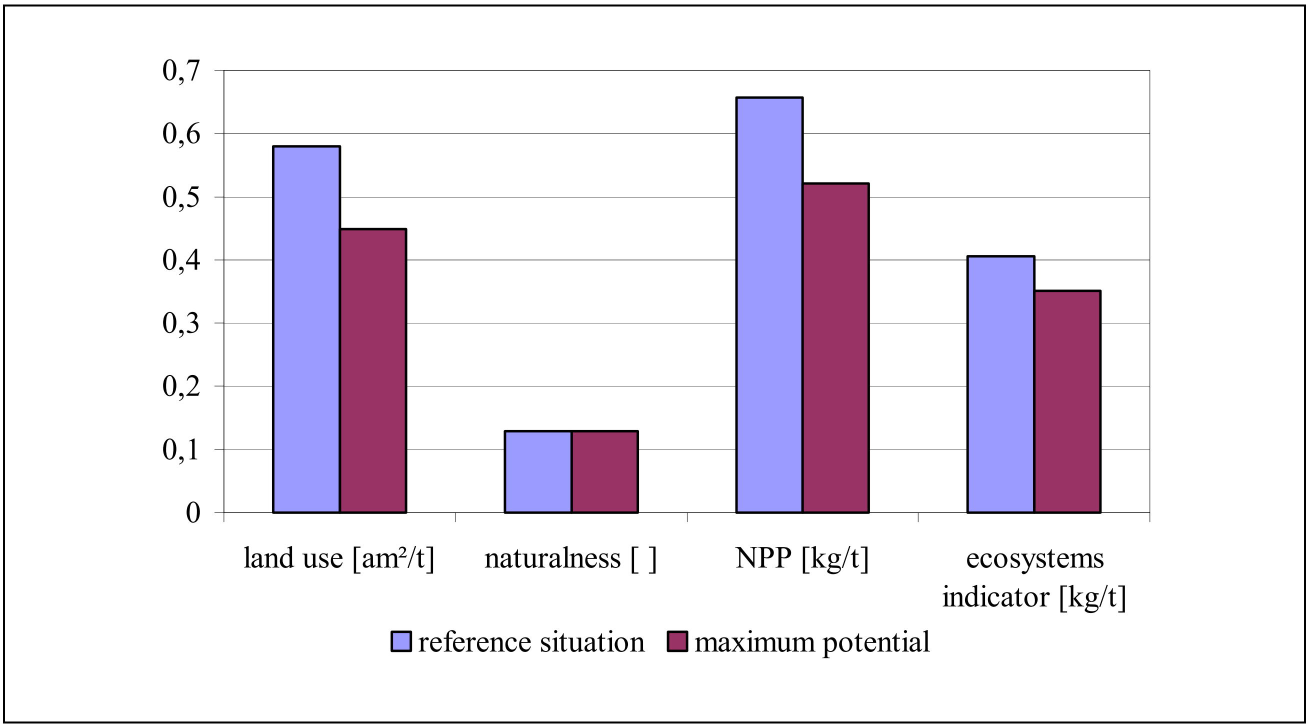

Figure 2: Land use indicators for open pit bauxite mining as a global average per ton bauxite.

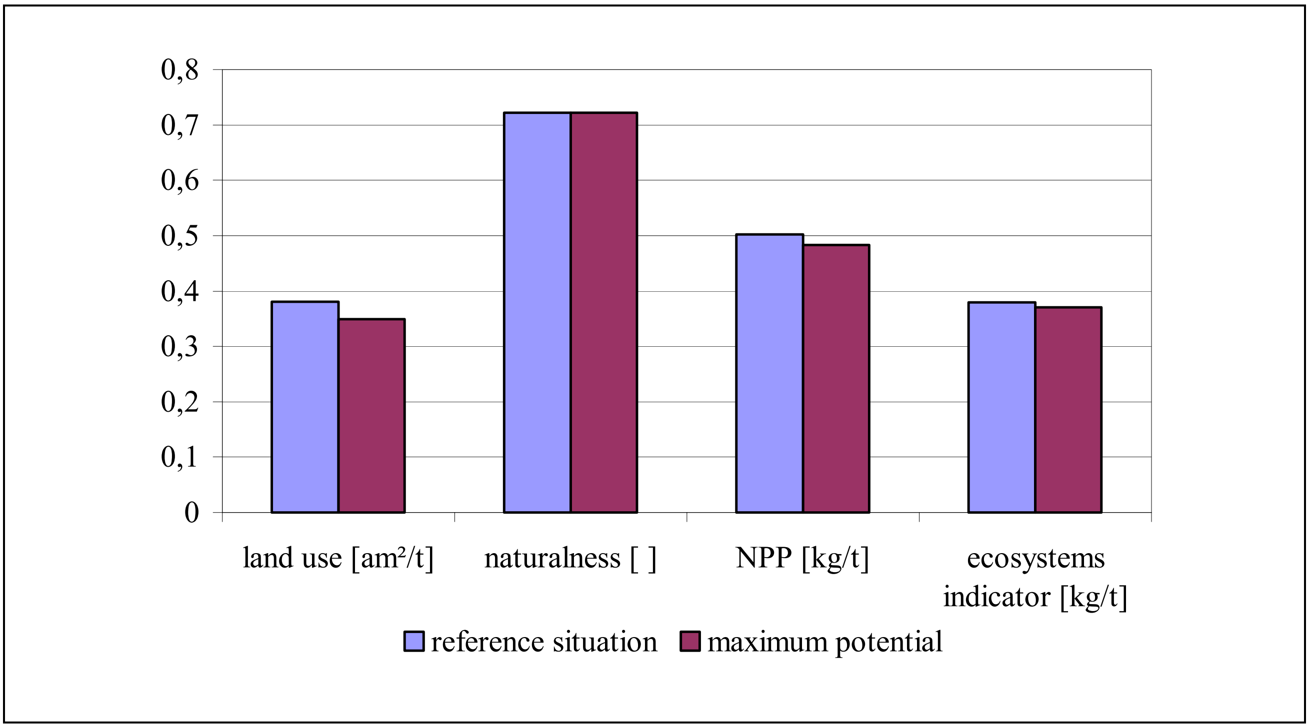

Figure 3: Land use indicators for open pit bauxite mining of the packaging sector in Germany in 1997 per ton Bauxite.

Due to different deposit characteristics, the land use in the reference situation and the maximum potential case are minor to the global average. The small difference between both cases persues in the effect orientated indicators NPP as well as the ecosystem indicator and is negligible considering data uncertainties. Compared to figure 1 the naturalness is with 0,7 larger than the worlds average, indicating that bauxite is mined in remote and so far undisturbed regions. This suggests, that even if best practice land management would be applied, the NPP would not change significantly.

Water Consumption

Water consumption is addressed by the LCIA-category "extraction of abiotic resources from the natural environment" [6]. Freshwater (except fossil ground water) is a renewable resource being limited in quality and availability on both local and regional scales and varying considerably from site to site. Compared to other abiotic resources freshwater can be a flow or fund resource. The exceptional case of using fossil groundwater is considered as depletion of a stock. Depleting a flow resource addresses the reduction of the regeneration rate. Depleting a fund addresses an overexploitation regarding the regeneration rates.

Effects on quality, which are caused by air born pollutants or waste water are modelled in other, more appropriate categories in the LCIA framework. Water consumption in the CRC 525 framework is defined as the amount of freshwater which is withdrawn from the local environment by evaporation or as moisture in products or wastes. The linked damage mechanism is the depletion of a fund resource. Considerable water consumption during primary aluminium production is related to the refining process. Cooling waters and the final moisture content of the residues (red mud) are consumption in the stricter definition framework. The average consumption in the refining process is figured with a minimum of 1 m^3/t alumina. The final moisture content of red mud is determined by the processed bauxite as well as the disposal technology. It varies between 30% and 50% and lies between 0,2 and 0,8 m^3/t alumina [10]. The freshwater source can not be determined within the technical inventory and the location information base. In some cases sea water and waste water from other industries are used, which is not considered in this methodology.

To oppose a specific industrial withdrawal with the supply situation, a characterisation factor was developed to express site specific scarcities. This factor is the ratio between water demand and water availability. Demand is calculated from population densities and country specific freshwater withdrawals per capita and year (disregarding industry and agriculture) [11]. Availability is characterised by regional runoff per km^2 and year as difference of monthly mean precipitation and actual evapotranspiration rates. River discharges are not considered. This ratio describes the portion of used water in relation to the annual water recharge. This factor scores 1 where the availability meets the consumption behaviour of the population in the vicinity of the site. According to Kulshreshtra [12] a ratio > 0.8 [m^3/capita a] of the renewable freshwater resources indicates a severe scarcity regardless of the available amount of renewable freshwater per capita and year. The map in figure 4 shows the worlds alumina refineries and the estimated annual freshwater runoff based on data of the information system [13;14].

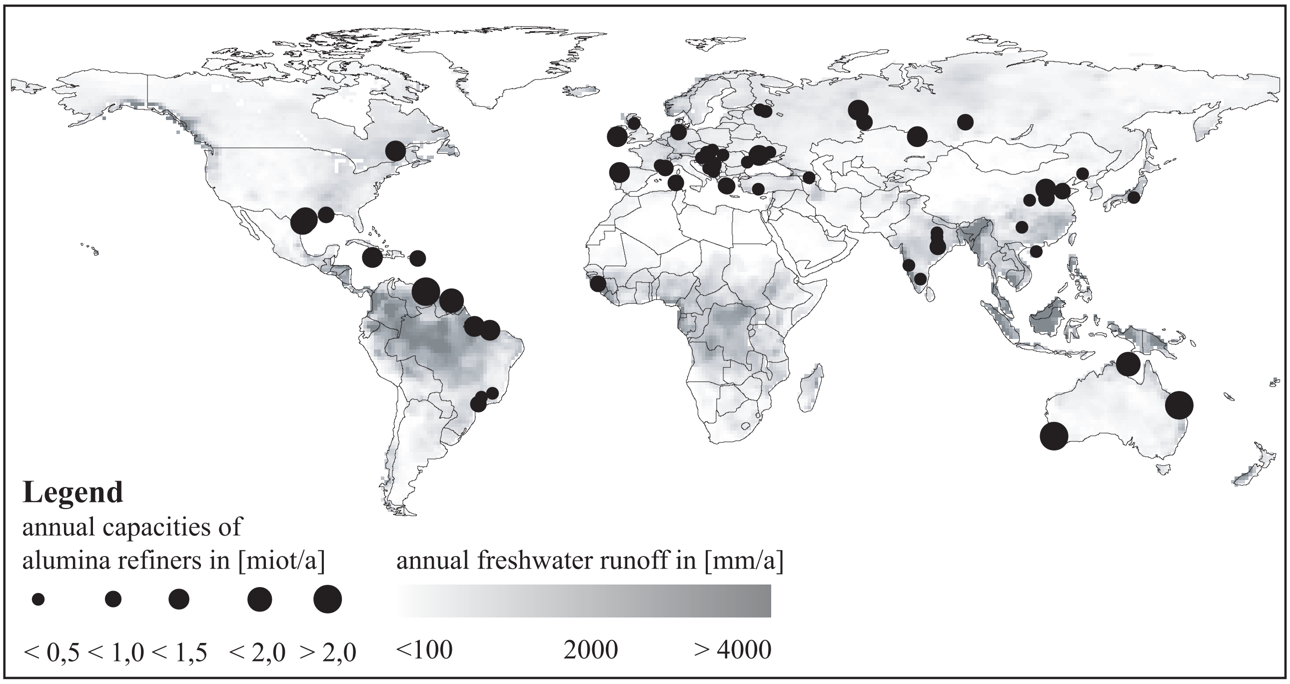

Figure 4: Global distribution of alumina refineries and estimated runoff

For each site water consumption of the production and local water scarcities have been estimated. Similar to the formerly discussed land use, the most reliable estimation is the reference situation. The minimum consumption due to disposal and treatment was assumed at all sites as a maximum potential. The technical potential to reduce water consumption during the process, e.g. by tube digestion, was not considered as its impact on water withdrawals is negligible. Corresponding to land use the import mix for the German packaging sector has been followed upstream [5]. Country averages from 16 countries with 39 refineries have been calculated and aggregated by their share in the import mix. In figure 5 average consumption and the indicator named water competition (derived by the product of consumption and scarcity) are shown for the two cases as global average and in relation to the German packaging sector in 1997.

The global reduction potential due to red mud conditioning can be figured with 7%. As the consumption depends on the refined bauxite the import mix figure for Germany differs slightly from the global average. Taking scarcities into account, the difference between both aggregates is with about 50% significantly high. This indicates, that although the consumption figures are similar to the global averages, the scarcity and thereby the competition is much lower for this particular subset of sites. Comparing the differences between the cases the differences are negligible. This indicates that water saving measurements are already implemented at sites with larger scarcities. The reduction potential is obviously larger at sites where scarcities are not relevant.

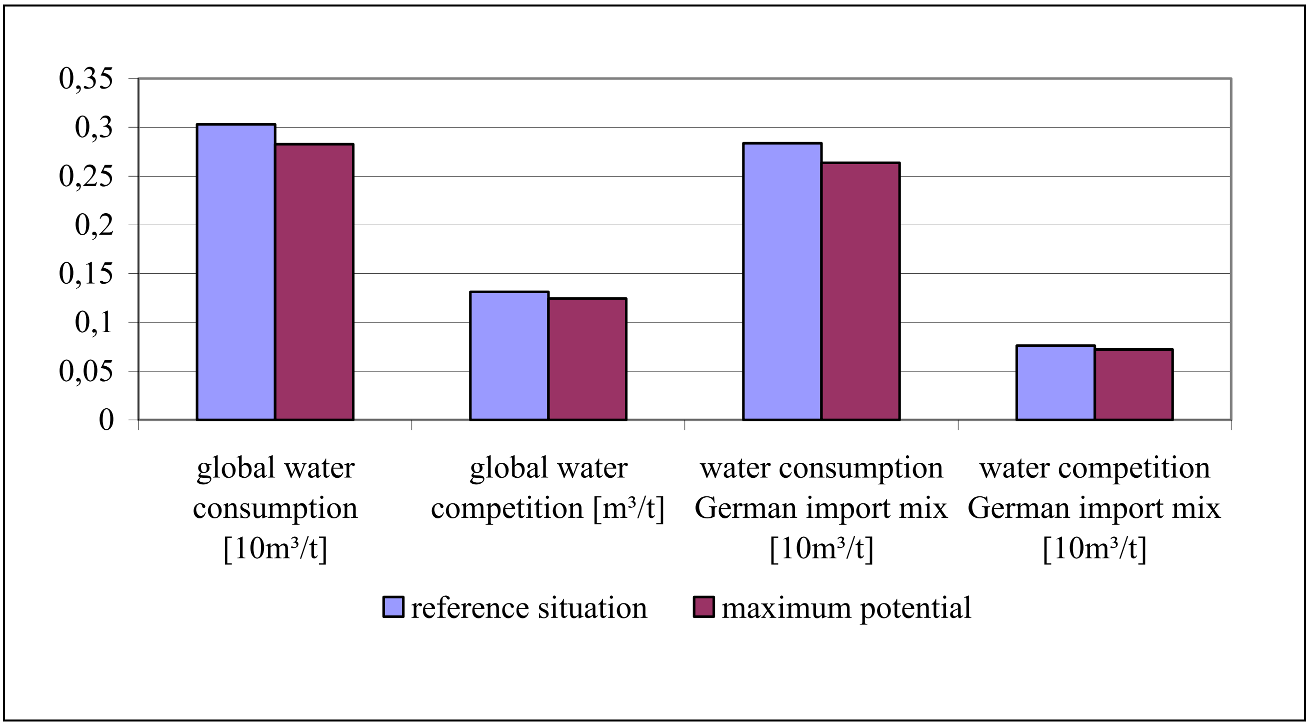

Figure 5: Water consumption and competition global and related to the German packaging sector per ton primary aluminium.

Discussion

The given examples land use and water consumption show the application range of a site specific environmental impact assessment within the framework of a global material flow analysis. Applying a standardised comprehensive procedure, environmental interventions and site specific characterisation factors are aggregated within different scales. By this procedure it is possible to discuss not only fallback strategies like general reduction plans but also to identify urgent needs of further action considering the conditions on site. Taking one well-known service function of nature as an indicator, it can be shown, that the reduction of the duration of mining is still a challenge in reclamation and rehabilitation measurements. Referring to water consumption it seems that the reduction potential at sites with an indicated scarcity is exhausted.

Within the interpretation of such indicators several restrictions apply. At first, precision and accuracy of the background data is oftentimes low. Therefore aggregates should be considered as potentials like in the traditional LCIA. Only differences in magnitudes should be considered and discussed rather qualitatively than quantitatively. At least one example exists for any outlined impact exists in practice which illustrates that the considered intervention is neutral or even beneficial for the local environment.

Adverse effects such as a rising energy demand for the disposal of dehydrated muds or the installation of infrastructure as stimulation for regional development are systematic limitations of any indicator approach complicating the communication of a single indicator score. To resolve contradicting or two-sided statements it is necessary to study all relevant impacts. Considering sustainability social or economic consequences should be addressed equally important. This is only possible within an integrated indicator framework representing a challenge of further research. The inevitable basis for such a framework is a clear cut definition of the single indicator. To avoid confusion, a possible interpretation and a comprehensive summary of limitations have to guarantee transparency. The integration of site specific aspects into such an indicator framework contributes to resolve contentious issues in the discussion about sustainable material flow design.

Acknowledgement

The author is member of the German Collaborative Research Centre 525 „Resource-orientated analysis of metallic raw material flows", established in 1997. Thanks are due to the German Research Council (DFG) for financial support. Special thanks are due to several colleagues for discussion and data, namely Dr. P. Zapp, Dipl.-Geol. P. Sliwka, Dipl.-Geol. M. Mistry and Dipl.-Geol. J. Hausberg.

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METALLIC RAW MATERIAL FLOWS AND GENERIC SITE-SPECIFIC CHARACTERIZATION FACTORS*

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ABSTRACT

Many potential environmental impacts considered in LCA and raw material flow studies vary considerably on both local and regional scales depending on the affected environment. Particularly metals being generally associated with large concentration processes at single sites, are covered insufficiently in global generic inventories and impact assessments. Current available data on site-specific issues are rarely comparable or representative. Thus, the environmental information system SARIS (Site-Specific Natural Resources Information System) has been developed based on a geographic information system to quantify distinct environmental properties in the vicinity of any producing site. The main application of SARIS is the characterization of environmental safeguard objects which may be affected by the activity of concern. Based on site-specific estimates for in- and outputs such as land use, water consumption or emissions, the environmental properties can be used to derive characterization factors within LCIA. The weighted impact scores can be interpreted on any desired aggregation level ranging from sites to technologies to countries or even global average values.

KEYWORDS

Metals, impact assessment, land use, water, acidification, site-specific, GIS

* Source: Proceedings of Fifth International Conference on EcoBalance, p. 59-62, Tsukuba, Japan

OBJECTIVE

Most methods describing physical flows and technological systems, such as process chain analysis or Life Cycle Assessment (LCA), often show a lack of integration of site-specific conditions, which can have a large influence on environmental, but also social or economical impacts. Particular processes which initiate large mass- and energy flows at a single location require a detailed analysis. In order to reflect different site-specific environmental properties, global data has been collected and analyzed to develop site-specific characterization factors. This study is part of the research undertaken by the Collaborative Research Center 525 (CRC 525) aiming at a resource orientated analysis of material flows of metallic raw materials.

METHODOLOGY

To derive site-specific characterization factors it is obligatory to collect and manage a plethora of environmental data. In order to quantify distinct environmental properties in the vicinity of any producing site the environmental information system SARIS (Site Specific Natural Resources Information System) has been developed based on a Geographical Information System (GIS). Latter is used to structure the information for the regionalized environmental impact assessment in a spatio-temporal database.

At present the major categories of the database are land cover, soils, climate, water, morphology and population density. For each data source separate routines and models were developed to derive characteristic parameters for any location with importance for the primary metal production. The site data comprises co-ordinates and capacities and important technological specifications. Currently 257 sites of the primary aluminum production (bauxite mining, alumina refining, electrolysis) are incorporated in the system. The reported production figures of these sites correspond to 100% of the known world production in 1997. Most environmental parameters are estimated as average values for an unit circle with a radius of 50 km which is due due to the obtainable precision of location data and the small scale of the spatial data between 1:1.000.000 and 1° x 1° longitude/latitude. A subset of the estimated parameters has been classified, combined and aggregated resulting in characterization factors within the relational database.

APPLICATION

Within the raw material flow analysis this system is used to identify conflict areas on a first screening level. Characterization factors are used to weight different interventions according to potential site specific impacts in order to provide concise information derived from the multitude of environmental parameters. Due to the detailed modeling of technical inventories within the CRC 525 it is possible, not only to determine potential interventions for each location, but also to estimate the avoidable fractions of material and energy flows using different technology levels [1]. In the following, the characterization factors are used to assess the avoidable interventions according to their contribution to local and regional environmental mechanisms. Water consumption and acidification are taken as examples along the primary aluminum production. Land use was depicted in previous studies [2,3].

Water Consumption

Freshwater (except fossil ground water) is a renewable resource being limited in quality and availability on both local and regional scales and varying considerably from site to site. Compared to other abiotic resources freshwater can be a flow or fund resource. Due to the uncertainty of the inventory data the determination of the water sources being in use at a particular location is impossible. Consumption can not be distinguished from use due to different reporting an definition problems. As an operative parameter in this study consumption is defined as the amount of water which is lost to the local environment by evaporative processes (e.g. cooling water) or water as final moisture content of solid wastes. Considerable water consumption is related to alumina refining processes, the subsequent processing steps of the mined bauxite. The average consumption can be estimated for “red mud” as a mass intensive solid waste [4]. By dehydrating of such muds water can be re-used within the process.

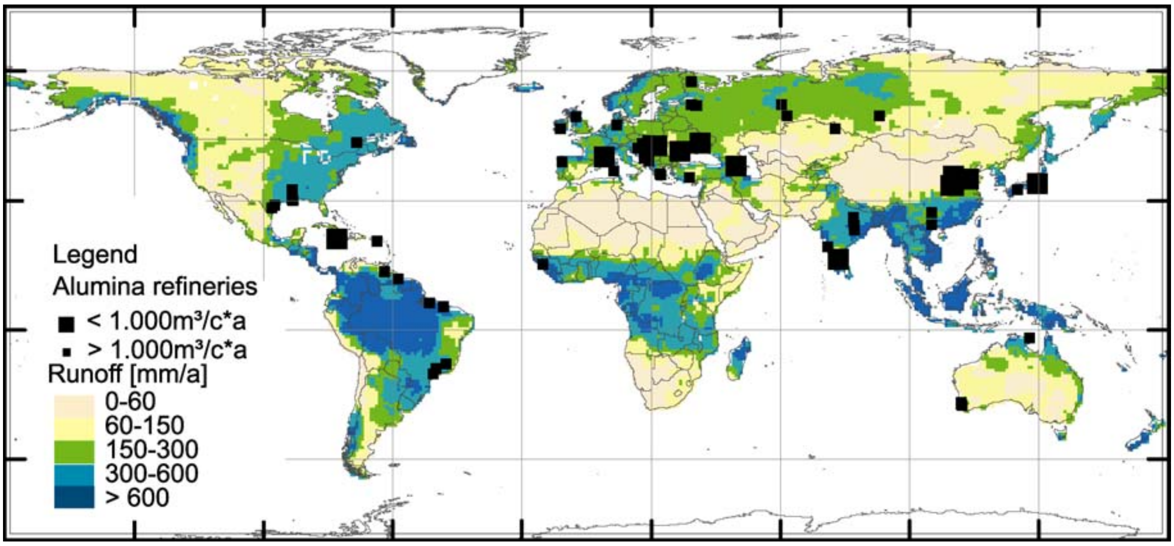

Fig. 1: Renewable annual freshwater and alumina refineries

Using environmental data of SARIS a generic factor to characterize water availability is developed for a global assessment. Water availability in given catchments is commonly quantified by the difference between the monthly precipitation and evapotranspiration. This difference is an estimate for the renewable surface and subsurface runoff of freshwater. Problems in water supply occur in areas, where competitive withdrawals lead to water scarcities. As an operational figure the availability is related to the population density, given in capita(c) per square kilometer. This serves as estimate to determine whether a particular location is situated in a region, where water stress is highly probable, According to literature, availabilities below 1000m³/c x a indicate water stress in a region [5].

The map in Figure 1 reveals all alumina refineries and runoff-values derived from SARIS. Each site is classified according to the water availability per capita and the operative threshold of 1000 m³/c x a. In arid but sparsely populated areas (e.g. SW-Australia) availabilities per capita may be sufficient. In humid areas of Europe or Asia water is rather scarce due to high population densities.

A characterization factor is used in order to aggregate site specific consumptions similar to the example land use. In this case, the reverse ratio of the water availability per capita is used. This factor is small, if water is abundant and increases with rising scarcity. In Figure 2 those alumina refineries are depicted, where water might be reused, their fraction of the total global water consumption and the indicator value representing a reduction potential of water stress.

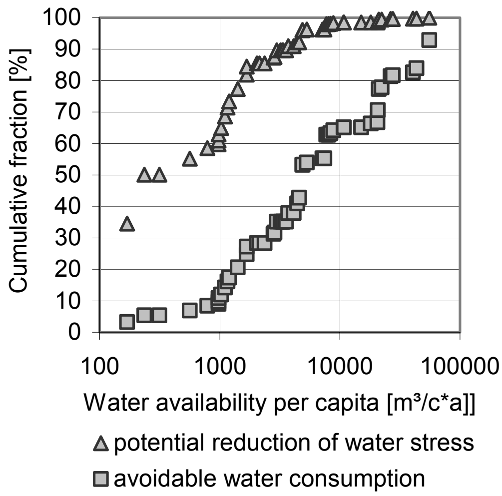

Fig. 2: Avoidable water consumption and water stress at alumina refineries

Approximately 10% of the avoidable water consumption occurs at sites, where the availability indicates water scarcity. The weighted reduction potential implies, that 60% of the overall reduction potential for water stress is reached at these sites.

This preliminary data analysis is based on a couple of assumptions. The use of gray water or sea water for instance is not take into account in this study. The emphasis of this study has rather been put on a top down distinction of locations.

Acidification

The acidification potential (AP) addresses serious environmental damages to natural ecosystems in the last decades. After in Europe and North America also in Asia, Africa and South America negative effects of acid deposition are to be expected in the next decades. According to a study of UNEP/RIVM[6] between 7-17% of the worlds terrestrial (semi-)natural ecosystems may be negatively affected in 2010. The sensitivity of ecosystems is expressed in critical loads [meq] which figure the amount of acidifying substances which can be brought into the environment without damages. The critical loads exceedance ratio (CRTL-EXR) is the ratio of the deposition rate of acidifying substances and the critical loads. This ratio can be used to differentiate distributed emission sources in a spatial reference system, considering areas where critical loads are exceeded already and where no or low exceedance ratios can be assumed.

Emissions of SO_2 during aluminum production occur é.g. during the electrolysis. The emission rates can be quantified within the technical inventory. Information on installed filters and their efficiency is also available. This facilitates the quantification of avoidable SO_2 emissions.

To define a generic characterization factor a radius of 1300 km was assumed as an operational figure representing the area which could be affected by stack emissions. Within this selection geometry three surface types have to be distinguished: Agricultural land and water for which no critical loads can be estimated and areas carrying (semi-) natural ecosystems. To obtain a single factor for a site vicinity, the exceedance ratios were summed weighted by their area. The resulting value indicates the exceedance ratio in the site vicinity and can directly applied as a weight. The derived indicator supports the comparison between sites and their relevance according to this environmental issue. The map in figure 3 reveals the expected CRTL-EXR for the year 2015 according to a study of UNEP/RIVM 1999 [6] and the producing aluminum sites. Each location is classified by the CRTL-EXR of its region.

In Figure 4 each site with its cumulative contribution to the avoidable emissions and the weighted indicator score is plotted versus the CRTL-EXR. More than 80% of the emissions take place in areas, where the carrying capacity of the environment will not be exceeded in the next decades.

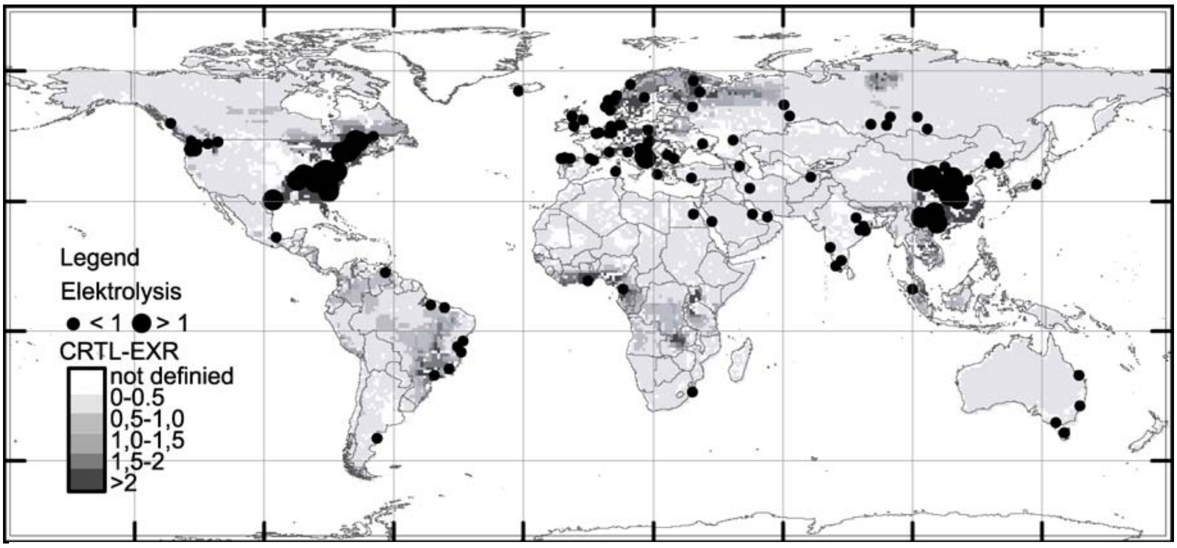

Fig. 3: Critical loads exceedance ratios (CRTL-EXR) for acidification and aluminum electrolysis

About 20% of emission reduction would reduce 50% of the indicator score. This analysis suggests to focus a more detailed study on those sites, where the acidification problem is potentially serious.

CONCLUSION

The presented study on a metallic raw material flow illustrates, how additional spatial data can be used to address and specify potential environmental impacts. The underlying data uncertainty of the environmental data as well as of the estimates of the environmental interventions restricts the applicability of such characterization factors. Though it is possible to predict environmental mechanisms which are pre-defined by the unique distribution pattern of sites one a comparable and repeatable global basis.

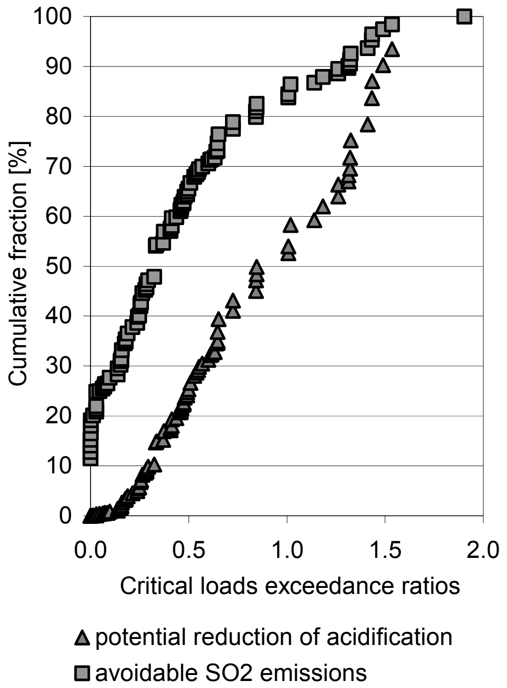

Fig. 4: Avoidable S02-Emissions and potential acidification at aluminum electrolysis locations

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A GLOBAL ENVIRONMENTAL IMPACT ASSESSMENT FOR BAUXITE MINING
- LAND USE AND SOIL EROSION -

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Introduction

Bauxite is the main raw material for the aluminum production. Most bauxite is mined in surface operations in tropical and subtropical climates. Due to the land use of mining processes serious environmental impacts may be caused in the close vicinity of the pits.

To gain information on the extent of environmental impacts from bauxite mining on a global scale, three sub-programs of the Collaborative Research Center 525 Aachen (CRC 525) have assessed major environmental impacts due to the land use. The land use and soil erosion potential have been calculated [1] for 52 open pit mines world-wide .

For this case study information has been used from three data bases of the CRC 525. The first database, “Bauxite deposits”, contains information on the deposit type, reserves and statistical life time of each individual mine. The second database, “WOBEX”, contains information on mining processes, annual production and operational management. In addition to the databases mentioned above, the environmental information system “EIS” presents data on climate, topography, morphology, soil types, and geology.

Methodology

The study has been carried out in two major steps. The first part of the study, the land use assessment, deals with the estimation of site-specific values for specific land use per ton of bauxite. It is distinguished between land use by mining process and land use by infrastructure. In the second step, the erosion assessment itself, site-specific soil erosion potentials have been calculated for water- and wind-induced erosion processes.

In this study an important distinction between “land requirement” and “land use” has been made. Whereas the former describes the specific affected area associated with the production of one ton bauxite [m²/t], the latter additionally considers the duration of land use [y·m²/t].

The erosion assessment proposed in this paper relies on common methods which allow the calculation of the average eroded soil per hectare and year [t/ha·y] considering site-specific environmental properties. The product of mining land use and annual erosion factor leads to the specific soil erosion induced by water or wind per ton bauxite.

Land use assessment

As previously mentioned, the methodical approach of this study regards land use as the product of land requirement and duration of use. Land requirement (L_r [m²/t]) depends on typical deposit characteristics concerning bauxite thickness (T [m]), density (ρ [t/m³]) and quality (washery gain Q [%]). It is calculated after:

$$L_r = \frac{1}{T * \rho} * \frac{1}{Q} \qquad (1)$$

The average duration of land use - the time between surface cleaning and reclamation - mainly depends on reclamation management, production processes and shape of the deposits. Values for the average duration of land use are not sufficiently documented in literature and can only be estimated roughly for the purpose of this study. Six field studies at selected mine sites distributed around the world revealed that the duration of land use is approximately one year at mine sites with small deposits or with consequent strip mining and an existing reclamation management. Sites where it can be supposed that no reclamation management system is applied, the duration between surface cleaning and natural succession of vegetation can be assumed with ten years. For all other sites the average duration of land use is assumed to be about two years.

Land use for mined land (L_m [y·m²/t]) is calculated as a product of land requirement and duration (t [y]):

$$L_m = L_r * t \qquad (2)$$

Land use by infrastructure is estimated through the information gathered from field studies. The estimation is based on the assumption that there is a strong dependence between the mean annual production of a mine and the corresponding area which is used by the infrastructure for buildings, maintenance, processing and short range transportation. Land used for long range transportation on a site - e.g. between deposits and treatment plants and seaport - could not be considered for this assessment. Figure 1 shows the correlation between the annual production and the specific land occupation by infrastructure [m²/t] of the investigated mine sites.

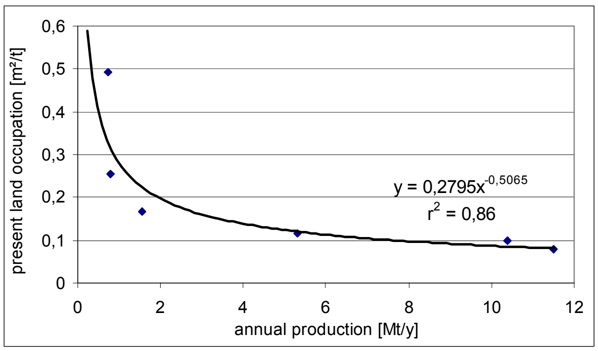

Figure 1: Correlation between land occupation and annual production.

The squared correlation coefficient r^2=0,86 shows a strong correlation for the six visited sites. This exponential function is used as an estimator for the land use of infrastructure. (L_{inf} [y·m²/t]). This land use is calculated with the annual production (P [t]), the mine lifetime (l [y]), the past production (P_p [t]) and the future production (reserves R [t]) after:

$$L_{\text{inf}} = 0{,}2795 * P^{0{,}4935} * \frac{l}{(P_p + R)} \tag{3}$$

Assessment of soil erosion by water

The assessment of the soil erosion potential by water relies on the UNIVERSAL SOIL LOSS EQUATION (USLE) [2]. The equation has been modified to fit the information content of the databases. The simplified equation leads to the average soil erosion potential by water at bauxite mines considering rainfall characteristics, soil erodibility and morphological conditions. Whereas the vegetation cover factor is not relevant for the purpose of this study, the factor for conservation practice from the original USLE could not be taken into account due to the lack of data. The assessment of the soil erosion potential by water has been conducted by using the equation:

$$A = R * K * LS \tag{4}$$

with the annual soil erosion potential A [t/ha·y], the rainfall erosivity index R [kJ/m²·mm/h], the soil erodibility K [t·h/ha·N] and the slope-length and slope-steepness factor LS [-].

To determine the R-index 10 years average monthly precipitation data have been used to calculate the FAO modified Fournier-factor for different climates [3], [4]. The K-factor is classified by main soil-types and soil-textures after SCHWERTMANN et al. [5]. The LS-factor takes into account the slope steepness and the length of the eroding bare area, and was calculated after WISCHMEIER & SMITH [6] considering the average gradient of the mine terrain.

Assessment of soil erosion by wind

The assessment of the specific soil erosion potential by wind per ton of bauxite follows the approach of WOODRUFF & SIDDOWAY [7], using the WIND EROSION EQUATION (WEQ). This equation allows the assessment of the average annual soil erosion by wind considering parameters referring to soil types, precipitation and evaporation conditions as well as the size of the pit. Regarding the global scope of this study an adaptation of the formula is necessary in order to address specific conditions and data availability at the assessed bauxite mines. The erosion assessment has been carried out after the function:

$$E = f(I, K, C, L) \tag{5}$$

with the annual soil erosion potential E [t/ha·y], the soil erodibility I [t/ha·y], the ridge-roughness K [-], a climate factor C [-] and the field factor L.

Soil erodibility is classified in main soil-types and soil-textures which take the Wind Erosion Groups of the USDA [8] into account. In this assessment the ridge-roughness factor is set one for surface mining operations. The climate factor has been calculated considering mean wind velocities and mean monthly precipitation and temperature values after CHEPIL et al. [9]. The size of the open pit depends on deposit shape, annual production and reclamation management and is expressed in the field factor.

Information System

Within the CRC an information system was implemented during the early stages of the project. This information system was designed to concatenate a variety of databases which have been set up in the different sub-programs. Each database was designed to contribute to the material flow analysis, but also to answer specific questions for the individual processes. For the site specific assessment of environmental impacts of mining processes three data bases are of particular importance:

- "BAUXITE DEPOSITS" data concerning deposit type, reserves, statistical life time and geology
- "WOBEX" data on mining processes, annual production and operational management
- "EIS" data on climate, topography, morphology and soil types

Each of these are essential for the described methodology and are explained in detail below.

Within the information system the different data sources are connected by the location. Each location has a unique name, an associated process and a country. The latter is used to aggregate results by country or economical regions. The location inventory covers all known deposits. Each deposit is characterized by the BAUXITE DEPOSIT database. If a deposit is mined, production figures and process data on the mining operation is stored in WOBEX. For each location environmental properties are available via the environmental information system EIS. To follow the material flow downstream, alumina plants and aluminium smelters are also bound to locations. Long range transportation and electricity supply is modelled in separate data bases.

Database of Ore Deposits

The database BAUXITE DEPOSITS was designed to supply resource oriented geological, mineralogical, ecological and economical data of bauxite and alternative aluminum raw materials, such as alunite and nephelin. The data stored in BAUXITE DEPOSITS is mainly used to calculate future bauxite availability and to forecast future trends in bauxite mining. In addition to this aim of research it supplies important data for interdisciplinary studies [10].

The database comprises 174 main data sets (deposits or groups of neighboring deposits). 46 of those are karst bauxite deposits, 124 are lateritic deposits and 4 are nephelin/alunite deposits. About 170 possible fields of properties exist for each data set [11][12][13].

The basic data is given on 174 deposits (name, geographic location, state of the project, geomorphology, climate zone). Information concerning the geology, exploration, ore reserves, ore quality and statistical lifetime of mines is linked to each main data set.

Since the geometry of bauxite ore bodies depends on the ore deposit type, in “Bauxite Deposits” lateritic bauxite deposits are separated from deposits of karst bauxite. While laeritic bauxite deposits in general have a big lateral extension but a small thickness, karst bauxites show smaller surface extension, but greater thicknesses. The geometry of ore bodies has a considerably high impact on various aspects of mining and subsequently on the environmental impact of mining activities. In this study the different geometry of deposits is represented by the bauxite thickness and the spatial extent of the deposit which are essential for calculating the land requirement and the duration of land use.

Mining database

The database WOBEX was designed to collect and to manage data on mineral extraction. It comprises of 170 bauxite deposits, of data from 70 bauxite mines from which are about 60 currently operating sites, and of 52 producing metallurgical grade bauxite. The remaining 8 operating sites were mainly producing chemical and refractory grade bauxite.

Main purpose of the database is to store information on bauxite mines from field trips and literature [13][14] systematically. Therefore the opportunity is given to describe the very specific site by general information, mining method and all stages of the mining activities. The general information also contains a correlation code which enables the CRC 525 to combine WOBEX with other CRC databases and produce results for different fields of research. The mining method influences the duration of land use and therefor is an important aspect for calculating erosion. The description of the stages of mining activities also contains information about mineral processing which encloses amounts of washery product and refuse. On the other hand information on mineral production, mining equipment and process inputs - e.g. the use of electrical energy and fossil fuel - and outputs - e.g. waste and air emissions - are stored as well.

Environmental database

To characterize the environmental properties at a single site within a raw material flow an environmental information system has been established by means of a geographic information system (GIS) [15]. Within the GIS important property data with a global coverage have been structured in a spatio-temporal data base.

At present the major themes are land cover, soils, climate, water, morphology and population density. For each data source separate routines and models have been developed to derive characteristic parameters for each of the currently 378 known sites with importance for the primary aluminum production. These parameters are stored in the information system of the CRC. With particular importance for the case study are the soil data from the FAO [16], the climatological data from the GCPP [17] and the CIDC [18], as well as the digital terrain model GTOPO30 from the USGS [19].

Figure 2 shows the structure of these environmental themes within the information system.

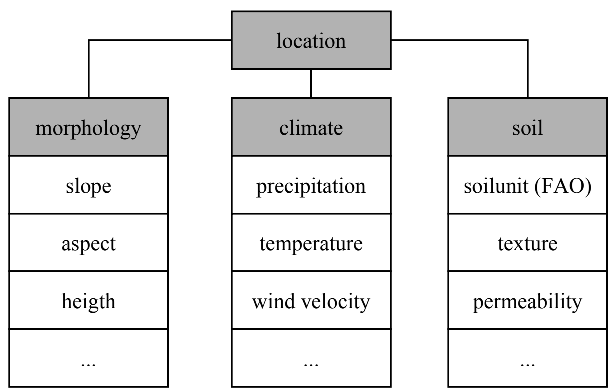

Figure 2: Environmental themes in the information system

Due to the partly inaccurate location information and the small scale of the spatial data between 1:1.000.000 and 1° x 1° longitude/latitude most parameters are estimated as average values for a unit circle with 50 km radius. The morphology is characterized by statistics on the height and the derivates of the digital terrain model slope and aspect, as well as their maximum and minimum within the unit circle. Climatological parameters are given as a 12 month averaged time series based on long range satellite and measurement surveys. Soils are modeled by the portion of each FAO-Mapping unit in the unit circle. Each mapping unit can consist of up to eight different soil units each of which is linked to representative soil property data like texture class, profile depth, permeability, fertility and many others.

To suit for the equations of the described methodology a subset of the estimated parameters has to be classified, combined and aggregated to indexes. This is done by separate tables within the relational database. By separating the raw parameter base from the combination rules the integration of new sites and the implementation of further methodologies can be done independently.

Results of the global assessment

The global environmental assessment of land use and soil erosion has been carried out for surface mined bauxite which is used mainly for metallurgical production. In total, 52 mining operations have been considered, including large operations with a huge annual production in Australia, Jamaica, South-America and West-Africa, as well as small and medium-sized mines, e.g. in India, China, Russia and Europe (Figure 3)

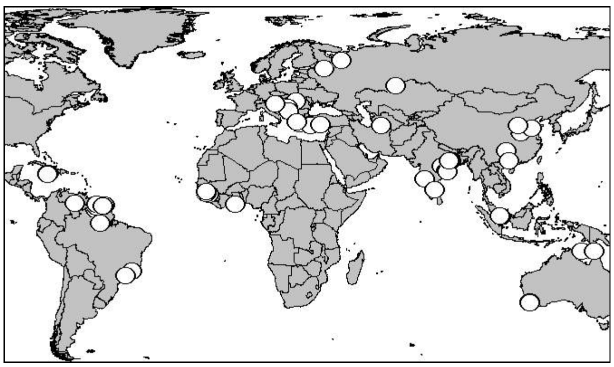

Figure 3: Investigated bauxite mines [1].

Land use

The quantification of specific land use for each bauxite mine is the basis of the following erosion assessment. As previously mentioned, land use is distinguished in land use by mining and land use by infrastructure.

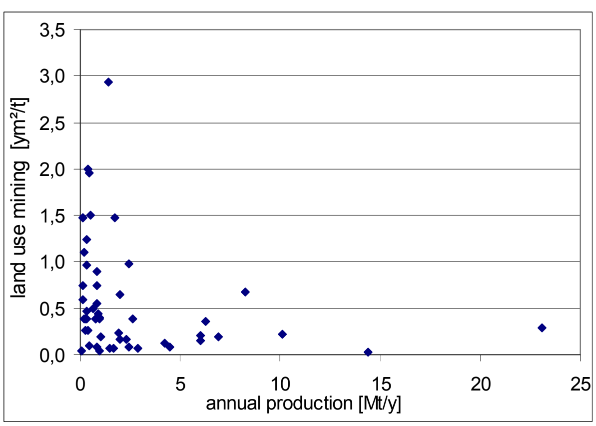

Figure 4: Specific land use by mining.

In 1997, the annual occupation of new land (land requirement) by bauxite mining sums up to 1,650 ha. For the erosion assessment the concept of land use considering area size as well as the duration of use has to be taken into account. In Figure 4 land use by mining of each site in correlation to its annual production is shown. Land use by mining mainly depends on the site-specific parameters, bauxite thickness and quality as well as on reclamation management. Specific land use by mining varies in a wide range between 0.02 and 3 y·m²/t bauxite. It is remarkable that sites with more than 3 Mt/y have relatively low land use values compared to sites characterized by a lower annual production.

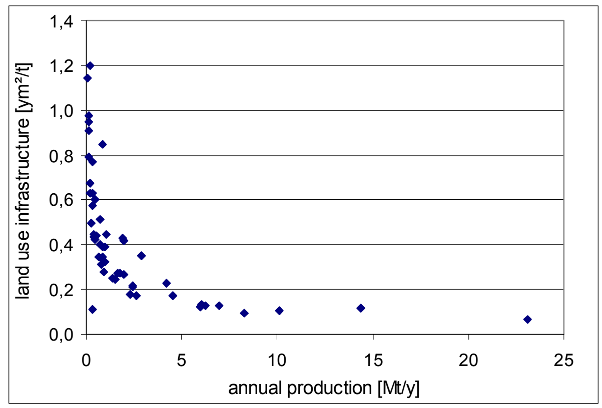

Figure 5: Specific land use by infrastructure.

In 1997, the land which is needed for mining infrastructure sums up to 1,860 ha. In this assessment the area for transportation facilities e.g. roads or railroads from pit to treatment plants or seaports could not have been considered. Therefore, the actual land use by infrastructure can be significantly higher than the values plotted in Figure 5. The figures vary between 0.1 and 1.2 y·m²/t. The correlation between land use by infrastructure and annual production is close. This depends on the calculation approach which is shown in Figure 1.

The sum of land use by mining and land use by infrastructure is the total specific land use. It has a wide span between 0.2 and 3.2 y·m²/t. The world average weighted by production is about 0.53 y·m²/t.

Soil erosion

With combining the annual soil erosion potential by water or by wind with the land use by mining it is possible to calculate the specific soil erosion per ton of extracted bauxite for all the investigated bauxite mines. Similar to the land use the specific soil erosion varies over a wide range.

The specific soil erosion potential by water in correlation to the annual production is plotted in in Figure 6. Low values vary around 0.01 kg eroded soil per ton of bauxite. Extreme values reach 140 kg/t. The average world production is about 12 kg/t.

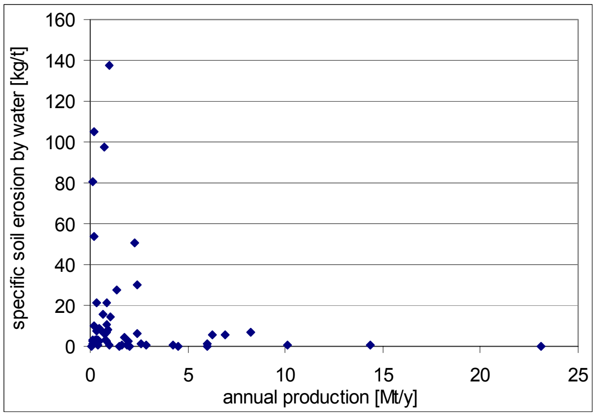

Figure 6: Specific soil erosion potential by water in relation to the annual production.

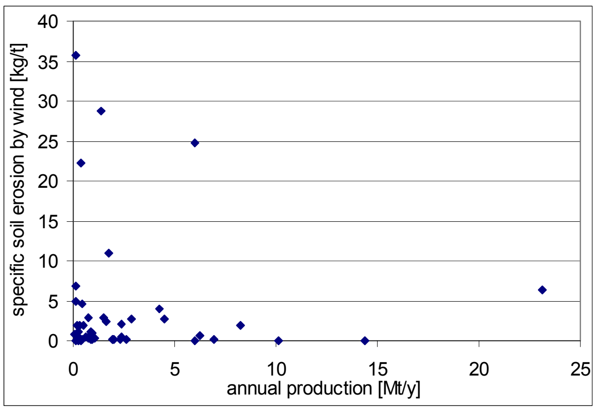

Figure 7: Specific soil erosion potential by wind in relation to the annual production.

The variation of the figures of specific soil erosion potential by wind is significantly lower than the erosion induced by water. The span lies between 0.01 and 35 kg/t Figure 7. The average for the world production is also significantly lower than the erosion by water, and is approximately 3.5 kg/t.

The correlation between erosion potential and annual production leads to similar results as the correlation between land use and annual production. In general, mine sites with a high annual production have values in the medium or low range (Figures 6 and 7). Extremely high values only appear at mine sites with a lower annual production. At these sites less advanced reclamation management in combination with adverse environmental properties can lead to serious environmental impacts in the vicinity of these sites.

Discussion

The methodical approaches for the assessment of soil erosion have originally been developed for US-conditions. For the purpose of this study some parameters of the equations have been modified in order to carry out a global assessment. Therefore, it is evident that the results of the erosion assessment have to be analyzed carefully. The interpretation of results must consider the assumed simplifications. Site-specific results from the global assessment should be understood as general potentials revealing the approximate scale at generic mine sites, and do not necessarily reflect site-specific conditions. It has to be considered that the results in fact show the average erosion potential and not apparent soil erosion which can be measured at the individual sites.

Keeping in mind these limitations on local scales, the strength of this methodology is the global assessment. Based on comparable data for almost all sites, new insights in the world wide environmental burden associated with bauxite mining will be achieved. By aggregating and averaging the site specific impact potentials by country or within the supply chain of subsequent processing plants, material flow analyses or Life Cycle Assessments can be carried out reflecting site specific conditions. In Figure 8 the most important alumina producers of the world (Australia, Jamaica, Brazil and China), and additionally the USA as well as Germany, and the world average are compared.

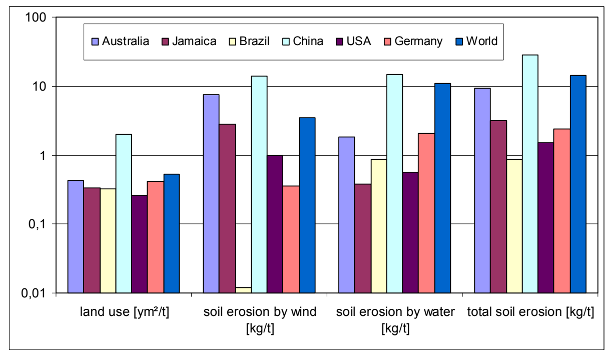

Figure 8: Comparison of selected countries.

The total land use of bauxite mining associated with the alumina production in China has the significant highest values. With 2 y·m²/t bauxite it is close to ten times higher than the corresponding land use for the USA (considering bauxite imports). The other countries have values a little smaller than the world average of 0.53 y·m²/t.

The lowest value for soil erosion by wind is related to bauxite used for alumina production in Brazil. With 0.012 kg eroded soil per ton of bauxite it is a thousand times smaller than the one for China. Despite of the advanced reclamation efforts in Australia and Jamaica the corresponding soil erosion potential by wind is relatively high due to adverse climatic conditions at some sites in these countries. Nevertheless, they are in the range of the world average of 3.5 kg/t.

The soil erosion potential by water for the world average is approximate 12 kg/t bauxite. Bauxite from China has values close to that. Mid values around 2 kg/t bauxite can be associated with Australia and Germany. Jamaica, Brazil and the USA have the lowest values.

The total soil erosion potential reaches the highest values (29 kg/t) in China. The world average is with 15 kg/t the half of this value and is followed by Australia with 10 kg/t. Brazil, the USA, and Germany show low values between 1 and 3 kg/t.

The results show the extreme variety of the specific land use and soil erosion per ton of bauxite. Due to environmental conditions and reclamation management at individual sites, erosion rates can differ significantly. Not at least due to the lack of available public data the comparison of globally assessed figures and figures measured on site is still a challenge.

At present a validation is possible only for the worldwide land requirement of bauxite mining. The International Primary Aluminum Institute (IPAI) has carried out a panel study concerning this topic. In two questionnaires in 1992 and 1999 data for land use and reclamation processes have been collected and analyzed [20][21]. The worldwide land requirement for 1997 from these two studies shows a good concordance with the results presented above. The land requirement for mining comes to 1590 ha/a (this study 1650 ha/y) whereas the land requirement for infrastructure comes to 2800 ha (this study 1860 ha). As mentioned above, the assessment for land requirement by infrastructure has not considered the demand of land for on site transportation which can reach high values. The difference between the figure of the IPAI survey and the figure presented in this paper can be explained with this fact.

In contrast to the IPAI study this investigation has considered all open pit bauxite mines worldwide and the results are available for each individual site. Due to this fact the results can be used for further investigations of the global material flow for the aluminum production as well as for scenario analyses within the CRC. Furthermore the results will be very valuable for future Life Cycle Assessments of aluminum products.

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NACHHALTIGES MANAGEMENT METALLISCHER STOFFSTRÖME -INDIKATOREN UND DEREN ANWENDUNG-*

(SUSTAINABLE MANAGEMENT OF METALLIC RAW MATERIAL FLOWS -INDICATORS AND THEIR APPLICATION-)

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ABSTRACT

Since the adoption of Agenda 21 in 1992, sustainable development is the most popular concept with regard to the future of mankind. Although the concept gains increasing recognition in science, politics and business it is still very difficult to be interpreted. Therefore, a necessary precondition when dealing with the concept is the formulation and usage of a distinguished knowledge of ecological, economic, social and institutional cohesions. The complexity and inherent conflicts between these different sustainability dimensions complicate the evaluation of different measures and decisions that could be characterised as sustainable or not. Basic understanding is somewhat different between varying actors and therefore responsibilities to implement a sustainable development path are difficult to allocate. As a matter of fact, a necessary step prior to the formulation of options for action is the selection of a consistent indicator set followed by their qualitative and quantitative application. In this context, a variety of important activities are already carried out at the international level but also at national level. Areas under investigation differ and include for example countries, regions, economic sectors, material flows as well as products. With regard to specific metallic raw material flows one can say that a necessary operationalisation is still in its infancies although some activities are already in progress.

The CRC 525 organised the workshop "Sustainable management of metallic raw material flows" in 2001. The workshop is a contribution to the significant challenge of identifying and applying sustainability criteria and indicators to metallic raw material flows. The contributions included in the proceedings depict how complex a concretisation of the concept is, when taking into account conditions and characteristics like intra- and intergenerational equity, strong and weak sustainability, stakeholder participation, management rules etc. Nevertheless, the contributions bring to light relevant sustainability indicator related considerations from different point of views and slightly different areas under investigation. All contributions are closely related to metallic raw material flows and add to a clearer but inevitably not closing assessment of how sustainable metallic raw material flows should and could be put into practice.

KEYWORDS

Sustainable development, sustainable management, operationalisation, indicators

* Source: Kuckshinrichs, W.; Hüttner K.L. (eds.): Nachhaltiges Management metallischer Stoffströme -Indikatoren und deren Anwendung-. Schriftenreihe des Forschungszentrums Jülich, Reihe Umwelt/Environment, Bd. 31, 2001

THEMATIC AND CONCEPTUAL CLASSIFICATION OF SUSTAINABILITY INDICATORS OF CRC 525*

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ABSTRACT

Products of metallic raw materials are of crucial importance to the satisfaction of human needs. Meanwhile, social, economic as well as ecological implications of mining and processing of metallic raw materials considering local, regional and global scales of impact have been taken into account only isolated from each other, if at all. Meanwhile, the discussion of the concept Sustainable Development enables a holistic consideration and evaluation of metallic raw material flows, covering both positive and negative impacts. Theoretical considerations as well as definitions of Sustainable Development are also important for metallic raw material flows. However material flow specific dimensioning and application is missing. Therefore, the following paper analyses characteristics of metallic raw material flows that are important to Sustainable Development as discussed on a theoretical level. For the operationalisation of concepts, indicators are essential. Only by means of indicators is to be identified, if and to what extent Sustainable Development is realised within metallic raw material flows. In this context the paper also analyses indicator frameworks for the systematisation of sustainability indicators and the conceptual classification of sustainability indicators for metallic raw material flows.

KEYWORDS

Sustainable development, operationalisation, indicators, indicator frameworks

* Source: Kuckshinrichs, W.; Hüttner K. L. (Hrsg.): Nachhaltiges Management metallischer Stoffströme – Indikatoren und deren Anwendung (Sustainable Management of metallic raw material flows – Indicators and their application). Proceedings SFB-Workshop, Schriftenreihe des Forschungszentrums Jülich, Reihe Umwelt, Bd. 31. S. 43-63

1 Einleitung

Das Leitbild der Nachhaltigen Entwicklung trat 1987 durch die populäre Definition der Brundtland-Kommission auf die internationale Agenda und vereint im Rio-Folgeprozess die ehemals dualistischen entwicklungspolitischen Begriffe Entwicklung und Umweltschutz.

Historische Wurzeln der durch die Brundtland-Kommission initiierten modernen Nachhaltigkeitsdiskussion reichen zurück bis zu dem vielzitierten sächsischen Berghauptmann von Carlowitz, der das Leitbild einer Nachhaltigen Forstwirtschaft geprägt hat [2]. In der sozialen und ökonomischen Dimension ist als ein Vorläufer John Stuart Mill zu nennen, der sich - unter anderen Vorzeichen – sowohl mit dem was heute als „steady-state Ökonomie“ bezeichnet wird als auch mit bürgerlicher Partizipation auseinandergesetzt hat [3, 4].

In der Phase nach der Veröffentlichung des Brundtland-Berichts stand die Suche nach stichhaltigen und prägnanten Nachhaltigkeitsdefinitionen im Vordergrund. Mit Stand 1992 wies Pezzey mehr als dreißig in der Literatur diskutierte Definitionen nach [5]. Bei den meisten der Vielzahl von Definitionsansätzen wird die Mehrdimensionalität des Leitbildes implizit anerkannt. Nichtsdestotrotz spiegelt sich in der Definitionsvielzahl auch der jeweilige fachliche Hintergrund der Wissenschaftler wider. Die Gewichtung der Dimensionen zueinander (Drei-Säulen versus Ein-Säulen Konzept) ist unterschiedlich und vielfach ebenfalls Ausdruck fachlicher und fachwissenschaftlicher Präferenzen der jeweiligen Wissenschaftler.

Auch aufgrund der expliziten Forderung in Kapitel 40 der Agenda 21 fokussieren sich die Bemühungen in der zweiten Hälfte der 90er Jahre schwerpunktmäßig auf die Konstruktion von Nachhaltigkeitsindikatoren und –systemen. Diese sind bis dato weitgehend für politisch-administrative Untersuchungsebenen, insbesondere für Staaten und Kommunen, aufgestellt worden [6]. Auf sektoraler Ebene bemüht sich die Organisation for Economic Co-Operation and Development (OECD) um die Inte-gration von Umweltaspekten in einzelne Politikfelder [7-9]. Bei der Bewertung eines Stoffstroms unter Nachhaltigkeitsaspekten fokussieren sich die Aktivitäten bisher primär auf die Abbildung von Einzelindikatoren der ökologischen Nachhaltigkeitsdimension wie etwa der Materialintensität pro Serviceeinheit (MIPS) [10] und des Ecological Footprint (EF) [11] oder auf die primäre Diskussion der ökologischen Dimension im Rahmen von Life Cycle Assessments (LCAs) zu Produkten. Im folgenden Beitrag werden demgegenüber dimensionsübergreifende Anforderungen, die an den Stoffstrom metallischer Rohstoffe zu stellen sind und die die inhaltliche Grund-lage für Nachhaltigkeitsindikatoren bilden, erörtert. Anschließend werden die die Umweltindikatoren und Nachhaltigkeitsindikatorberichterstattung dominierenden Sy-stematisierungsoptionen analysiert. Hierauf basierend werden Indikatorentypen und die Systematisierung von Nachhaltigkeitsindikatoren des Stoffstroms metallischer Rohstoffe diskutiert. Letztere Ausführungen basieren auf den Arbeiten zu Aluminium, können aufgrund der allgemeinen Vorgehensweise jedoch auf andere mineralische und metallische Rohstoffe angepasst werden.

2 Nachhaltige Entwicklung im Kontext des Stoffstroms metallischer Rohstoffe

Der Begriff Nachhaltigkeit bezieht sich primär auf die Aufrechterhaltung eines Status quo. Hingegen ebnet das Begriffspaar Nachhaltige Entwicklung unter Berücksichtigung dimensionsübergreifender Kriterien den Weg für eine Veränderung. Diese Veränderung muss hierbei eine Verbesserung im Vergleich zu einer Referenz-entwicklung darstellen. Aus dieser Überlegung heraus, kann im konkreten Fall auch der Stoffstrom metallischer Rohstoffe im Sinne einer "Sensible Sustainability“ grundsätzlich als kompatibel mit dem Leitbild Nachhaltige Entwicklung angesehen werden. Im Umkehrschluss bedeutet dies, dass der Stoffstrom metallischer Rohstoffe nicht a priori als nicht-nachhaltig zu beurteilen ist. „Sensible Sustainability“ bedeutet, dass das gesellschaftliche Produktivkapital als Summe aller Elemente natürlichen und menschlichen Ursprungs nicht verringert werden darf, wobei auch der Zusammensetzung des Kapitalstocks zugunsten des Naturkapitals Bedeutung zukommt [12]. Wenn die grundsätzliche Frage nach der Vereinbarkeit des Stoffstroms metallischer Rohstoffe mit dem Leitbild Nachhaltiger Entwicklung positiv beantwortet wird, bleibt als zentrale Frage, welche Charakteristika er aufweisen muss, um die grundsätzlich zugrundegelegte Kompatibilität dauerhaft zu gewährleisten. Eine Definition wie etwa die vielzitierte Brundtland-Definition „development that meets the needs of the present without compromising the ability of the future generations to meet their own needs“ [13] hilft in diesem Zusammenhang aufgrund ihrer mehrdeutigen Interpretationsmöglichkeiten nicht viel weiter. Andererseits sind aufgrund der Tatsache, dass Veränderungen in einem mehrdimensionalen Nachhaltigkeitsverständnis inhärent sind, zu eng an einem Status quo orientierte Charakteristika ebenfalls nicht adäquat. Grundsätzlich ist die Frage daher damit zu beantworten, dass innerhalb des Stoffstroms die Triade ökologische Integrität, ökonomische Stabilität sowie intra- und intergenerationell soziale Gerechtigkeit sicherzustellen ist.

Abbildung 1: Allgemeine Ziele einer dimensionsübergreifenden Nachhaltigen Entwicklung

Da intragenerationelle Gerechtigkeit oft mit intergenerationeller Gerechtigkeit einhergeht, und globale Metallstoffströme auch im Zusammenhang der Nord-Süd-Diskussion zu sehen sind, liegt ein Betrachtungsschwerpunkt zunächst auf der intragenerationellen Gerechtigkeit.

2.1 Ökologische Dimension

Um ökologische Integrität zu gewährleisten, müssen auch vom Stoffstrom me-tallischer Rohstoffe die Managementregeln der Nachhaltigkeit befolgt werden. Diese werden aufgrund ihrer fehlenden Operationalisierung zwar kritisiert, sind gleichzeitig aber allgemein ebenso als zentral anerkannt [14]. Die Verbindlichkeit der Regeln differiert im Hinblick auf eine Stoffstrombetrachtung mit dem geografischen Horizont. Die Regel, die Abgabe von Emissionen dürfe nur bis zur Regenerationsfähigkeit der Senke erfolgen, ist für Wirkungsmechanismen auf lokaler, regionaler und globaler Ebene eigenständig zu verfolgen. Aufgrund prognostizierter Zuwächse der Metallnachfrage ist davon auszugehen, dass sukzessive Lagerstätten mit geringeren Erz- und Mineralqualitäten abgebaut werden, wodurch die spezifischen Umweltbelastungen durch die Erzgewinnung und die Weiterverarbeitung zunehmen. Im Gegensatz zu fossilen Brennstoffen stellt sich für metallische Rohstoffe - nicht zuletzt aufgrund der Möglichkeit des Recycling - trotz der wechselseitigen Abhängigkeit relativ das Problem einer möglicherweise abnehmen Senkenkapazität stärker als das Problem der Quellenkapazität. Die Regel, der Abbau nicht-erneuerbarer Ressourcen solle nur in dem Umfang erfolgen, in dem ein physisch und funktionell gleichwertiger Ersatz in Form einer erneuerbaren Ressource oder höherer Produktivität der erneuerbaren sowie der nicht-erneuerbaren Ressourcen geschaffen werde, ist grundsätzlich lediglich im globalen Maßstab zu befolgen. An einzelnen Standorten kann und wird es zur Erschöpfung von nicht-erneuerbaren Ressourcen kommen, die bei der gegenwärtigen Konfiguration metallischer Produktionssysteme als Input dienen. Im globalen Rahmen kann allerdings davon ausgegangen werden, dass entweder geeignete Substitute Verwendung finden oder alternative Produktionsverfahren und Techniken angewandt werden. Analoge Schlussfolgerungen gelten für die Managementregel zu erneuerbaren Ressourcen, die im Produktionsprozess eingesetzt werden. Folglich darf es hier nicht zu einer Übernutzung kommen, welche die Regenerationsfähigkeit gefährdet. Ebenso sind Rückkopplungseffekte zur sozialen und ökonomischen Nachhaltigkeitsdimension zu berücksichtigen.

Aufgrund unterschiedlicher Umweltbedingungen, aufgrund der Komplexität von Wirkungsmechanismen und aufgrund fehlender Kenntnisse über die Entwicklung der natürlichen Selbstheilungskräfte ist insgesamt nur von einem sehr begrenzten Wissen hinsichtlich emissionsbedingter Schadensakkumulationen und Hot-Spots, die aus Stoffstromaktivitäten resultieren können, auszugehen. Aus Gründen der inter- und intragenerativen Gerechtigkeit heraus kommt dem umweltpolitischen Vorsorgeprinzip innerhalb des Stoffstroms eine zentrale Rolle zu. Ökologische Integrität wird unter diesem Blickwinkel grundsätzlich durch die Reduktion von Umweltbeeinträchtigungen erreicht. Das Reduktionsziel erstreckt sich über den gesamten Stoffstrom metallischer Rohstoffe und umfasst alle tangierten Schutzgüter der Umweltmedien Boden, Luft und Wasser. Dieses beginnt damit, dass die Eingriffe in terrestrische Ökosysteme durch Bergbau und industriell determinierte Naturraumnutzung reduziert werden und eine Renaturierung von gebrauchtem Areal vorgenommen wird beziehungsweise dort, wo dieses aus sozialen oder ökonomischen Erwägungen heraus nicht durchführbar ist, eine Integration in die umgebende Landnutzung (Rekultivierung soweit diese als umwelt- und sozialverträglich anzusehen ist) vorgenommen wird. Hinzu treten insbesondere die Reduktion von qualitativen und quantitativen Beeinträchtigungen aquatischer Systeme und die Reduktion von Luftschadstoff- sowie Treibhausgasemissionen. Bei der Verfolgung dieser allgemeinen Ziele ist allerdings zu berücksichtigen, dass isolierte Vermeidungsstrategien in der Regel aufgrund intra- und interdimensionaler Wechselwirkungen zu einem suboptimalen Gesamtergebnis führen, weil gegenseitige adverse Effekte nicht berücksichtigt werden. Aus diesem Grund sind keine absoluten Vermeidungsstrategien einzuschlagen, sondern immer die Rückkopp-lungseffekte auf benachbarte Schutzgüter und Nachhaltigkeitsbereiche zu beachten. Aufgrund des mehrdimensionalen Charakters von Nachhaltiger Entwicklung und der integrativen Berücksichtigung ökonomischer und sozialer Aspekte ist die Reduktion von Umweltbeeinträchtigungen somit zwar von zentraler aber nicht exklusiver Relevanz. Vielmehr ist auch in Abhängigkeit des potenziellen Umweltschadens und der Eintrittshäufigkeit des Schadensereignisses die entsprechende Schadensvorsorge zu betreiben.[1] Nichtsdestotrotz kann die Verpflichtung zum Erhalt der Umwelt beispielsweise dazu führen, dass abbauwürdige Erz- und Mineralvorkommen nicht abgebaut werden, weil aus Gründen des Naturschutzes ein Abbau absolut fragwürdig erscheint [15].

2.2 Ökonomische Dimension

Die ökonomische Dimension des Stoffstroms ist durch eine einzelwirtschaftliche und gesamtwirtschaftliche Perspektive gekennzeichnet. Auf der einzelwirtschaftlichen Ebene geht es um die Zukunftsfähigkeit des Stoffstroms in seiner gegenwärtigen Konfiguration. In diesem Sinne sind als wesentliche Elemente einzelwirtschaftlicher Nachhaltigkeit die Wahrung und Steigerung der Wettbewerbsfähigkeit der in me-tallischen Stoffströmen engagierten Unternehmen und die langfristige Sicherung von Produktionsaktivitäten zu identifizieren. Letzteres bezieht sich insbesondere auf die derzeitige Konfiguration der Produktsysteme im Sinne der Verfügbarkeit von Produktionsfaktoren. Wie angedeutet handelt es sich hierbei zunächst um eine einzelwirtschaftliche Argumentation. Im internationalen Kontext ist eine Verlagerung von Standortaktivitäten möglich und gegebenenfalls sowohl einzel- als auch gesamtwirtschaftlich sinnvoll.

Nichtsdestotrotz ist die Berücksichtigung einer einzelwirtschaftlichen, standortbezogenen Ebene unabdingbar, weil die Aufgabe von Standorten zu weitgehenden sozialen und ökonomischen Auswirkungen auf lokaler und regionaler Ebene führen kann. Ein Engagement des Stoffstroms dergestalt, dass mit dem Ende der Aktivitäten die wirtschaftlichen Aktivitäten an dem Standort im Sinne einer „Geisterstadt-Kultur“ abstirbt, ist mit einer Nachhaltigen Entwicklung des Stoffstroms nicht kompatibel. Mit Blick auf nachfolgende Aktivitäten ist hier zuerst erfolgreiche Strukturpolitik gefragt. Auf gesamtwirtschaftlicher Ebene ist es in Abhängigkeit der Bedeutung des jeweiligen metallischen Stoffstroms für die Volkswirtschaft, in der er agiert, von zentralem Belang, dass eine stabile Entwicklung der Stoffstromaktivitäten gewährleistet wird. Wiederum ist zu beachten, dass aufgrund des auf Veränderung ausgerichteten Nachhaltigkeitsverständnisses kein Strukturkonservatismus propagiert wird. Die standortbezogene Verlagerung von Stoffstromaktivitäten muss erfolgen, wenn me-tallische Stoffströme ökonomisch zukunftsfähig agieren sollen und erfolgt de facto, weil sich die Erz- und Mineralvor-

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[1] Bezogen auf das deutsche Technikrecht bedeutet dies, dass je nach Schadensrisiko Schadensvorsorge nach Stand der Technik, Stand von Wissenschaft und Technik oder Stand der Wissenschaft betrieben werden muss. Eine derartige Schadensvorsorge ist weitestgehend kompatibel mit dem Gedanken des Safe Minimum Standards, nach dem alles unterbleiben muss, was nicht „nachweislich“ unschädlich ist.

kommen einzelner Standorte erschöpfen oder Kostenfaktoren zu Standortverlagerungen führen. Nichts desto Trotz müssen analog zur betriebswirtschaftlichen auch auf volkswirtschaftlicher Ebene Veränderungen der Stoffstromaktivitäten grundsätzlich moderat und vorausschauend erfolgen. Vorausschauung ist hierbei ein zentrales Moment, welches einschneidende kurzfristige ökonomische Anpassungserfordernisse mit negativen sozialen und ökologischen Folgen auf regionaler und nationaler Ebene vermeidet. Ein weiterer Aspekt der ökono-mischen Nachhaltigkeit des Stoffstroms ist die Internalisierung externer Kosten und Nutzen, die zu einer ökonomisch effizienten und sozial und ökologisch verträglichen Allokation von Ressourcen führt. Der Internalisierungsaspekt ist als Komplement des gesamten Stoffstroms anzusehen und dient dazu, die sozialen Kosten und Nutzen der Metallproduktion, -nutzung und -entsorgung vollständig zu erfassen. Auf verschiedenen Ebenen nationaler, regionaler und internationaler Politik ist nicht zuletzt auch den Themenbereichen Sicherung des Wettbewerbs und Abbau von Marktverzerrungen Rechnung zu tragen. Es gilt hier der Tatsache Rechnung zu tragen, dass Marktverzerrungen zu einer suboptimalen globalen Allokation führen können.

Aufgrund der Eigenschaft des Preises als Richtgröße für betriebswirtschaftliche Entscheidungen und als gesamtwirtschaftliches Steuerungsinstrument zur Abstimmung von Produktion und Nachfrage ist eine stabile Preisentwicklung ein zentrales Moment eines nachhaltigen Stoffstroms. Die Preisentwicklung von Produktionsfaktoren wird durch zahlreiche Determinanten bestimmt, die nicht zwingend auf den Stoffstrom zurückzuführen sind. Da Standortentscheidungen in der Regel mittelfristig angelegt sind, sind kurzfristige Anpassungsaktivitäten auf exogene Preissignale nur bedingt möglich. Im Hinblick auf eine risikominimierende Investitionspolitik trägt eine stetige Preisentwicklung bei Metallen und den eingesetzten Produktionsfaktoren dazu bei, ökonomisch rationale und gleichzeitig ökologisch und sozial verträgliche Investitionsentscheidungen zu treffen.

Implizit ist eine stetige Preisentwicklung auch Voraussetzung dafür, dass eine durch Externalisierung von Kosten, das heißt zu Lasten von Umweltschutz und unter-privilegierten Stakeholdern, erworbene Wettbewerbsfähigkeit, deren Notwendigkeit mit auf dem Weltmarkt geltenden Marktbedingungen begründet wird, die Legitimation entzogen wird. Nicht zuletzt ist eine stetige Preisentwicklung notwendig, damit die Betreiber von Anlagen im nationalen Kontext auf umweltpolitische Maßnahmen reagieren können, ohne im Hinblick auf internationale Wettbewerbsfähigkeit dazu gezwungen zu sein, eine Verbesserung der Umweltperformance über Gebühr auf Kosten ökonomischer und sozialer Trägerfunktionen zu kompensieren. Im Hinblick auf Nachhaltige Entwicklung ist ebenfalls die ressourcenökonomische Perspektive des Stoffstroms metallischer Rohstoffe zu berücksichtigen. Bei der Herstellung von Metallen werden sowohl nicht-erneuerbare als auch erneuerbare Ressourcen eingesetzt. Im Sinne der Einhaltung der Managementregeln decken sich die Anforderungen, die aus Nachhaltigkeitsaspekten an metallische Stoffströme zu stellen sind, mit der zur Wahrung der ökologischen Integrität genannten Managementregeln. Innerhalb der ökonomischen Dimension ist mit dem Preis das Instrument angesiedelt, durch das die Anforderungen der Managementregeln sowie die Forderung nach der Internalisierung von externen Kosten grundsätzlich in die Tat umgesetzt werden können. Durch den Marktpreis reflektiert sich idealerweise die relative Knappheit des Gutes, bzw. der im Stoffstrom metallischer Rohstoffe eingesetzten Produkte.

2.3 Soziale Dimension

In der sozialen Dimension des Stoffstroms metallischer Rohstoffe ist im Sinne sozialer Gerechtigkeit von einer innerbetrieblichen und überbetrieblichen Nachhaltigkeitskomponente auszugehen. Subjekte der innerbetrieblichen Komponente sind die Angestellten und Arbeiter innerhalb des Stoffstroms. Folglich geht es um die Wahrnehmung der Verantwortung der im Stoffstrom tätigen Unternehmen für deren Angestellte und Arbeiter. Diese Verantwortung umfasst im Sinne der Einhaltung sozialer Standards zunächst die Einhaltung allgemeiner Arbeits(schutz)gesetze sowie Gesetze zum Gesundheitsschutz und zur Arbeitssicherheit. Hierbei handelt es sich in der Regel um nationale Rechtsnormen, die allerdings vielfach auf internationale Anstöße zurückgehen, wie etwa die Konventionen der Internationalen Arbeitsorganisation (ILO). Die Einhaltung gesetzlicher Normen - deren Existenz vorausgesetzt - ist zwar eine notwendige, aber keine hinreichende Bedingung zur Realisierung innerbetrieblicher sozialer Nachhaltigkeit. Aufgrund des Umstands, dass die materiellen Anforderungen der gesetzlichen

Vorschriften über den gesamten Stoffstrom variieren, ist die Einhaltung national begründeter sozialer Standards lediglich als Mindestregel für soziale Nachhaltigkeit anzusehen. Insbesondere, wenn man einbezieht, dass die Gesetzesvorschriften primär der direkten Gefahrenabwehr dienen und keine inter-nationalen Sanktionsmechanismen für den Fall existieren, dass ILO-Konventionen, die als materielle Mindestnormen angesehen werden können, nicht ratifiziert werden.

Hinzu treten vielmehr Anforderungen, die aus rechtlicher Sicht nur fakultativer Natur sind, wie etwa berufliche Fortbildungsmaßnahmen, Lohnfortzahlungen im Krank-heitsfall und Maßnahmen zur Unfallverhütung in Betriebsbereichen mit erhöhtem Gefahrenpotenzial. Neben diesen objektiven Aspekten ist die subjektive Wahrnehmung der Arbeitsplatzbedingungen aus Sicht der Angestellten von Nachhaltigkeitsrelevanz. Eine derartige Überlegung nimmt den aus der Lebensqualitätsdiskussion der siebziger Jahre stammenden Ansatz auf, dass sich Lebensstandard nicht ausschließlich über die materielle Versorgung von Gütern definiert, sondern auch die subjektive Wahrnehmung der Lebenssituation umfasst, und überträgt ihn auf den Arbeitsplatz. Nur bei unzureichenden Bedingungen außerhalb des direkten Tätigkeitsfeldes, sei es aufgrund fehlender staatlicher Infrastruktur oder sozialpolitischer Fehlentwicklungen, sowie entsprechender Dominanz des Stoffstroms im jeweiligen Umfeld erweitert sich die Verantwortung des Stoffstroms metallischer Rohstoffe exklusiv oder anteilig mit anderen Stoffströmen ausnahmsweise auf die außerbetrieblichen Lebensbedingungen des Arbeitnehmers (und der Nachbarschaft), wobei die Unternehmen allerdings nicht in der Pflicht stehen, staatliche Unzulänglichkeiten ausnahmslos zu kompensieren.

Die überbetriebliche Komponente sozialer Nachhaltigkeit befasst sich mit den Auswirkungen des Stoffstroms metallischer Rohstoffe auf dessen Anspruchsgruppen unter besonderer Berücksichtigung der Nachbarschaft von Anlagen und hinterfragt, wie diese Auswirkungen materiell und formell zu behandeln sind. Aus formeller Sicht fordert soziale Nachhaltigkeit im Sinne von Partizipation zunächst die Einbeziehung aller Stakeholderinteressen. Diese erfolgt in erster Linie durch die entsprechende Öffentlichkeitsbeteiligung beim Bau, der wesentlichen Änderung und der Stillegung von Anlagen sowie durch sowohl inner- als auch überbetriebliche Konsultationen und diskursive Verfahren bei wichtigen Entscheidungen. Die Kenntnisnahme und Berücksichtigung der Interessen der von Stoffstromaktivitäten tangierten Akteure ist von zentraler Bedeutung, um die Identifizierung sozialer Kosten und Nutzen zu gewährleisten und eine verursachergerechte Verteilung zu realisieren. Soziale Nachhaltigkeit verlangt hierbei materiell, dass der Saldo positiver und negativer Einwirkungen maximiert wird. Die Sozialpflichtigkeit von Eigentum kann hierbei dazu führen, dass die Bewahrung individueller Schutzgüter zugunsten übergeordneter Interessen der Gesellschaft zurückstehen muss. In den Fällen, in denen Beeinträchtigungen unvermeidbar sind, müssen jedoch adäquate Kompensationsmechanismen vorgehalten werden. Solange Kompensationsmaßnahmen die legitimen Rechte und Schutzinteressen betroffener Bürger - etwa Gesundheitsschutz oder Gefährdung der Existenz - unzureichend berücksichtigen, sind auch bei Vorliegen übergeordneter gesellschaftlicher Interessen Aktivitäten des Stoffstroms metallischer Rohstoffe aus Nachhaltigkeitsüberlegungen heraus nicht legitimiert. Im Umkehrschluss heißt dieses, dass der Stoffstrom, soweit er seiner sozialen Verantwortung durch adäquate monetäre und nicht-monetäre Präventions- und Kompensationsmaßnahmen gerecht wird, nicht für negativ interpretierte soziale Entwicklungen und Verwerfungen verantwortlich zu machen ist. Eine diskriminierungsfreie, gleichberechtigte und kontinuierliche Beteiligung und Berücksichtigung von Stakeholdern beim Bau, der wesentlichen Änderung und der Stilllegung von Anlagen stellt für den Stoffstrom eine weitgehende Legitimation seiner Aktivitäten dar und verhindert Schuldzuweisungen für als fehlerhaft geltende Entwicklungen im Umfeld des Stoffstroms. Andererseits kann das Resultat einer gleichberechtigten Partizipation auch sein, dass aus übergeordneten kulturellen Gründen, etwa um Beeinträchtigungen angrenzender Gemeinschaften zu vermeiden, beispielsweise der Abbau von Erzen oder deren Weiterverarbeitung an einem bestimmten Standort nicht bis zum ökonomischen Optimum betrieben wird.

2.4 Politisch-Institutionelle Dimension

Die institutionelle Dimension ist bisher in der Nachhaltigkeitsdiskussion in noch stärkerem Maße als die soziale Dimension vernachlässigt worden. Institutionen sind in der Nachhaltigkeitsdiskussion in einem politikwissenschaftlichen Kontext zu interpretieren. Sie decken hier als „polity“ die institutionelle

Dimension von Politik ab, die ferner eine inhaltliche Dimension („policy“) und eine prozessuale Dimension („politics“) besitzt [16]. Die Verankerung der institutionellen Dimension in der Nachhaltigkeitsdebatte ist auf die Erkenntnis zurückzuführen, dass durch und in Institutionen die Entscheidungen kanalisiert und getroffen werden, die sich auf die soziale, ökonomische und ökologische Nachhaltigkeitsdimension auswirken und letztlich die Merkmalsausprägungen dieser Dimensionen determinieren. Bei der politisch-instutionellen Dimension handelt es sich – auch im Hinblick auf den Stoffstrom metallischer Rohstoffe - um eine Querschnittsdimension der Nachhaltigen Entwicklung. Es liegt zu einem wesentlichen Teil in den Strukturen von Institutionen begründet, ob suboptimale dimensionsorientierte Entscheidungen oder aus einer dimensionsübergreifenden Betrachtung heraus optimale Entscheidungen getroffen werden. Somit werden auch innerhalb der institutionellen Dimension des Stoffstroms metallischer Rohstoffe die Entscheidungen getroffen, die die Merkmalsausprägungen des Stoffstroms in der ökologischen, ökonomischen und sozialen Dimension determinieren. Aus diesem Grund ist bei den zivilgesellschaftlichen und politischen Akteuren sicherzustellen, dass sie das Leitbild Nachhaltige Entwicklung als wichtiges Ziel ansehen und gleichzeitig durch formale und materielle Anpassungen sicherstellen, dass das Leitbild Nachhaltige Entwicklung bei stoffstromrelevanten Entscheidungen Berücksichtigung findet. Beispiele hierfür sind etwa die Einsetzung von Nachhaltigkeitsbeauftragten, oder die legislative Verankerung einer vorgeschriebenen Sozialverträglichkeitsprüfung für geplante Stoffstromaktivitäten an einzelnen Standorten.

3 Operationalisierung des Leitbildes Nachhaltige Entwicklung

3.1 Nachhaltigkeitsindikatoren

Zur Messung und Bewertung von Untersuchungsgegenständen auf repräsentative Eigenschaften hin werden in allen gesellschaftlichen Subsystemen Indikatoren verwendet. Auch für die Nachhaltigkeitsdiskussion bilden Indikatoren ein notwendiges Werkzeug, um Aussagen zu treffen, ob der mit dem Leitbild bezeichnete Sachverhalt in der Realität existiert, oder ob auf eine Annäherung geschlossen werden kann. Nachhaltigkeitsindikatoren dienen explizit der Operationalisierung des Leitbildes Nachhaltige Entwicklung etwa im Sinne der Brundtland-Kommission, der in Rio de Janeiro verabschiedeten Agenda 21 oder einer alternativen Nachhaltigkeitsdefinition. Im Gegensatz zu traditionellen ökologischen, sozialen und ökonomischen Indikatoren beschränken sich Nachhaltigkeitsindikatoren nicht auf die Abbildung repräsentativer Größen lediglich eines Teilsystems sondern sind bei Anerkennung der Multidimen-sionalität des Leitbildes Teil einer dimensionsübergreifenden Betrachtung [17]. Durch Nachhaltigkeitsindikatoren werden Daten, die in den einzelnen Dimensionen für eine Nachhaltigkeitsbetrachtung vorliegen und von Bedeutung sein können, im Kontext des jeweiligen Untersuchungsgegenstandes komprimiert und auf kommunikationsfähige Ebenen transformiert. Auf diesen Ebenen können schließlich Entscheidungen getroffen werden, die die Merkmalsausprägung der Nachhaltigkeitsindikatoren im Hinblick auf den bezeichneten Sachverhalt und die aufgestellten Ziele verbessern. Die Systematisierung von Nachhaltigkeitsindikatoren ist immer dann notwendig, wenn über die Abbildung und Modellierung von Einzelindikatoren hinausgegangen wird. Im wesentlichen setzen sich bei Konzepten zur Systematisierung von Nachhaltigkeitsindikatoren thematische Systematisierungen sowie Indikatorenkonzepte durch.

3.2 Thematische Systematisierung

Die Gruppierung von Indikatoren gemäß ihrer thematischen Zugehörigkeit zu den Dimensionen stellt das dominierende Konzept zur Systematisierung von Nachhaltigkeitsindikatoren dar [6]. Je nach Detaillierungsgrad wird innerhalb der Dimensionen eine unterschiedliche Anzahl von Themenbereichen untergliedert. Diese ist ebenso wie die Auswahl der Indikatoren von dem betrachteten Untersuchungsgegenstand und der Untersuchungsebene abhängig. Um Aussagen darüber zu treffen, ob und inwieweit die durch einen Indikator repräsentierte Merkmalsausprägung auf Kompatibilität mit nachhaltiger Entwicklung schließen lässt, ist die Kopplung der Nachhaltigkeitsindikatoren an qualitative Ziele oder quantitative Grenz- bzw. Schwellenwerte zweckmäßig.

In diesem Zusammenhang bilden die zugehörigen Indikatoren sogenannte Distance-to-target-Indikatoren, die hinsichtlich der jeweiligen Merkmalsausprägung die Differenz zwischen Ist- und Soll-Werten abbilden. Ein Beispiel für eine thematische Sy-stematisierung gibt Tabelle 1.

Tabelle 1: Beispiel für thematische Systematisierung von Nachhaltigkeitsindikatoren

Thema	Ziel	Indikatoren
Schutz der Erdatmosphäre	Reduktion von Treibhausgas-emissionen ...	CO_2-Emissionen pro Tonne Systemoutput Jährliche Energieeffizienz-verbesserungen ...

Als Kritikpunkt an der thematischen Systematisierung gilt, dass sie nicht auf einem kohärenten Indikatorkonzept beruhe, sondern sich aus einer Sammlung voneinander isolierter Indikatoren zusammensetzt, der die methodische Zuordnung der einzelnen Indikatoren innerhalb des abgebildeten Themenbereiches im Sinne von Ursachen, Wirkungen und Antworten fehle. Allerdings ist dieses Defizit weitgehend durch die bisherige Konstruktion und Verwendung einzelner Indikatoren bestimmt, die partiell unreflektiert aus der traditionellen Indikatorberichterstattung in Nachhaltigkeitsindikatorenlisten übernommen werden. Eine konsistente Auswahl und Konstruktion von Nachhaltigkeitsindikatoren mindert diesen Mangel. Hinzu kommt, dass eine ausschließlich thematische Systematisierung losgelöst von methodischen Zuordnungskonzepten einzelner Indikatoren einen Freiheitsgrad besitzt, der im Hinblick auf eine methodisch und inhaltlich konsistente Konstruktion von Nachhaltigkeitsindikatoren, beispielsweise zur Konstruktion von Interlinkage-Indikatoren, genutzt werden kann.[2]

3.3 Indikatorenkonzepte

Indikatorenkonzepte haben das Ziel, zusätzlich zu einer themenorientierten Zuordnung zwischen einzelnen Nachhaltigkeitsindikatoren einen kohärenten Zusammenhang zu konstruieren oder den empirisch wahrgenommenen Zusammenhang zu rekonstruieren. Als Konzepte zur Systematisierung von Nachhaltigkeitsindikatoren dominieren das von der OECD entwickelte Pressure-State-Response-Konzept (PSR-Konzept) sowie das von der Commission on Sustainable Development (CSD) auf Basis des PSR-Konzepts entwickelte Driving Force-State-Response-Konzept (DFSR-Konzept).

Das PSR-Konzept unterscheidet drei Indikatortypen. Belastungsindikatoren (Pressures) zeigen die von menschlichen Aktivitäten auf die Umweltqualität und den Bestand natürlicher Ressourcen ausgehende Umweltbelastung an, etwa durch Emissionsdaten und Abbauraten von Rohstoffen. Zustandsindikatoren (States) beschreiben die Umweltqualität und den Ressourcenbestand, beispielsweise in Form von Immissionsdaten und Reichweitenzahlen. Antwortindikatoren (Responses) erfassen gesellschaftliche Reaktionen auf die von der Gesellschaft als unbefriedigend interpretierte Umweltqualität und den Ressourcenbestand, in der Regel in Form von Maßnahmen zur Vermeidung und Verminderung von Umweltbelastungen oder der Erhöhung der Ressourceneffizienz [18]. Ein Beispiel einer entsprechenden Systematisierung nach dem PSR-Konzept gibt Tabelle 2.

Das PSR-Konzept wird bei Umweltproblemen angewandt, bei denen ein Wirkungszusammenhang zwischen Aktivitäten von einzelnen Wirtschaftssubjekten oder allgemeiner gesellschaftlichen Teil- oder Gesamtsystemen mit der Umwelt besteht und der aus dem Wirkungszusammenhang resultierende Zustand der Umwelt von der Gesellschaft als Umweltproblem wahrgenommen wird [17]. Abhängig ist die Anwendbarkeit schließlich auch davon, ob eine Verbesserung des Umweltzustands durch die Durchführung legislativer, technischer oder organisatorischer Maßnahmen absehbar ist. Insofern sind klare Querverbindungen zum Policy-Zyklus zu erkennen, wie er in der Politikwissenschaft diskutiert wird. Die Kritik an dem PSR-Konzept entzündet sich an der durch die Wirkungskette abgebildeten

[2] Interlinkage-Indikatoren sind Indikatoren, die die einzelnen Dimensionen der Nachhaltigen Entwicklung miteinander verknüpfen (horizontale Interlinkage-Indikatoren) oder intra- oder extradimensional unterschiedliche Wirkungsebenen miteinander verknüpfen (vertikale Interlinkage-Indikatoren).

Monokausalität, die bei der Betrachtung eines komplexen Systems von Interaktionen und positiven und negativen Interdependenzen zwischen Gesellschaft und Umwelt nicht adäquat erscheint [17]. Ungeachtet dieses Kritikpunkts ist im Hinblick auf das Leitbild Nachhaltige Entwicklung anzumerken, dass das PSR-Konzept ausschließlich die ökologische und zum Teil ökonomische Dimension umfasst. Für eine umfassende Nachhaltigkeitsbetrachtung unter zusätzlicher Einbeziehung sozialer und institutioneller Aspekte ist das Indikatorkonzept wesentlich weniger gut geeignet [17]. Eine konsistente Zuordnung einzelner Indikatoren aller Dimensionen zu den drei Indikatorklassen ist nicht möglich. Dieses ist letztlich darauf zurückzuführen, dass dem Begriff Pressures negative Implikationen in Form von Umweltbelastungen zugeschrieben werden und Responses entsprechend Maßnahmen zur Reduzierung der Belastungen und Verbesserung des Umweltzustandes abbilden. Bei einer dimensionsübergreifenden Nachhaltigkeitsbetrachtung können und sind Pressures in der ökologischen Dimension gleichzeitig mit Benefits für die ökonomische und soziale Dimension verbunden, was mit dem PSR-Konzept jedoch nicht abgebildet werden kann. Analoge Schlussfolgerungen gelten für die Indikatorenkonzepte, die das PSR-Konzept weiter ausdifferenzieren und in noch stärkerem Maße für die Umweltberichterstattung präzisiert haben. Im einzelnen handelt es sich hierbei um das Pressure-State-Impact-Response-Konzept sowie das Driving Force-Pressure–State–Impact–Response-Konzept [19, 20].

Tabelle 2: Beispiel zur Systematisierung von Umweltindikatoren nach dem PSR-Konzept

Thema	Pressure	State	Response
Schutz der Erdatmosphäre	Treibhausgasemissionen ...	Treibhausgaskonzentration der Atmosphäre ...	Erhöhung der Energieeffizienz Verbesserung von Prozesstechnologien ...
Bekämpfung der Entwaldung	Holzernteintensität ...	Entwicklung des Waldbestandes ...	Anzahl verabschiedeter und implementierter Forstwirtschaftspläne ...

Als Konsequenz hat die CSD bei der Aufstellung ihres Nachhaltigkeitsindikatorenkatalogs das PSR-Konzept in ein DFSR-Konzept transformiert. In Abwandlung der Pressures stellen Driving Forces (Triebkräfte) menschliche Aktivitäten, Vorgänge und Verhaltensweisen dar, die Auswirkungen auf den State (Zustand) haben. Die zugehörigen Indikatoren sollen Anhaltspunkte und Verweise auf die Ursachen positiver und/oder negativer Veränderungen im Hinblick auf den Status der Nachhaltigen Entwicklung geben [21]. Tabelle 3 gibt Beispiele zur dimensionsübergreifenden Verwendung des DFSR-Konzeptes.

Durch die Transformation erhofft sich die CSD eine verbesserte Anwendung für dimensionsübergreifende Betrachtungen. Eine horizontale Verknüpfung von Driving Force-, State- und Response-Indikatoren im Rahmen der Abbildung eines Kausalitätsstrangs kann grundsätzlich konstruiert werden. Gerade bei einer dimensionsübergreifenden Nachhaltigkeitsbetrachtung führt die Abbildung von Wirkungsketten allerdings zu einer um den Faktor 3 höheren Indikatorenanzahl, was grundsätzlich den Repräsentationscharakter der abgebildeten Indikatoren in Frage stellt. Wird, wie es die CSD bei ihrer Indikatorenliste getan hat, auf die Abbildung von horizontalen Kausalitäten verzichtet, verringert dies zwar die Indikatorenzahl aber gleichzeitig verliert dieses Indikatorenkonzept grundsätzlich an Bedeutung. Schwerer wiegt allerdings, dass das aus dem PSR-Konzept abgeleitete DFSR-Konzept nicht vollständig auf die ökonomische, soziale und institutionelle Dimension übertragbar ist. In diesen Dimensionen ist eine eindeutige Zuordnung von Indikatoren zu den drei Indikatortypen Driving-Forces, States und Responses nicht möglich. Wird der der Indikatorbildung zugrundeliegende Wirkungsmechanismus variiert, verändert sich in der Folge auch die Zuordnung der Indikatoren zu Driving Forces, States und Responses, was ein wesentliches Defizit im Hinblick auf eine forscherübergreifende Verwendung darstellt.

Tabelle 3: Beispiele zur Systematisierung von Nachhaltigkeitsindikatoren nach dem DFSR-Konzept

Thema	Driving-Force	State	Response
Schutz der Erdatmosphäre	Treibhausgasemissionen ...	Treibhausgaskonzentration in der Atmosphäre ...	Erhöhung der Energieeffizienz Verbesserung von Prozesstechnologien ...
Partizipation aller Stakeholder	Partizipationspräferenzen ...	Öffentlichkeitsbeteiligung bei Genehmigungsverfahren ...	Institutioneller Ausbau von Öffentlichkeitsbeteiligung ...
Stabile Preisentwicklung	Schwankungen der Rohstoffpreise ...	Aktuelles Preisniveau der Rohstoffe ...	Handelspolitische Interventionen zur Stabilisierung der Preisentwicklung ...

3.4 Gegenüberstellung der Systematisierungsoptionen

Folgende Synopse gibt einen Überblick über die Systematisierungsoptionen.

Tabelle 4: Charakteristika und zentrale Vor- und Nachteile der Systematisierungsoptionen

Systematisierungs-option	**Indikatorzuordnung nach:**	**Zentrale Vorteile**	**Zentrale Nachteile**
Thematisch	Themenbereichen	Vereinfachte Zuordnung der Indikatoren Methodischer Freiheitsgrad bei Indikatorkonstruktion	Keine gegenseitige methodische Zuordnung der Indikatoren
Konzeptionell **PSR-Konzept**	Themenbereichen; Zusätzliches Ordnungskriterium: Pressures, States and Responses	Abbildung von Wirkungsmechanismen Rahmen für Abbildung von Umweltqualitäts- und –handlungszielen	Unterstellung von Monokausalität Fokussierung auf Pressures schränkt Anwendung auf Umweltprobleme ein
Konzeptionell **DFSR-Konzept**	Themenbereichen; Zusätzliches Ordnungskriterium: Driving Forces, States and Responses	Abbildung von Wirkungsmechanismen Ansatz einer dimensionsübergreifenden Betrachtung	Durchgängige Anwendung für soziale, ökonomische und institutionelle Dimension problematisch

In der Summe ist festzuhalten, dass Indikatorenkonzepte eine Systematisierungsoption darstellen, die methodisch grundsätzlich stichhaltig ist, die allerdings gleichzeitig auf methodische Hindernisse stößt. Die thematische Systematisierung ist methodisch weniger anspruchsvoll, erlaubt aber dementsprechend eine sach- und themenbezogene Indikatorenkonstruktion. Aus Transparenzgründen ist eine „Hybridlösung", also die konzeptionelle Zusammenstellung der Indikatoren dort, wo es offensichtlich sinnvoll ist (in der Umweltdimension), und eine thematische Systematisierung für die anderen Nachhaltigkeitsdimensionen, nicht zu befürworten.

Die methodischen Defizite der Indikatorenkonzepte und der methodische Freiheitsgrad bei einer thematischen Systematisierung legen es vielmehr nahe, bei einer dimensionsübergreifenden Betrachtung einer thematischen Systematisierung den Vorzug zu geben.

4 Nachhaltigkeitsindikatoren des Stoffstroms metallischer Rohstoffe

4.1 Indikatorabgrenzungen

Die Betrachtung des Stoffstroms metallischer Rohstoffe unter Nachhaltigkeitsaspekten im SFB 525 erfolgt unter Einbeziehung unterschiedlicher Untersuchungsebenen. Zum einen erfolgt eine prozessorientierte Betrachtung, die ökologische, ökonomische und soziale Merkmalsausprägungen von Indikatoren auf eine produktionstechnische Ebene des Stoffstroms bezieht. Ein zweiter Betrachtungswinkel ist auf die unterschiedlichen ökonomischen, ökologischen, sozialen und institutionellen Umweltbedingungen gerichtet, in die der Stoffstrom eingebettet ist. Zwischen diesen und dem Stoffstrom finden dimensionsübergreifend Interaktionen statt. Nicht zuletzt stehen auch Produkte, die das Sachziel der Stoffstromaktivitäten darstellen, im Mittelpunkt von Stoffstrombetrachtungen. Das durch den Stoffstrom metallischer Rohstoffe gebildete Indikatorenset ist somit ein Konglomerat von Stoffstrom-, Sektor- und Produktindikatoren. Diese Indikatoren setzen sich grundsätzlich aus aggregierten Daten und gegebenenfalls auch Indikatoren einzelner Standorte zusammen, wobei letztere die Lagerstätten oder Produktionsstätten des Gesamtsystems bezeichnen.

Stoffstromindikatoren sind hierbei Indikatoren, die auf Basis von (Teil-) Produktsystemen (sowohl Haupt- als auch Nebensystemen) für ökologische, ökonomische und soziale Gesichtspunkte des betrachteten Gesamtsystems gebildet werden. Bezugspunkt ist die physische Transformation von Material- und Energieflüssen im Rahmen des Produktsystems. Die Konfiguration des Produktsystems ist wiederum abhängig von den jeweiligen ökologischen, ökonomischen, sozialen und institutionellen Umweltbedingungen. Die Merkmalsausprägung von Stoffstromindikatoren ist an das Produktsystem gekoppelt. Aus diesem Grund erfolgt eine Normierung auf eine Einheit des System-Outputs oder System-Inputs, wobei die Normierung auf System-Output aus Kompatibilitätsgründen präferiert wird. Beispiele für Stoffstromindikatoren sind etwa Wasserverbrauch pro Tonne Metall, Gestehungskosten pro Tonne Metall oder prozessspezifisches Gesundheitsrisiko pro Tonne Metall.

Sektorindikatoren aggregieren sich aus Daten des Hauptproduktsystems und reflektieren ökologische, ökonomische und soziale Beziehungen. Sektorindikatoren fokussieren das politische und ökonomische Umfeld, in das der jeweilige Metallsektor eingebettet ist. Ihre Bezugsgröße ist daher ein Wirtschaftsraum oder die Ebene eines politischen Systems. Sektorindikatoren tragen der Überlegung Rechnung, dass der Stoffstrom nicht nur in unterschiedliche Umweltbedingungen eingebettet ist, sondern hieraus ökologische, ökonomische, ökologische und institutionelle Faktoren abzuleiten sind, die im Hinblick auf eine ganzheitliche Nachhaltigkeitsbetrachtung von zentraler Bedeutung sind. Indikatoren, die in diesem Zusammenhang zu nennen sind, sind etwa Anteil des Metallsektors an dem Steueraufkommen einer Region sowie Anteil der Treibhausgasemissionen des Metallsektors an nationalen Treibhausgasemissionen.

Produktindikatoren als dritter Indikatortyp sind Indikatoren, die zur Charakterisierung von intermediären Gütern oder Endgütern in Form von Konsum- oder Investitions-gütern dienen. Intermediäre Güter werden durch Unternehmen hergestellt und dienen für andere Unternehmen über eine physische Transformation als Ausgangsprodukte für die Herstellung anderer intermediärer Güter oder Endprodukte. Über den physischen Transformationsprozess finden metallische Werkstoffe Eingang in die

Nutzungsphase, in der in Form von Konsum- und Investitionsgütern die originäre Nutzung von Produkten stattfindet. Indikatoren von Konsum- und Investitionsgütern stehen hierbei in unmittelbarem Zusammenhang mit der Funktion und den Charakteristika des Produktes (Wetterbeständigkeit, Tragfestigkeit, Transportgewicht, Ästhetik). Im Regelfall bestehen die Produkte der Nutzungsphase aus mehreren Werkstoffen. Das Vorliegen monometallischer, beispielsweise ausschließlich aluminiumbasierter Produkte, stellt eine Ausnahme dar, was eine Nachhaltigkeitsbetrachtung gegenüber Produkten, die nur aus einem Werkstoff bestehen, erschwert.

In Abhängigkeit des jeweiligen Untersuchungsausschnitts, -ziels, des gewählten Messverfahrens und der bestimmten Systemgrenzen ist die jeweilige Indikatorzuordnung zu Stoffstrom-, Sektor- oder Produktindikator festzulegen. Eine Teilmenge von Indikatoren kann durch Transformation von einem Indikatortyp in einen anderen überführt werden. Wasser stellt für den Stoffstrom ein erforderliches Betriebsmittel dar. In diesem Sinne ist beispielsweise Wasserverbrauch pro Tonne Metall im Hinblick auf produktionstechnische Aspekte des gesamten Stoffstroms als Stoffstromindikator zu identifizieren. Setzt man den Wasserverbrauch einer bestimmten Hauptprozessstufe in Verbindung zur lokalen (lokal im Sinne einer politisch-administrativen Ebene) Wasserverfügbarkeit, handelt es sich um einen Sektorindikator, da man hierdurch die ökologische, ökonomische und soziale Interaktion des Stoffstroms mit der Umwelt in der agiert, etwa im Sinne des Konfliktpotenzials lokaler Wassernutzung, thematisiert. Betrachtet man aus einem weiteren Blickwinkel eine aus Aluminium hergestellte Verpackungsfolie als Konsumgut, ist Wasserverbrauch ein Produktindikator, der einen Rückschluss auf die Umweltverträglichkeit der Produktion von Verpackungsfolie zulässt.

Für einzelne Indikatoren ist im Gegensatz hierzu ausschließlich die Zuordnung zu einem Indikatortyp möglich, wie etwa bei einem Indikator Dosenpfand auf Aluminiumdosen. Die Indikatordifferenzierung dient im Hinblick auf den jeweiligen Untersuchungsgegenstand und das Untersuchungsziel dazu, eine größere Trennschärfe in der Nachhaltigkeitsdiskussion des Stoffstroms metallischer Rohstoffe zu schaffen. Die Differenzierung ist insbesondere deshalb von Bedeutung, weil die Akteure des Stoffstroms zur Wahrnehmung von Gestaltungsoptionen in ihrem Handlungsrahmen auf unterschiedliche Systemgrenzen angewiesen sind.

4.2 Systematisierung der Nachhaltigkeitsindikatoren

Basierend auf den Ausführungen von Kapitel 3 stellt sich die Frage, welche Systematisierungsoption für ein Nachhaltigkeitsindikatorenset des Stoffstroms metallischer Rohstoffe angemessen ist. Lässt man die Vor- und Nachteile Revue passieren, so spricht für die thematische Systematisierung die unkomplizierte Darstellung und der methodische Freiheitsgrad bei der Konstruktion der Indikatoren. Für eine konzeptionelle Systematisierung, wobei aufgrund der mehrdimensionalen Betrachtungsebene ausschließlich das DFSR-Konzept in Frage kommt, spricht grundsätzlich die transparente Abbildung von Wirkungsmechanismen. Allerdings ist eine konzeptionelle Systematisierung mit einer unterlegten Kausalität nur für Untersuchungsräume sinnvoll anwendbar, wo gleichwertige Wirkungsketten zu unterstellen sind. Sobald Umweltbedingungen, Aspekte der politischen Kultur, ökonomische und institutionelle Gesichtspunkte zu berücksichtigen sind, die in den betrachteten Untersuchungsräumen unterschiedlichen Wirkungsmechanismen unterliegen, ist die Verwendung des DFSR-Konzeptes in einem den Stoffstrom charakterisierenden Indikatorensystem nicht zweckmäßig. Bei einem Verzicht auf Kausalitäten bleibt das zentrale Problem bestehen, dass eine ähnlich konsistente Zuordnung von Indikatoren der ökonomischen, ökologischen und institutionellen Dimension zu den Indikatortypen Driving Force, State und Response, wie dies für die ökologische Dimension möglich ist, nicht durchgeführt werden kann. Aus diesen Überlegungen wird im Hinblick auf eine Systematisierung von Nachhaltigkeitsindikatoren des Stoffstroms metallischer Rohstoffe eine thematische Systematisierung bevorzugt.

4.3 Beispiel: Vorläufiges Indikatorenset des globalen Aluminiumstoffstroms

Das auf Basis der allgemeinen Ausführungen in Bearbeitung befindliche Indikatorenset des globalen Aluminiumstoffstroms umfasst im Sinne einer ganzheitlichen Betrachtung Indikatoren aller vier Dimensionen. Als Anknüpfungspunkte dienen die 1992 auf der Konferenz für Umwelt und Entwicklung verabschiedete Agenda 21, die neben dem Brundtland-Bericht das bedeutendste Dokument der

Nachhaltigkeitsdiskussion darstellt, und die Indikatorenliste der Commission on Sustainable Development von 1996, die ein erster Schritt zur Operationalisierung der Agenda 21 für die staatliche Ebene darstellt [22]. Hierdurch wird der Forderung gefolgt, konkrete Projekte stärker an den internationalen Rahmenarbeiten auszurichten [23].

Aufgrund der identifizierten Defizite der konzeptionellen Systematisierung wird eine thematische Systematisierung angewendet. Hierbei werden die generellen Nachhaltigkeitsziele ökologische Integrität, ökonomische Stabilität und soziale Gerechtigkeit dimensions- und themenbezogen in Unterziele differenziert.

Die themenbezogene Gewährleistung der Nachhaltigkeitsrelevanz wird allgemein durch die inhaltliche Transformation der Kapitel der Agenda 21 auf den Stoffstrom metallischer Rohstoffe am Beispiel von Aluminium sichergestellt. Parallel werden Themenbereiche integriert, die Stoffstromrelevanz besitzen, aber in der Agenda 21 nicht ausdifferenziert werden, was etwa auf Themen wie Marktstruktur und Öffentlichkeitsbeteiligung zutrifft. Innerhalb der ökologischen Dimension werden Wirkungsbilanzkategorien der gegenwärtigen LCA-Praxis angewendet. Um unterschiedliche räumliche und Akteursebenen anzusprechen, werden zusätzliche Wirkungsbilanzkategorien eingeführt. In der ökonomischen Dimension werden Indikatoren, die grundsätzlich als repräsentative Größen für das ökonomische System identifiziert sind, auf den Stoffstrom von Aluminium übertragen. Indem sie auf die aufgestellten Ziele ausgerichtet werden, ermöglichen die transformierten Indikatoren auf Basis der gegenwärtigen Konfiguration und Bedeutung Interpretationen über die ökonomische Zukunftsfähigkeit des globalen Aluminiumstoffstroms. Die soziale Dimension berücksichtigt Ergebnisse der Sozialindikatorenforschung, die auf die Lebensqualitätsdiskussion der siebziger Jahre folgte. Es werden überwiegend objektive Indikatoren betrachtet. Ergänzend werden allerdings auch subjektive Indikatoren einbezogen, die sich auf die Wahrnehmung von Umweltbedingungen richten. Um den räumlichen Bezug zum Stoffstrom sicherzustellen, werden die Indikatoren der sozialen Dimension im wesentlichen auf die Nachbarschaft, die im Umweltrecht als räumlicher Einwirkungsbereich der Anlage definiert wird, bezogen [24]. Die Indikatoren der institutionellen Dimension geben darüber Aufschluss, zu welchem Grad institutionelle Veränderungen, die im Hinblick auf nachhaltigkeitsrelevante Entscheidungsprozesse des Stoffstroms metallischer Rohstoffe zentrale Relevanz haben, erfolgen.

Insgesamt deckt die Indikatorenliste auf einer wissenschaftlichen Ebene relevante Nachhaltigkeitsindikatoren ab. Bei einer Fokussierung und Anwendung auf einzelne Akteure des Stoffstroms sowie einer möglichen Politikberatung ist die Indikatorpyramide zu berücksichtigen. Nach dieser erfolgt eine stufenweise Aggregation bzw. Selektion wissenschaftlicher Indikatoren für Entscheidungsträger und die Öffentlichkeit [25].

5 Schlussfolgerungen und Ausblick

Stoffströme metallischer Rohstoffe besitzen dimensionsübergreifende Nachhaltigkeitsrelevanz und sind in unterschiedliche soziale, ökonomische, ökologische und institutionelle Umweltbedingungen eingebettet, die pauschale Aussagen im Hinblick auf eine Nachhaltige Entwicklung des Stoffstroms ausschließen. Die die Umweltindikatoren- und Nachhaltigkeitsindikatorberichterstattung dominierenden Konzepte Pressure-State-Response sowie Driving Force-State-Response sind zur Systematisierung von Nachhaltigkeitsindikatoren des Stoffstroms metallischer Rohstoffe nur bedingt geeignet. Der derzeitige Ansatz des SFB 525 identifiziert am Beispiel des globalen Aluminiumstoffstroms Indikatoren aller Nachhaltigkeitsdimensionen und koppelt sie durch die Bildung von stoffstrombezogenen Unterzielen an die übergeordneten Ziele einer Nachhaltigen Entwicklung. Im Rahmen dieser thematischen Systematisierung lokalen, regionalen und nationalen Besonderheiten Rechnung zu tragen, ist ein notwendiges Vorgehen, um eine systematische Betrachtung und Bewertung zur Nachhaltigen Entwicklung des globalen Aluminiumstoffstroms zu gewährleisten. Hierzu dient nicht zuletzt auch die Indikatordifferenzierung in Stoffstrom-, Sektor- und Produktindikator. Zum jetzigen Zeitpunkt werden auf qualitativer Ebene Nachhaltigkeitsindikatoren identifiziert und diskutiert. Das weitere Vorgehen besteht in der qualitativen und quantitativen Konsolidierung des Indikatorensets und der Abstimmung der Indikatoren mit den im SFB 525 verwendeten Methoden und Modellen. Mittelfristiges Ziel ist es, neben Aussagen auf qualitativer Ebene durch eine dimensionsübergreifend angelegte

Szenarioanalyse ausgewählter Indikatoren zu in die Zukunft gerichteten Aussagen im Hinblick auf die Nachhaltige Entwicklung des globalen Aluminiumstoffstroms zu gelangen. Langfristig gilt es, den Ansatz sowohl qualitativ als auch quantitativ auf den Stoffstrom anderer metallischer Rohstoffe zu übertragen.

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RESSOURCENORIENTIERTE NACHHALTIGKEITSINDIKATOREN FÜR NICHT-ERNEUERBARE ROHSTOFFE*

(RESOURCE-ORIENTATED SUSTAINABILITY INDICATORS FOR NON-RENEWABLE RESOURCES)

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ABSTRACT

The limited availability of non-renewable resources is in the centre point of discussions on sustainable development. Indicators represent suitable tools in order to measure sustainability. Only on the base of measurement the availability of non-renewable resources could be evaluated and analysed following. Different approaches as e.g. life cycle assessment, raw material flow analysis as well as action programs e. g. Agenda 21 aim at a defining of indicators. Thus indicators are commonly variables, which characterise the status of a system. Therefore variables are based on collection as well as systematic arrangement of monitoring, data and experiences. The paper summarizes both different approaches and concepts as their respective resource oriented indicators. At this life cycle analysis, agenda 21 and raw material flow analysis are in scope of the publication. Resource oriented indicators defined by the CRC 525 will be presented and discussed considering as example bauxite/aluminium and copper.

KEY WORDS

Bauxite, aluminium, copper, reserves, resource oriented indicators, availability of nonrenewable resources, static and dynamic life time, raw material flow analysis, ore deposit characteristics, mine production

* Source: Kuckshinrichs, W; Hüttner, K.-L. (Hrsg.): Nachhaltiges Management metallischer Stoffströme. Schriften des Forschungszentrums Jülich, Reihe Umwelt, Bd. 31, S. 87-108

1 Einleitung

Die Verfügbarkeit erneuerbarer und nicht-erneuerbarer Rohstoffe ist seit Jahrzehnten Mittelpunkt kontroverser Diskussionen. Hierbei stehen Befürchtungen im Vordergrund, dass aufgrund des beschränkten Vorhandenseins nicht-erneuerbarer Rohstoffe die wirtschaftliche Stabilität und das Wirtschaftswachstum gefährdet sein können. So wurden 1972 die Knappheit an Rohstoffen sowie nutzbaren Ackerlandes als Faktoren identifiziert, die das Wirtschaftswachstum eines Landes kontrollieren [1].

Ende des 20. Jahrhunderts werden diese Fragestellungen in den Rahmen der Nachhaltigen Entwicklung integriert. Dabei stellt die Diskussion über die Nachhaltigkeit der Nutzung erneuerbarer und nicht-erneuerbarer Rohstoffe seit Jahren eines der umfangreichsten und komplexesten Themen in Politik, Wissenschaft und zunehmend auch in der Wirtschaft dar.

Vor diesem Hintergrund wurde 1997 von der Deutschen Forschungsgemeinschaft (DFG) der Sonderforschungsbereich 525 eingerichtet. Unter dem Titel „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“ werden die Stoffströme nicht-erneuerbarer metallischer Rohstoffe und die dadurch entstehenden direkten und indirekten Wirkungen auf die Umwelt, sowie wirtschaftliche und soziale Aspekte untersucht. Dazu werden bestehende Indikatoren ausgewählt und gegebenenfalls weiterentwickelt, um den Stoffstrom im Spannungsfeld globaler und lokaler Implikationen darzustellen. Ein besonderer Stellenwert fällt dabei der Betrachtung der Verfügbarkeit nicht-erneuerbarer Rohstoffe zu.

2 Rohstoff – Reserve – Ressource

Die Veredelung und Nutzung von Rohstoffen ist eine Grundlage der heutigen Zivilisation. Zur Charakterisierung von Rohstoffen hinsichtlich der Verfügbarkeit und Gewinnbarkeit werden in verschiedenen nationalen Klassifikationssystemen die Begriffe Reserven und Ressourcen verwendet. Die allgemein gebräuchlichste Definition, die auch in das Klassifikationssystem der United Nations integriert ist, stammt vom „Council for Mining and Metallurgical Institutions (CMMI)“ [2]. Demnach sind *Gesamtressourcen* die natürlich vorkommenden, wirtschaftlich interessanten Konzentrationen mineralischer Rohstoffe mit bestimmter geologischer Sicherheit. *Reserven* sind der durch eine Feasibility-Untersuchung abgegrenzte, ökonomisch abbaubare Teil der Gesamtressourcen. Eine Feasibility-Studie bewertet hierbei abschließend im Detail die technische Machbarkeit und wirtschaftliche „Lebensfähigkeit“ eines Bergbauvorhabens. Sie dient als Grundlage für die Investitionsentscheidung und als „bankable“ Dokument für die Projektfinanzierung [3]. Die ü*brigen Ressourcen* sind der nach Abzug der Reserven verbleibende Teil der Gesamtressourcen [2].

Zum besseren Verständnis dient Abbildung 1. Das dreidimensionale Koordinatensystem für die Definition von Rohstoffreserven und -ressourcen wird durch eine geologische Achse (G), eine Feasibility-Achse (F) und eine Wirtschaftlichkeitsachse (E) aufgespannt. Die Blöcke (111), (121) und (122) repräsentieren Reserven. Demnach sind Reserven grundsätzlich wirtschaftlich abbauwürdig (E1), allgemein (G2) bzw. detailliert (G1) exploriert und durch eine Prefeasibility-Studie (F2) bzw. eine Feasibility-Studie (F1) zu charakterisieren.

Alle weiteren dargestellten Blöcke, die nicht als wirtschaftlich (E1) klassifiziert wurden, sind demnach Ressourcen. Die Wirtschaftlichkeit einer Rohstoffressource ist relativ und unterliegt in hohem Maße der Nachfrage. Je nach Preis können Rohstoffreserven zurückgestuft (E2), oder Ressourcen zu Reserven aufgewertet werden.

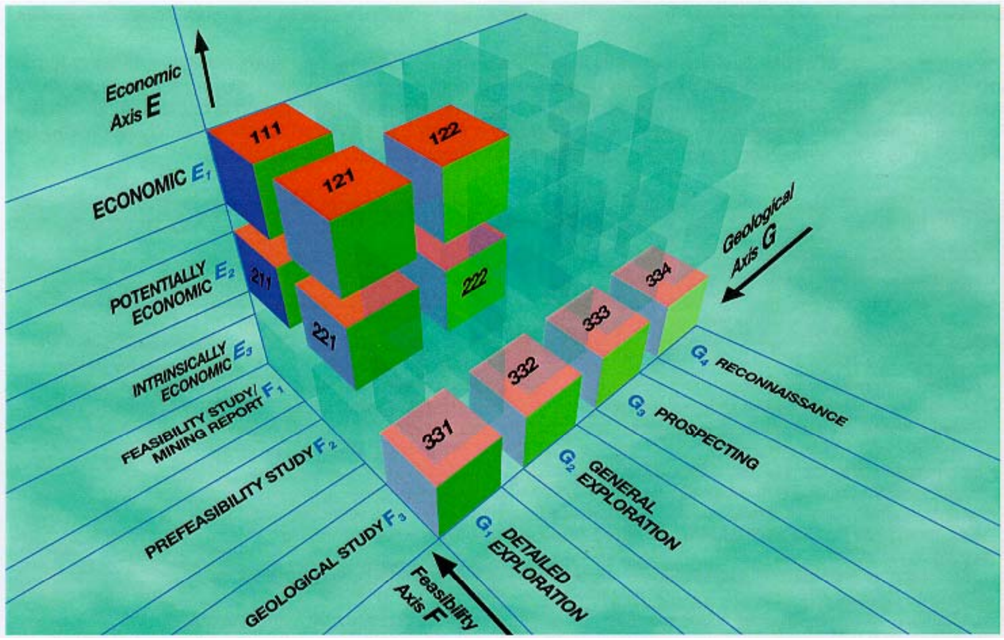

Abbildung 1: Definition für Rohstoffreserve und -ressource nach United Nations [2]

Das „International Council on Metals and the Environment (ICME)“ unterscheidet zudem noch zwischen erneuerbaren/nicht-erneuerbaren Ressourcen und erneuerbaren/nicht-erneuerbaren Materialien [4]. So werden mineralische Rohstoffe als nicht-erneuerbare Ressourcen betrachtet, wobei aber die Eigenschaften des gewonnenen Metalls beim Recycling vollständig erhalten bleiben. Somit werden Metalle als erneuerbare Materialien definiert. Im Vergleich hierzu ist z.B. Holz eine erneuerbare Ressource. Allerdings verliert Holz durch Recycling seine charakteristischen Ausgangseigenschaften. Dadurch ist Holz per Definition ein nicht-erneuerbares Material.

3 Stoffstrom metallischer Rohstoffe

Allgemein bilden Stoffströme metallischer Rohstoffe den Kreislauf ab, den ein Rohstoff von der Lagerstätte über Erzgewinnung, Aufbereitung und Verhüttung über Gebrauch und Recycling bis zur Deponierung räumlich und zeitlich durchläuft. Der Einfluss der betrachteten Rohstoffe auf die Ökonomien, Umweltbedingungen und die Gesellschaften, in die der Stoffstrom eingebettet ist, sind wichtige Bestandteile der Stoffstromanalyse. Das Ziel ist zu verstehen, wie und warum man Rohstoffe benutzt und Handlungsoptionen sowie Strategien zu entwickeln, wie man diese Rohstoffe effizienter und im Sinne einer Nachhaltigen Entwicklung einsetzen kann [5].

Das erste Konzept-Rahmenwerk für Stoffströme wurde 1973 in den Vereinigten Staaten von Amerika diskutiert. Dieses Rahmenwerk ist das Ergebnis einer Kommission, die aufgrund einer amerikanischen Gesetzesvorlage eingerichtet wurde. Dieses Gesetz war eines der ersten Versuche, die Umwelt effektiver zu schonen und Rohstoffressourcen schonender zu nutzen [6]. In diesem Bericht wurde ebenfalls bereits darauf hingewiesen, dass Umweltbelastung und der Umgang mit Rohstoffressourcen neben weiteren Faktoren sowohl das Wirtschaftswachstum wie auch die ökono-mische Stabilität eines Landes kontrollieren.

Die Enquete Kommission „Schutz des Menschen und der Umwelt“ des 12. Deutschen Bundestags definiert 1994 Stoffstrommanagement als „*das zielorientierte, verantwortliche, ganzheitliche und effiziente Beeinflussen von Stoffströmen, wobei die Zielvorgaben aus dem ökologischen und ökonomischen Bereich kommen, unter Berücksichtigung von sozialen Aspekten*“ [7]. Folgende Problembereiche werden u.a. von der Enquete-Kommission angesprochen:

- Verringerung des Verbrauchs nicht-erneuerbarer Rohstoffe und der Stoffeinträge durch Erhöhung der Material- und Energieproduktivität.
- Weitere Verbesserung von Produktionsmethoden unter ökologischen Gesichtspunkten.
- Entsorgung der Produktionsrückstände und der nicht mehr nutzbaren Produkte.

4 Lebenszyklusanalysen

Für die Analyse von Stoffströmen wird meist das „Cradle to Grave“ Konzept aufgegriffen, welches den Lebenszyklus von Produkten von der Wiege, also den natürlichen Rohstoffen, bis zur Bahre, also der Entsorgung von Reststoffen, umfasst. Für Metalle als vollwertig rückführbare Materialen wird auch von „Cradle to Cradle“ Konzepten gesprochen. Analytische Werkzeuge zur Interpretation von Stoffströmen sind z.B. die Methoden des „Risk Assessment (RA)“, das „Life Cycle Assessment (LCA)“ oder Materialintensitätsanalysen. Auf politischer Basis stehen Instrumentarien wie z. B. „Ecolabelling“ oder „Integrated Chain Management“ zur Verfügung [8]. Innerhalb dieser Analysen wird versucht, über Indikatoren das betrachtete System bewertbar zu machen. Allgemein kann ein Indikator als Variable verstanden werden, die den Zustand eines Systems beschreibt. Um klare Aussagen treffen zu können, müssen zunächst Beobachtungen, Daten und Erfahrungen gesammelt und systematisch geordnet werden. Anschließend werden diese Informationen ausgewertet und zu Schlüsselinformationen zusammengefasst [9].

Der Inanspruchnahme und der Erschöpfung nicht erneuerbarer Rohstoffressourcen wird in den Konzepten zur Lebenszyklusanalyse unterschiedlich Rechnung getragen. Die strikte abgestufte Unterteilung von Reserven und Ressourcen im Sinne des CMMI wird in diesen Konzepten nicht vorgenommen, diese beziehen sich i.d.R. auf die Gesamtressourcendefinition nach [2] (s.o.). Im Folgenden werden anhand der Materialintensitätsanalyse, des LCA sowie dem Konzept des Eco-indicator 99 stellvertretend Ansätze zur Quantifizierung der Ressourceninanspruchnahme vorgestellt.

Materialintensität

Der Begriff der Materialintensität wurde 1993 am Wuppertaler Institut für Klima, Umwelt und Energie in Deutschland geprägt. Das darauf beruhende MIPS-Konzept (Material-Intensität Pro Serviceeinheit) liefert einen Einzelindikator für die Umweltbelastungsintensität durch Produkte und Dienstleistungen oder auch durch Regionen und Länder. Hierzu werden die verbrauchten Stoffmengen als Einheitstonnen summiert und auf die Anzahl Dienstleistungen (Benutzungen) bezogen [10]. Die eingesetzten Stoffmengen werden differenziert nach *eingesetzten Materialien* und den *Materialintensitäten der Materialien*. Die *Materialintensitäten der Materialien* sind die Materialien, die zur Produktion der *eingesetzten Materialien* verwendet werden. Beispiel: Eingesetztes Material ist 1 kg Aluminium. Die Materialintensität für 1 kg Aluminium ist x kg Bauxit, y kg Wasser, z kg Kohle, etc. Die Summe des Gesamtmaterialinputs kann nun auf die *Serviceeinheit* bezogen werden. Die *Serviceeinheit* setzt sich zusammen aus der Anzahl der Benutzungen und der Anzahl der Personen.

$$\Sigma(Mi*MIMi) = MI \quad (1)$$

$$S = n*p \quad (2)$$

$$MIPS = MI/S \quad (3)$$

Mi = eingesetzte Materialien (z.B. Al); MIMi = Materialintensitäten der Materialien; MI = Gesamtmaterialinput; S =Serviceeinheit; n = Anzahl der Benutzungen; p = Anzahl der Personen

MIPS stellt einen Summenindikator über alle verwendeten Materialien dar. Das MIPS-Konzept differenziert nicht nach gefährlichen und ungefährlichen Materialien, die entlang eines Lebensweges bewegt oder freigesetzt werden. Ebenso wenig werden unterschiedliche Ressourcenverfügbarkeiten berücksichtigt. Der Schwerpunkt der MIPS-Analysen liegt auf der generellen Reduktion von Materialintensitäten eines Systems, unabhängig von der Bedeutung der einzelnen Rohstoffe.

Life Cycle Assessment

Das LCA, als direkt auf die Interpretation von Lebenszyklen zugeschnittene Verfahren, wurde in seiner Urform 1969 im Auftrag der Coca Cola Company erstmalig angewandt. Ziel dieser ersten Studie war, die energieeffizienteste Getränkeverpackung für Getränkeprodukte des Unternehmens zu identifizieren. Ein Ergebnis dieser und anschließender LCA-Studien für weitere Unternehmen war es, Stärken und Schwächen in der Produktherstellung aufzuzeigen [6]. Die „Society of Environmental Toxicology and Chemistry“ (SETAC) begann 1990 eine Methodik zu entwickeln, um Studien zukünftiger LCAs zu standardisieren. Diese Methodik beinhaltet Richtlinien zur Durchführung eines LCAs sowie dessen Anwendung unter Berücksichtigung ethischer Gesichtspunkte [11].

Innerhalb des LCA werden für einzelne Prozesse eines Produktsystems oder einer Dienstleistung Inputs und Outputs bilanziert (Life Cycle Inventory - LCI). Um diese im Hinblick auf die Bewertung der Umweltrelevanz aggregieren zu können, werden diese Massen und Energieströme in einzelnen Wirkungskategorien zusammengefasst und in Wirkungspotenzialen ausgedrückt (Life Cycle Impact Assessment – LCIA). Die Wirkungskategorien bezeichnen unterschiedliche Umweltwirkungen. Der Begriff Umwelt wird in den vier „Areas of Protection“ (Schutzgüter) festgelegt. Diese sind die menschliche Gesundheit, die natürliche Umwelt, Ressourcen und die menschgemachte Umwelt. Der Abbau bzw. die Erschöpfung nicht-erneuerbarer Rohstoffe wird dabei in einer eigenen Kategorie angesprochen. Innerhalb dieser Kategorie sollen die multiplen Inanspruchnahmen unterschiedlicher Rohstoffe operabel zusammengefasst werden. Hierfür werden zunächst rohstoffspezifische Faktoren identifiziert, um anschließend die Ressourcenerschöpfung aggregiert abzubilden. Die Erschöpfung von Ressourcen wird dabei über die Größe der Ressource des jeweiligen Rohstoffes charakterisiert. Für diese Darstellung werden folgende Faktoren diskutiert:

$$Q_1 = 1/D \quad (4)$$

$$Q_2 = U/D \quad (5)$$

$$Q_3 = 1/D*U/D \quad (6)$$

Q = Charakterisierungsfaktor; D = Ressource eines Rohstoffes; U = jährlicher Verbrauch eines Rohstoffes

Diese drei Quotienten Q, zusammengestellt von [12], bilden eine mögliche Ressourcenerschöpfung unterschiedlich ab. Q wird spezifisch für alle beanspruchten Ressourcen nicht-erneuerbarer Rohstoffe eines Systems ermittelt, mit der jeweiligen Ressourceninanspruchnahme multipliziert und anschließend zu einem Wirkungspotenzial aggregiert. Die Zusammenfassung der über die einzelnen Charakterisierungsfaktoren gewichteten Ressourceninanspruchnahmen bildet einen Indikator für den Beitrag eines Systems zur möglichen Erschöpfung von Ressourcen. Durch die Division mit der vorhandenen Ressource wird die spezifische Erschöpfung umso größer, je weniger von einer Ressource vorhanden ist (Q_1). Diese Abschätzung wird von der SETAC-WIA als relativ ungenau bzw. unsicher eingestuft. Als beste Annäherung gelten diejenigen Charakterisierungsfaktoren, die sowohl die Ressourcen eines Rohstoffes als auch dessen jährlichen Verbrauch berücksichtigen (Q_2, Q_3) [13].

Eco-indicator 99

Der Eco-indicator 99 [14] setzt auf den Wirkungskategorien des LCA auf und versucht, über die Quantifizierung von Schäden die einzelnen Wirkungspotenziale zu einem Einzelindikator zu aggregieren. Für die Erschöpfung von Ressourcen wird zunächst davon ausgegangen, dass die Vorräte praktisch aller mineralischer Rohstoffe in der Erdkruste im Überfluss vorhanden sind. Allerdings kann der Anteil nutzbarer, hochgradiger Vorkommen für bestimmte Rohstoffe stark limitiert sein. Zunächst vergleicht man die kumulative Ausbringung eines Rohstoffes seit Beginn der Industrialisierung mit der krustalen Konzentrationsverteilung des Rohstoffs. Dies ermöglicht eine Aussage in wie weit sich die Qualität eines Rohstoffes erniedrigt hat, sobald man eine gesamte, kumulative Menge ausgebracht hat. Das heutige Ausbeuten qualitativ hochwertiger Rohstoffvorkommen ist daher mit zusätzlichen ökologischen Eingriffen zu belasten, die durch das zukünftige Erschließen von niedriggehaltigen Vorkommen eines Rohstoffes bedingt werden. Abbildung 2 veranschaulicht, dass sich bei Erniedrigung der abbauwürdigen Metallgehalte die kumulierten abbauwürdigen Erztonnagen erhöhen.

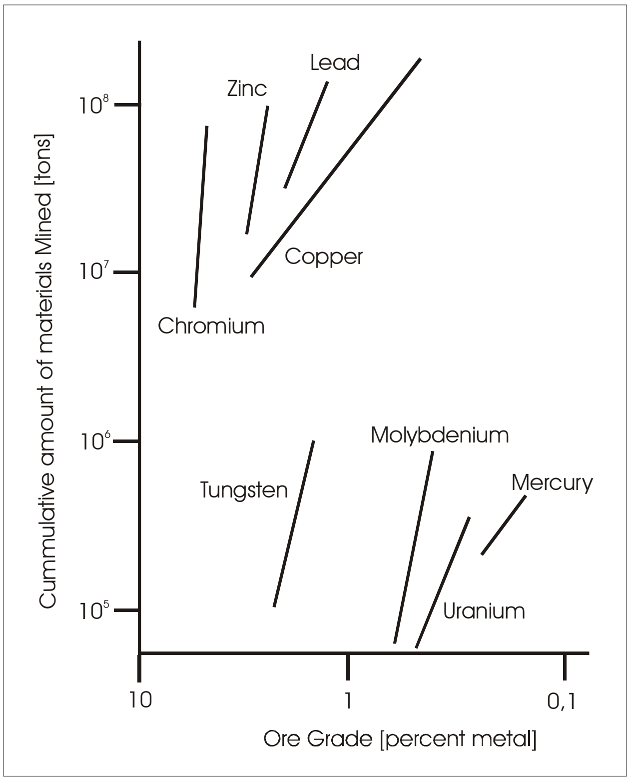

Abbildung 2: Geostatistisches Modell zu Rohstoffverfügbarkeit und Erzgehalten [nach 14]

Vereinfacht kann somit der zukünftige energetische Mehraufwand, der notwendig ist, um einen Rohstoff zu gewinnen, als Indikator für die Ernsthaftigkeit der Erschöpfung der Ressource gewertet werden [14].

5 Nachhaltigkeitsindikatoren

In den „traditionellen“ Lebenszyklusanalysen steht die Umwelt als eine der Nachhaltigkeits-Dimensionen im Vordergrund. Als Teil der Umwelt werden die nicht-erneuerbaren Ressourcen als „erschöpfbare“ Schutzgüter betrachtet. Soziale und wirtschaftliche Implikationen der Rohstofferschließung, Förderung und Vermarktung bleiben weitestgehend unberücksichtigt. Mit der Forderung nach inter- und intragenerativer Gerechtigkeit fällt diesen Aspekten jedoch eine größere Bedeutung zu. Maßgeblich für die Definition der Nachhaltigen Entwicklung ist der Bericht der Brundtland-Kommission 1987, die die am häufigsten gebrauchte und allseits anerkannte Definition beinhaltet [15]. Hierbei wird Nachhaltige Entwicklung als Entwicklung definiert, die die Bedürfnisse der heutigen Generation erfüllt, ohne die Bedürfnisse zukünftiger Generationen zu gefährden. Allerdings wird diese Definition auch vielerseits als zu verschwommen und unpräzise angesehen [16]. Demnach wäre ein Betrachtungszeitraum von ca. tausend Jahren für diese Definition geeignet. Eine klare Definition der Nachhaltigen Entwicklung ist schwierig. Eine elementare Betrachtung ist jedoch, dass Veränderungen im Gebrauch nicht-erneuerbarer Rohstoffe im Zusammenhang der Nachhaltigen Entwicklung stattfinden müssen, wobei eine klare Lokalisierung und Zielsetzung dieser Entscheidungen fehlen. Einige Autoren beschränken ihre Definitionen auf die physikalischen Grenzen des Wachstums [17], wobei die meisten Autoren soziale, ökonomische und ökologische Fragestellungen und deren Interaktionen berücksichtigen [17].

Zur Operationalisierung der Nachhaltigkeit wurden im Jahr 1992 in der Rio de Janeiro-Deklaration Regeln aufgestellt, woraus unmittelbar Gestaltungsziele für die nicht-erneuerbaren Ressourcen abzuleiten sind [18]:

„Die Staaten sollen im Sinne einer globalen Partnerschaft kooperieren, um die Gesundheit und die Einheit des Ökosystems der Erde zu erhalten, zu schützen und wiederherzustellen. ... .“ (Principle 7)

Basierend auf der Rio-Deklaration ist die Agenda 21 ein umfassender Aktionsplan auf lokaler, nationaler und globaler Ebene für staatliche und zivilgesellschaftliche Akteure. Die Agenda 21 gilt für jeden Bereich, in dem der Mensch die Umwelt beeinflusst [19].

Um Nachhaltigkeit messbar zu machen, hat die „Commission on Sustainable Development (CSD)“ auf Basis der Agenda 21 eine Indikatorenliste erstellt [19]. Auf die Verfügbarkeit nicht-erneuerbarer Rohstoffe wird vor allem in der wirtschaftlichen Dimension in Kapitel 4 der Agenda 21 eingegangen [20]:

Agenda 21 - Kap. 4: Changing Consumption Patterns

4.5. „Besondere Aufmerksamkeit verdient die Beanspruchung natürlicher Ressourcen, die durch einen nicht nachhaltigen Verbrauch gekennzeichnet ist. Des weiteren sollte ebenfalls der effiziente Gebrauch dieser Ressourcen konsistent mit den Zielen der Minimierung der Ressourcenerschöpfung sowie der Reduzierung der Verschmutzung sein. ...“.

Als Indikatoren für nicht-erneuerbare Ressourcen/Rohstoffe stellt die CSD folgende Indikatoren vor:

- Sichere Mineralreserven
- Wertgeschöpfter Anteil der Rohstoffindustrie (z.B. Eisen- und Stahlindustrie, Raffinerien , Chemische Industrie) zur allgemein verarbeitenden Industrie
- Intensität des Materialeinsatzes. Hierbei wird der Quotient aus eingesetztem Material [kg, t, m^3] zu Bruttoinlandsprodukt gebildet und auf 1000 US$ normiert.

Die Einbeziehung nicht-erneuerbarer Rohstoffe in die Diskussion über Nachhaltigkeit ist kompliziert. Obwohl die Rohstoffknappheit nach wie vor eine zentrale Frage darstellt, hat sich die Diskussion um Themen wie Ökosystem, Gesundheit, Substitutionsmöglichkeiten, Reversibilität und intergenerative Gerechtigkeit erweitert. Verschiedene Methodenansätze stehen zur Verfügung, um das Ziel Nachhaltigkeit zu erreichen. Eine bekannte Definition betont die Notwendigkeit, die Verwendungsmöglichkeiten und die Qualität natürlicher Rohstoffe auf Dauer zu gewährleisten [21]. Ein anderer Ansatz stellt die begrenzte Verfügbarkeit nicht-erneuerbarer Rohstoffe sowie eingeschränkte Absorptions- und Regenerationsmöglichkeiten eines natürlichen Systems in den Mittelpunkt [22]. In diesem Zusammenhang bietet die Natur Nutzungspotenziale, bei denen jedoch eine Substitution ausgeschlossen ist [22]. Die Ressourcen nicht-erneuerbarer Rohstoffe sind per Definition begrenzt [23] und deren Exploration, Abbau, Aufbereitung, Nutzung und Deponierung können natürliche Systeme negativ beeinflussen. Oft gelten die Gesundheit der Menschen und ein funktionierendes Ökosystem als Hauptinhalte für eine nachhaltige Entwicklung. Dadurch wären nachhaltige, nicht-erneuerbare Rohstoffe ein Oxymoron in der Diskussion um Nachhaltigkeit.

Allerdings sind Energie- und Rohstoffressourcen integrierte Bestandteile von ökonomischen, ökologischen und sozialen Systemen. Einen ausführlichen Überblick über verschiedene Ansätze, Nachhaltigkeit bzw. nachhaltige Entwicklung zu definieren, bieten [23, 24].

6 Nachhaltigkeitsindikatoren des SFB 525

Die bislang im Rahmen der Lebenszyklusanalyse vorgestellten Indikatoren leisten unterschiedliche Beiträge zu den zwei Themenstellungen „Gegenwärtige Rohstoffverfügbarkeit“ und „Zukünftige Rohstoffverfügbarkeit“ für nicht-erneuerbare Rohstoffe. So erlaubt der Charakterisierungsfaktor $Q_1 = 1/D$ des LCIA nur eine unklare Aussage über die gegenwärtige Rohstoffverfügbarkeit, wenn für D die jetzig bekannten Gesamtressourcen verwendet werden. Für eine Abschätzung der gegenwärtigen sowie der zukünftigen Verfügbarkeit nicht-erneuerbarer Rohstoffe eignet sich der Charakterisierungsfaktor Q_3 = (1/D)*(U/D). Es kann hierdurch ein gegenwärtiger Trend ermittelt werden, der als eine erste Annäherung für eine zukünftige Rohstoffversorgung angesehen werden kann. Der Eco-indicator 99 ist eine geeignete Methode, die Erschöpfung eines Rohstoffes sowie die Qualität einer zukünftigen Ressource abzuschätzen.

Vor dem Hintergrund der Agenda 21 wurden hingegen im SFB 525 Indikatoren entwickelt, die Darstellungen auf den unterschiedlichen Maßstabsebenen lokal, regional und global, als auch für unterschiedliche Zeithorizonte erlauben. An den Beispielen Bauxit/Aluminium und Kupfererz sollen exemplarisch Indikatoren des SFB 525 für die Einschätzung der Verfügbarkeit nicht-erneuerbarer Rohstoffe vorgestellt und erläutert werden.

Hierbei ist jedoch zu beachten, dass sich die hier vorgestellten Indikatoren nur auf Bauxit/Endprodukt Aluminium bzw. Kupfererz/Endprodukt Kupfer beziehen. Die Indikatoren beinhalten Charakteristika der Lagerstätte, des Abbaus und der Aufbereitung sowie der Verhüttung des mineralischen Rohstoffes. Die für die Gewinnung von Aluminium und Kupfer zusätzlich benötigten nicht-erneuerbaren, mineralischen Rohstoffe (z.B. Zuschlagstoffe bei der Verhüttung) werden noch nicht berücksichtigt. Hierfür müssen die Indikatoren gegebenenfalls modifiziert werden.

7 Nachhaltigkeitsindikatoren des SFB 525 – Beispiele

7.1 Jahresverbrauch

Der Indikator beschreibt, als Zeitreihe betrachtet, die Entwicklung des Jahresverbrauchs eines nicht-erneuerbaren Rohstoffes mit der Masseneinheit Tonnen pro Jahr (t/a). Die Prognose einer Verbrauchsentwicklung hängt von einer Vielzahl von Faktoren ab. In der Regel können Aussagen über einen Zeitraum von 5 – 10 Jahren gesichert und bis 20 Jahren über die Größenordnung einer Verbrauchsentwicklung getroffen werden. Somit bezieht sich der Indikator auf kurz- bis mittelfristige Zeiträume. Räumlich ist der Indikator auf der globalen Wirkungsebene einzuordnen.

Der Indikator beschreibt den Trend einer Inanspruchnahme. Er stellt eine unverzichtbare Grundlage für die Interpretation anderer Indikatoren dar, die den Zustand eines Systems oder den Erfolg von Maßnahmen beschreiben. Im betrachteten Referenzsystem liefert dieser Indikator erste Hinweise auf den Innovationsdruck in der Technikentwicklung sowie die Effizienz des Rohstoffeinsatzes. Weiterhin können Hinweise auf Tendenzen im Recycling und der Substitution eines Metalls sowie die Notwendigkeit verstärkter Explorationstätigkeit abgeleitet werden. Adressaten des Indikators sind Industrie und Regierungen.

Der Jahresverbrauch wird über Daten aus Literatur, Statistiken und Bilanzrechnungen ermittelt. Für die Beurteilung einer absoluten Nachfrage sollte auch die Entwicklung des spezifischen Verbrauchs eines Rohstoffes pro Nutzeneinheit berücksichtigt werden. Nur so kann die Beurteilung eines möglichen Bedarfsanstiegs in Bezug auf einen Anstieg aufgrund von Bevölkerungswachstum oder Substitutionseffekten sowie die Abnahme aufgrund eines effizienten Umganges mit einem Rohstoff erfolgen. Zur Veranschaulichung des Indikators „Jahresverbrauch“ dient im Folgenden Abbildung 3, die den Jahresverbrauch von Kupfer und Aluminium als Zeitreihe über die letzten 13 Jahre darstellt.

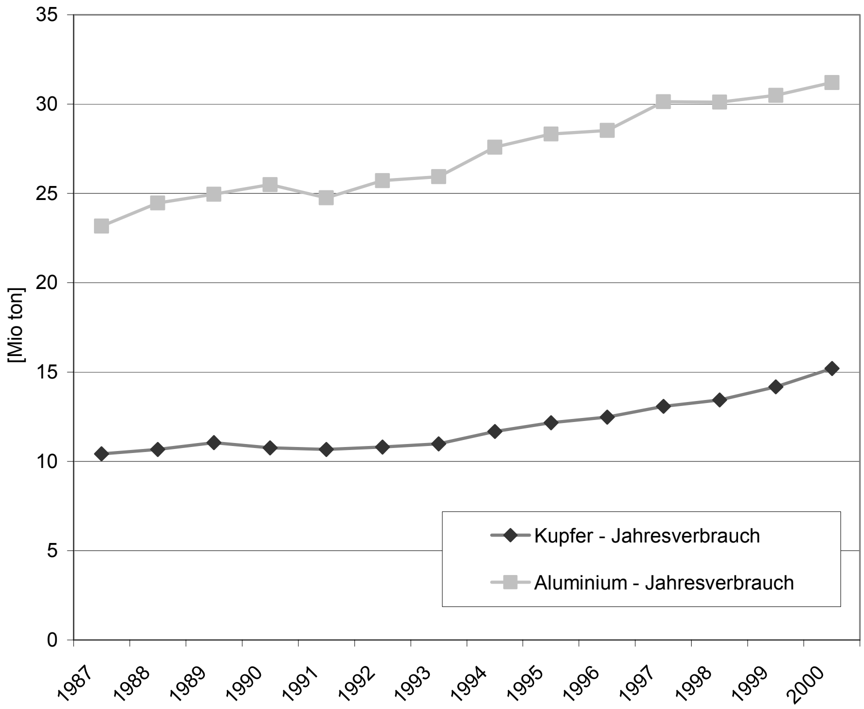

Abbildung 3: Zeitreihe über den globalen Kupfer- und Aluminiumverbrauch (Datenquelle: [25])

7.2 Statische Lebensdauer der Reserven - Lebensdauerkennziffer

Die Lebensdauerkennziffer bestimmt die Reichweite einer ausgewiesenen Reserve eines nicht-erneuerbaren Rohstoffes mit der Messeinheit Jahre (a).

Für die Bestimmung der statischen Lebensdauerkennziffer wird der Quotient aus im Bezugsjahr ausgewiesenen gesicherten und wahrscheinlichen Reserven und der Jahresproduktion gebildet. Hiervon zu unterscheiden ist die dynamische Lebensdauerkennziffer, bei der die Produktion mittels eines angenommenen Wachstumsfaktors dynamisiert wird. Der Indikator kann sowohl auf lokaler (Standort) wie auch regionaler (Land) oder globaler Wirkungsebene angewendet werden.

Der Indikator besitzt in Bezug auf das Auslaufen des Abbaus an einem Standort bzw. den Bedarf für verstärkte Explorationsaktivitäten eine kurzfristige Aussagekraft (< 5 Jahre). Ebenfalls können Aussagen getroffen werden über mittelfristige Reserven einer Region (< 20 Jahre) sowie langfristige Zeiträume (> 20 Jahre) als Maß für den Innovationsdruck eines Systems in Bezug auf Rohstoffabhängigkeit, Einsatzintensität und Substitutionsmöglichkeiten. Der Innovationsdruck ist um so geringer, je höher die statische Lebensdauer ist.

Einschränkungen resultieren aus der Annahme, dass Reservenmengen und die Jahresproduktion statisch sind. Der Indikator liefert nur wenig Hinweise auf die tatsächliche, absolute Reichweite oder Erschöpfung einer geologischen Reserve im globalen Kontext. Für die Bestimmung kann die industriebezogene Jahresproduktion oder der konsumentenbezogene Jahresverbrauch eingesetzt werden. Alternative Indikatoren sind z.B. die Lebenszykluskurve (Depletion Midpoint) oder die Dynamische Reichweite.

Die statische Lebensdauer der globalen Bauxitreserven betrug für das Jahr 1997 ca. 170 Jahre. Abbildung 4 zeigt die weltweit größten Bauxit produzierenden Länder. Hierbei erkennt man, dass die statische Lebensdauer der Bauxitreserven einzelner Länder wie Jamaika, Surinam, Guyana oder Kasachstan deutlich unter der globalen Lebensdauer liegen. Länder wie Brasilien oder Griechenland besitzen im Vergleich jedoch deutlich höhere Lebensdauerkennziffern für Bauxit. Die ermittelte statische Lebensdauer muss jedoch im Kontext der jeweiligen Jahresproduktion und der zugehörigen ausgewiesenen Reserven vorsichtig interpretiert werden.

Die statische Lebensdauer der globalen Kupferreserven beträgt für das Jahr 1998 ca. 28 Jahre. Abbildung 5 zeigt die Länder mit der weltweit größten Kupferproduktion. Hierbei erkennt man, dass die statische Lebensdauer der Kupferreserven einzelner Länder wie z. B. Australien z.T. deutlich unter der globalen Lebensdauer liegen. Länder wie Peru oder Kasachstan besitzen im Vergleich jedoch deutlich höhere Lebensdauerkennziffern für Kupfer. Wie am Beispiel der statischen Lebensdauer für Bauxit müssen die ermittelten statischen Lebensdauerkennziffern immer zusammen mit der Jahresproduktion und den jeweilig ausgewiesenen Reserven betrachtet werden.

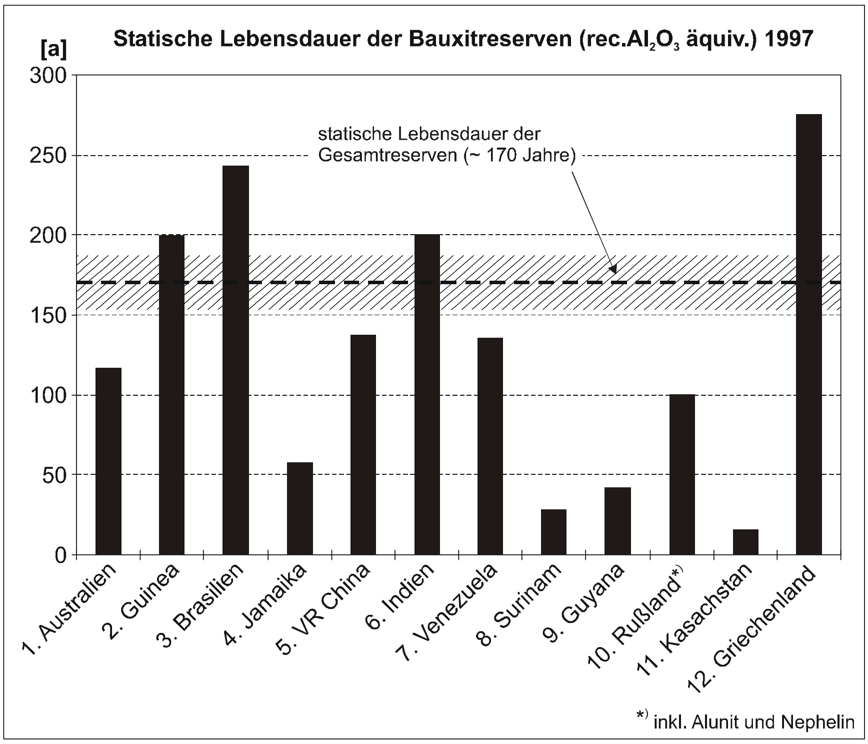

Abbildung 4: Statische Lebensdauer der globalen Bauxitreserven [26]

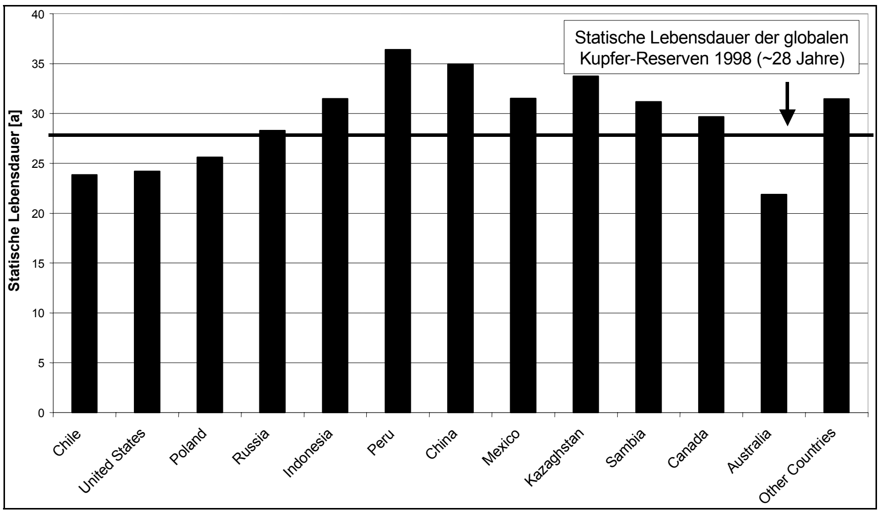

Abbildung 5: Statische Lebensdauer der globalen Kupferreserven [25]

7.3 Verhältnis Reserven aus noch nicht produzierenden Minen zu Reserven aus produzierenden Minen

Der Indikator ist eine Verhältniszahl, die die Änderung der gegenwärtig zur Verfügung stehenden Reserven im Zuge von neuer Ausweisung und Inanspruchnahme nicht-erneuerbare Rohstoffe beschreibt.

Der Indikator stellt ein Maß für den Umgang mit den bestehenden Reserven dar. Der Indikator ist als Änderung einer Bilanzgröße zu bestimmen. Es wird der Quotient aus neu ausgewiesenen gesicherten und wahrscheinlichen Reserven noch nicht produzierender Minen und ausgewiesenen gesicherten und wahrscheinlichen Reserven bereits produzierender Minen gebildet. Der Quotient bezieht sich hierbei immer auf ein Referenzjahr. Ist die Verhältniszahl größer 1, stehen mehr Reserven zur Verfügung als gegenwärtig in Anspruch genommen werden. Im Sinne einer intergenerativen Verteilungsgerechtigkeit kann durch Exploration (z.B. neue Lagerstätten, Erweiterung bestehender Lagerstätten) und durch technischen Fortschritt (z.B. Erschließung von Lagerstätten in größerer Teufe) der Aufzehrung der Reserven entgegengewirkt werden.

Der Indikator ermöglicht für sich alleine keine langfristigen, in die Zukunft gerichteten Aussagen. In Verbindung mit der statischen Lebensdauer wird allerdings eine mittelfristige Analyse eines Systems möglich. Kurzfristige Schwankungen im Verhältnis von Reservenausweisung und Inanspruchnahme können zu einer Verzerrung der Ergebnisse führen. Eine Interpretation sollte deshalb immer auf einer ausreichenden Zeitreihe beruhen. In jedem Falle wird es notwendig, einen Grundstock an Reserve zu definieren. Dieser sollte einen ausreichenden Vorrat darstellen, so dass dem System bei drohender Erschöpfung eine ausreichende Umstellungszeit zur Verfügung steht („respite time“). Als problematisch kann sich der Einfluss der Preisentwicklung eines Rohstoffes darstellen, da sich bei signifikanten und dauerhaften Preisänderungen der Cut-off-grade einer Lagerstätte und damit die zur Verfügung stehenden Reserven ändern. Bei rezyklierbaren metallischen Rohstoffen kann anstelle der natürlichen Reserven nicht-erneuerbarer Rohstoffe auch die Menge der extrahierten Metalle, die sich im Produktionskreislauf befinden, betrachtet werden. Für den Jahresverbrauch müssten dann die Verluste des Metalls beim Recycling angesetzt werden.

Als Daten zur Berechnung dienen Reserven produzierender Minen, neu ausgewiesene gesicherte und wahrscheinliche Reserven, Metallinhalt und Jahresverbrauch.

Die Anwendung des Indikators am Beispiel Bauxit verdeutlichen Abbildung 6 und Abbildung 7. Bei globaler Betrachtung setzen sich die Bauxitreserven für das Jahr 1997 zu 64% aus Reserven von Lagerstätten zusammen, die sich im Explorationsstadium befinden (Abbildung 6).

Eine regionale Betrachtung (Abbildung 7) zeigt, dass sich für einzelne Länder die ermittelten Bauxitreserven für das Jahr 1997 unterschiedlich zusammensetzen. So resultieren die Bauxitreserven von Ländern wie Indonesien, Brasilien und Vietnam nahezu vollständig aus Lagerstätten, die im Explorationsstadium sind. Im Gegensatz hierzu setzten sich die Bauxitreserven der VR China und Griechenland nahezu vollständig aus bereits produzierenden Minen zusammen.

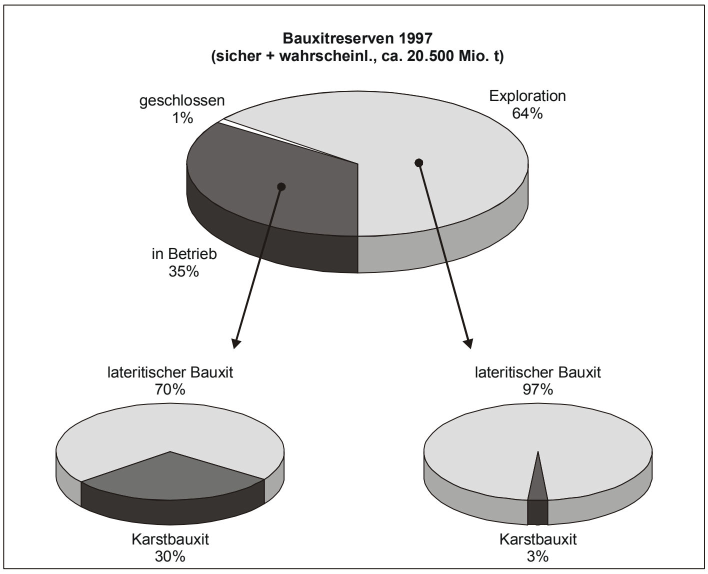

Abbildung 6: Verhältnis Reserven aus noch nicht produzierenden Minen zu Reserven aus produzierenden Minen, global betrachtet [25]

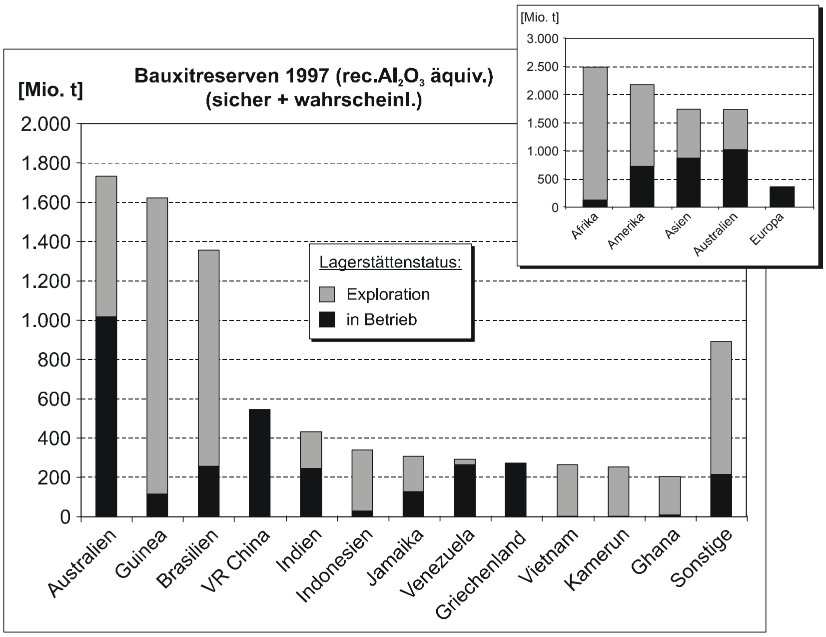

Abbildung 7: Verhältnis Reserven aus noch nicht produzierenden Minen zu Reserven aus produzierenden Minen, regional betrachtet [25]

7.4 Metallausbringung aus einem nicht-erneuerbaren mineralischen Rohstoff

Der Indikator beschreibt die Verluste an Wertstoffinhalten eines mineralischen Rohstoffes bei der Metallausbringung. Hierdurch kann ebenfalls die Effizienz eines technischen Verfahrens zur Metallgewinnung abgeschätzt werden.

Der Indikator soll zu einem effizienten Rohstoffeinsatz und zur Vermeidung von Wertstoffverlusten beitragen. Als Adressaten sind hierbei die Industrie und Regierungen zu nennen.

Es bestehen Verbindungen und Verknüpfungen zu anderen Nachhaltigkeitsindikatoren wie Jahresverbrauch an nicht-erneuerbaren Rohstoffen, Statische Lebensdauer, Verhältnis Reserven aus noch nicht produzierenden Minen zu Reserven aus produzierenden Minen, Qualitätsanforderungen an ausgewiesenen Reserven und technische Recyclingquote.

Der tatsächlich ausgebrachte Metallinhalt in Form des Halbzeugs wird in Beziehung gesetzt zum Metallinhalt der dafür in Anspruch genommenen nicht-erneuerbaren Rohstoffe. In Verbindung hierzu kann zusätzlich noch eine Betrachtung der technischen Recyclingquote des Metalls erfolgen.

Der Indikator muss immer in Verbindung mit dem Energieaufwand und den Umweltauswirkungen eines Prozesses betrachtet werden. Interpretationen sind oftmals in Form eines Benchmarkings unter Berücksichtigung von Verfahren, Technologiestand und Standortcharakteristika möglich. Weiteren Einfluss auf das Ausbringen haben in der Regel auch die Qualitätsansprüche und das erzielbare Preisniveau für das ausgebrachte Metall. Im Zuge des Vorhandenseins weiterer Wertinhalte kann es zu einem konkurrierenden Ausbringen im Zuge des gezielten Extrahieren eines anderen Wertstoffes kommen.

Daten zur Berechnung des Indikators sind Menge der in Anspruch genommenen Reserve, Metallinhalt und Ausbringen in Abbau, Aufbereitung und Verhüttung. Für Prognosen über zukünftige Wertstoffverluste müssen außerdem neu ausgewiesene, gesicherte und wahrscheinliche Reserven berücksichtigt werden.

Beispielhaft wird dieser Indikator im Folgenden für Kupfer angewendet (Abbildung 8, Abbildung 9).

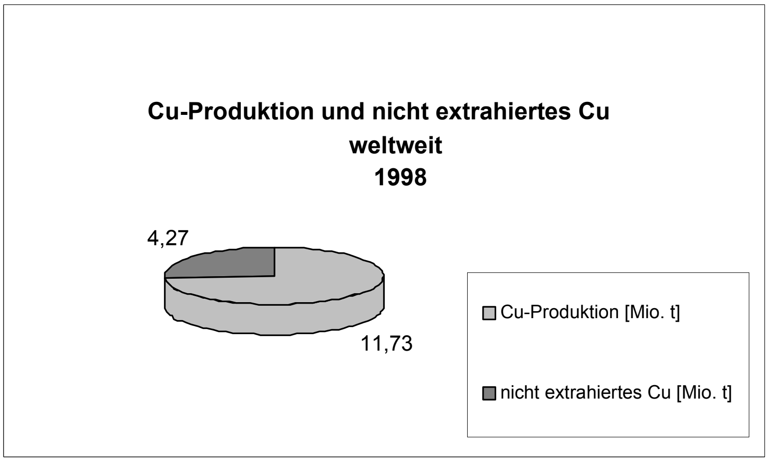

Abbildung 8: Kupferproduktion und -verluste 1998, global betrachtet [27]

Für das Jahr 1998 repräsentiert die erfasste Produktion von 11,73 Mio. t Kupfer ca. 97% der globalen Kupferproduktion von ca. 12,4 Mio. t Kupfer. Über die jeweilig ausgebrachten Erztonnagen und Kupfergehalte kann die tatsächliche Metallmenge errechnet werden, um die die ursprünglichen Reserven der Lagerstätten erniedrigt wird. Diese beträgt für das Jahr 1998 insgesamt 16 Mio. t Kupfer. Dies bedeutet einen Verlust von 4,26 Mio. t Kupfer durch Abbau und Aufbereitung. In der Berechnung sind noch keine Kupferverluste bei der Verhüttung von Kupferkonzentraten berücksichtigt. Somit ist hier der Kupferverlust als nicht extrahiertes Kupfer definiert. Eine teilweise zukünftige Gewinnung des nichtextrahierten Kupfers (z.B. aus Aufbereitungsabgängen) ist nicht ausgeschlossen.

Bei einer regionalen Betrachtung der prozentualen Verteilung der Kupferverluste fällt auf, dass Afrika mit knapp 40% Verlust bei der Metallausbringung (Gewinnung und Aufbereitung) an der Spitze der betrachteten Kontinente steht. Der prozentuale Kupferverlust ist beinahe 50% höher als der globale Durchschnittsverlust. Westeuropa und Asien liegen im Gegensatz hierzu knapp unter dem weltweit ermittelten Kupferverlust von 27%.

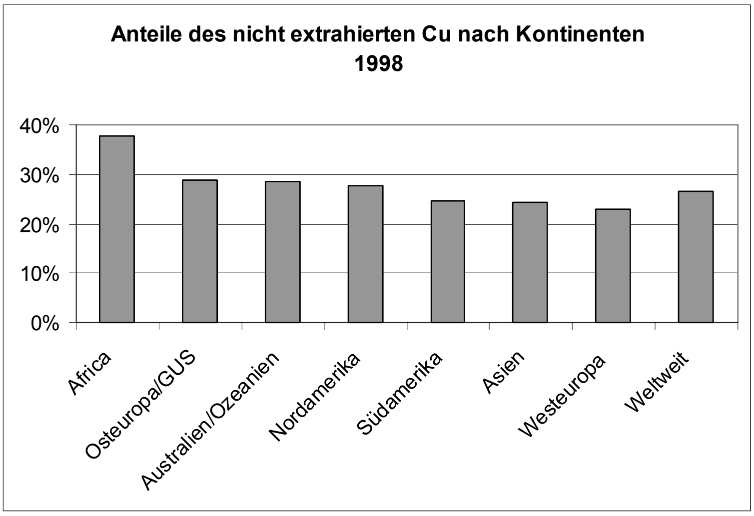

Abbildung 9: Prozentuale Kupferverluste 1998, regional betrachtet [27]

7.5 Abhängigkeit der Reserven in Bezug auf Qualitätsanforderungen

Abbauwürdige Reserven verändern durch die unterschiedlichen Lagerstättentypen und Mineralparagenesen die Material- und Energiebedarfe bei der Gewinnung und Aufbereitung. Je nach Qualitätsanforderung an die Lagerstätte eines nicht-erneuerbaren Rohstoff werden die gesamt abbauwürdigen Reserven erhöht oder gesenkt. Qualitätskriterien können als Indikatoren genutzt werden, um die zukünftig zu erwartenden Energie- und Materialbedarfe abzuschätzen. Gleichzeitig kann eine qualitative Lagerstättenauswahl die Reservenmenge senken. Dies nimmt direkt Einfluss auf die Indikatoren „Statische Lebenszeit“, „Verhältnis Reserven aus noch nicht produzierenden Minen zu Reserven aus produzierenden Minen“, „Metallausbringen“ und „Einsatzintensität eines nicht-erneuerbaren Rohstoffes“.

Abbildung 10 zeigt die Abhängigkeit der Weltbauxitreserven von einer kontinuierlichen Erhöhung der Anforderung an die Lagerstättenqualität. Die initialen Gesamtreserven (100 %) sind in Wertstoffäquivalente umgerechnet und entsprechen ca. 8.500 Mio. Tonnen rec.Al_2O_3. Ausgehend von einer gleichbleibenden Produktionsrate an Bauxit von ca. 50 Mio. Tonnen rec.Al_2O_3 jährlich (umgerechnet in Wertstoffäquivalente) ist auf der Sekundärachse der Abbildung die statische Lebensdauer der jeweils verfügbaren Reserven abgetragen [25].

Die Qualitätsanforderung bezüglich der Lagerstättenparameter wird kontinuierlich erhöht von der geringsten heute bekannten Qualität (0 %) bis zur höchsten heute bekannten Qualität (100 %).

Dieses Modell der Rohstoffverfügbarkeit verdeutlicht, wie unterschiedlich die Abhängigkeit der Reserven von den verschiedenen Qualitätskriterien ist [25]. So nehmen die Reserven bei leichter Erhöhung des Qualitätskriterium *TiO_2* deutlich ab. Im Vergleich hierzu ist die Rohstoffverfügbarkeit bei Erhöhung des Qualitätskriterium *Abraum/Erz* sehr stabil. Eine starke Verringerung der Reserven tritt hierbei erst ab einer Qualitätserhöhung bei 90% ein.

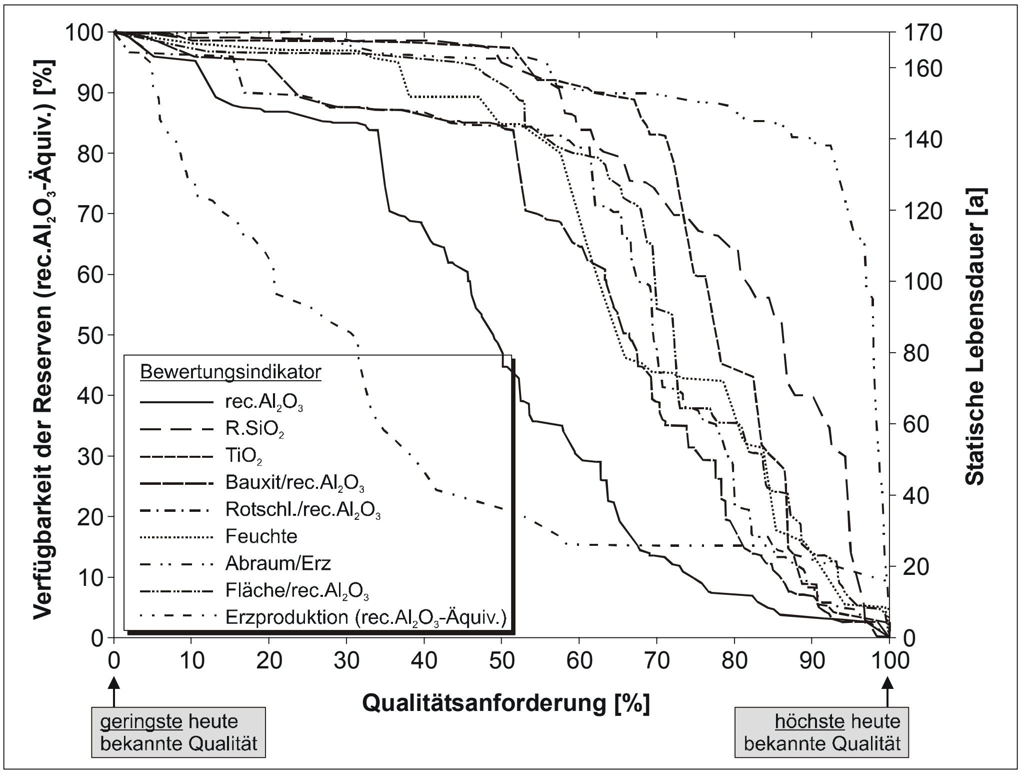

Abbildung 10: Abhängigkeit der Bauxitreserven in Bezug auf Qualitätsanforderungen [25]

Es existiert eine Vielzahl von möglichen standort- bzw. umweltbezogenen oder lagerstättenspezifischen Qualitätsanforderungen, die von Rohstoff zu Rohstoff variieren können. Bei Vergleichen mehrerer nicht-erneuerbarer Rohstoffe innerhalb einer Stoffstromanalyse sind hier entsprechende Qualitätskriterien zu definieren. Für Rohstoffvergleiche kann in der Regel der massenorientierte Metallinhalt herangezogen werden. Ein wichtiges Qualitätskriterium ist u. a. auch der Preis für den Rohstoff, da sich durch eine signifikante, dauerhafte Änderung des Preises der Cut-Off-Grade einer Lagerstätte und damit die zur Verfügung stehende Reservenmenge ändert.

Daten zur Berechnung des Indikators sind Reserven, Qualität der einzelnen ausgewiesenen gesicherte, und wahrscheinlichen Reserven, Metallinhalt, Qualitätsansprüche der produzierenden und weiterverarbeitenden Industrie.

8 Schlussfolgerungen

Die Verfügbarkeit nicht-erneuerbarer Rohstoffe ist eine wichtige Fragestellung im Rahmen der Nachhaltigen Entwicklung. Indikatoren stellen ein geeignetes Werkzeug dar, um Nachhaltigkeit messbar zu machen. Verschiedene Gesellschaften (SETAC), Kommissionen (CSD), Institute (Wuppertal Institut) und Forschungsinitiativen (SFB 525) entwerfen Indikatorkonzepte bzw. passen diese an bestehende Fragestellungen an. Mittlerweile steht eine Vielzahl unterschiedlicher Konzepte zur Verfügung. Der nachhaltigen Nutzung nicht erneuerbarer Rohstoffe wird dabei eine wichtige Stellung zugemessen. Die Vereinheitlichung der unterschiedlichen Ressourceneinsätze entlang von Produktsystemen und Stoffströmen in einem einzelnen Indikator ist jedoch bislang nur unvollständig gelöst. Dies hängt mit den einzigartigen Eigenschaften der jeweiligen Rohstoffe, ihrer Verbreitung und ihrer Vorkommen zusammen. Erst die Zusammenschau verschiedener Indikatoren erlaubt eine Beschreibung und Bewertung der Rohstoffverfügbarkeit.

Ressourcenorientierte Nachhaltigkeitsindikatoren für metallische Stoffströme basieren im Wesentlichen auf Daten zu Reserven, Produktion und Verbrauch sowie lagerstättenkundlicher Eigenschaften. In der Verknüpfung lassen sich Aussagen über Entwicklungstendenzen und Gestaltungsziele in unterschiedlichen Maßstäben (lokal bis global) und Zeitskalen (kurz- bis langfristig) ableiten. Der Abgleich der so erreichten Charakterisierung mit weiteren wesentlichen Gestaltungszielen nachhaltiger Entwicklung im wirtschaftlichen, gesellschaftlichen und ökologischen Kontext ist Gegenstand weiterer Untersuchungen.

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GEOGRAFISCHE INFORMATIONSSYSTEME UND NACHHALTIGKEITS-INDIKATOREN – MÖGLICHKEITEN UND GRENZEN *

(GEOGRAPHICAL INFORMATION SYSTEMS AND SUSTAINABILITY INDICATORS – POTENTIALS AND LIMITS)

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ABSTRACT

Sustainable Development can be characterised by the relation between the societal development and the natural, social and economical carrying capacities. The natural carrying capacity is determined by the regeneration rate and the resistance of the environment. Depending on the variety of interactions with the environment and the diversity of different environmental compartments sustainability is closely related to spatial characteristics.

Geographical Information Systems (GIS) are designed to support the analysis of spatial data in a broad variety of application areas and therefore support the continuous monitoring of spatial sustainability issues.

The possibility to differentiate spatially potential impacts but also the properties of the affected environment enables also a global assessment of global material flows considering local circumstances. Taking the primary production of aluminium as example of a metallic raw material flow indicators are developed and suggested which allow the assessment of land use and water consumption. The presented case studies have been conducted within the Collaborative Research Centre (CRC) 525 which aims at a resource orientated analysis of material flows of metallic raw materials. Within this Research Centre the Department for Engineering Geology and Hydrogeology is responsible as sub-programme for the methodological adaptation and further development of environmental impact assessment tools.

KEYWORDS

Sustainable development, indicators, Geographical Information System (GIS), land use, water

* Source: Kuckshinrichs, W; Hüttner, K.L. (Hrsg.): Nachhaltiges Management metallischer Stoffströme. Schriften des Forschungszentrums Jülich, Reihe Umwelt, Bd. 31, S. 65-87

1 [illegible]

Der Lehrstuhl für Ingenieurgeologie und Hydrogeologie (LIH) befasst sich als Untervorhaben des Teilprojektes „Umwelt“ des Sonderforschungsbereiches 525 „„Ressourcenorientierte Gesamtbetachtung von Stoffströmen metallischer Stoffströme“ (SFB 525) mit der Quantifizierung von Umwelteinwirkungen durch Flächen-inanspruchnahmen, der Nutzung lokal begrenzter Ressourcen wie Wasser und der Emission lokal und regional wirkender Substanzen. Ein Schwerpunkt liegt auf der Sammlung und Auswertung digitaler globaler Geodaten mit Hilfe Geografischer Informationssysteme (GIS), die es erlauben, die Naturraumeigenschaften beliebiger Produktionsstandorte zu quantifizieren und den auftretenden Belastungen gegenüberzustellen. Diese Parameter werden innerhalb des SFB 525 zur Bildung von Nachhaltigkeitsindikatoren genutzt.

2 [illegible]

Nachhaltige Entwicklung wird als eine dauerhafte (gesellschaftliche) Entwicklung ver-standen, die die Bedürfnisse der heutigen Generation befriedigt, ohne zu riskieren, dass zukünftige Generationen ihre Bedürfnisse nicht befriedigen können. Grundlage der nachhaltigen Entwicklung ist das Kriterium des konstanten Naturkapitalvorrats: Eine Wirtschaft ist dann nachhaltig, wenn sie einen unverminderten Kapitalvorrat pro Kopf von einer Generation zur nächsten weitergibt. Die Präzisierung von Handlungsfeldern und Themen wurde in der Agenda 21 1992 von der United Nations Conference on Environment and Development (UNCED) festgelegt [1].

Vor diesem Hintergrund hat die Enquete-Kommission "Schutz des Menschen und der Umwelt" des 12. Deutschen Bundestages vier grundlegende Regeln zum Management von Stoffströmen formuliert [2]. Die fünfte Regel wurde vom Sachverständigenrat für Umweltfragen [3] eingeführt, um dem "Aspekt der Risikovorsorge im Blick auf die Wahrung des Lebens und der Gesundheit des Menschen in Gegenwart und Zukunft" Rechnung zu tragen:

1. Die Abbaurate erneuerbarer Ressourcen soll deren Regenerationsrate nicht überschreiten. Dies entspricht der Forderung nach Aufrechterhaltung der ökologischen Leistungsfähigkeit, d.h. (mindestens) nach Erhaltung des von den Funktionen her definierten ökologischen Realkapitals;
2. Nicht-erneuerbare Ressourcen sollen nur in dem Umfang genutzt werden, in dem ein physisch und funktionell gleichwertiger Ersatz in Form erneuerbarer Ressourcen oder höherer Produktivität der erneuerbaren sowie der nicht-erneuerbaren Ressourcen geschaffen wird;
3. Stoffeinträge in die Umwelt sollen sich an der Belastbarkeit der Umweltmedien orientieren, wobei alle Funktionen zu berücksichtigen sind, nicht zuletzt auch die „stille“ und empfindlichere Regelungsfunktion;
4. Das Zeitmaß anthropogener Einträge bzw. Eingriffe in die Umwelt muss im ausgewogenen Verhältnis zum Zeitmaß der für das Reaktionsvermögen der Umwelt relevanten natürlichen Prozesse stehen;
5. Gefahren und unvertretbare Risiken für die menschliche Gesundheit durch anthropogene Einwirkungen sind zu vermeiden.

Die ersten vier grundlegenden Regeln stellen vor allem auf die Funktionsfähigkeit des Naturhaushaltes sowie die Nutzungsfähigkeit von Naturgütern ab. Die fünfte Regel knüpft zugleich an den ersten Grundsatz der Rio-Deklaration und an den Bericht der Enquete-Kommission der 12. Legislaturperiode an. Hier wird die menschliche Gesundheit in den Mittelpunkt um die Bemühungen zu einer nachhaltigen Entwicklung gestellt.

Da Naturraumeigenschaften im Bezug auf Regenerationsraten, Erneuerbarkeit, Belastbarkeit, und Reaktionsvermögen stark variieren, kann die Nachhaltigkeit einer gesellschaftlichen Entwicklung nur relativ zu den räumlichen Gegebenheiten betrachtet werden. Die räumliche Betrachtung spiegelt sich auch in der von der Commission on Sustainable Development (CSD) erarbeiteten Indikatorenliste wieder, die dazu konzipiert ist, die Nachhaltigkeit der Entwicklung einzelner Nationen zu messen. In Anlehnung an das Pressure-State-Response-Modell der Organisation for Economic Co-Operation and Development (OECD) [4] werden hierbei Indikatoren zur Messung von Triebkräften im Sinne von Belastungen, Referenzzuständen und Antworten im Sinne von Gegenmaßnahmen unterschieden. Für jedes Agenda-Kapitel werden auf diese Weise Messvorschriften erarbeitet. Nachhaltigkeitsindikatoren im Sinne der CSD sind Messgrößen innerhalb eines Indikatorensystems, mit denen der Zustand und die Trendentwicklung zur Erreichung des Ziels der nachhaltigen Entwicklung beschrieben wird. Diese Messgrößen können aus tatsächlichen Messungen von Parametern oder aus Berechnungen hervorgehen. In Tabelle 1 sind ausgewählte Agenda-Kapitel angeführt und durch die zugehörigen Indikatoren in der CSD-Liste ergänzt [5].

Es wird deutlich, dass einzelne Indikatoren nur durch das Zugrundelegen von Flächengrößen und Beobachtungen über die Zeit quantifiziert und interpretiert werden können. So ist beispielsweise die Veränderung der Landnutzung und des Landzustandes nur sinnvoll darstellbar, wenn sie auf eine Referenzfläche bezogen wird. Dies kann durchaus auf der Basis statistischer Erhebungen geschehen. Sollen jedoch Fernerkundungsdaten mit in die Messung aufgenommen werden, so wie es im CORINE-Programm für die EU durchgeführt wird, sind Werkzeuge notwendig, die die Verarbeitung und Analyse räumlicher Daten ermöglichen. Gleiches gilt für Verteilungs- und Verbreitungsparameter wie z.B. der Bevölkerungsdichte [6].

*Tabelle 1: Nachhaltigkeitsindikatoren nach CSD, *) kennzeichnet diejenigen Indikatoren, die auf eine Referenzfläche bezogen werden müssen (geändert nach [5])*

Agenda-Kapitel	Triebkraft	Zustand	Maßnahme
10 Integrierter Ansatz für die Planung und Bewirtschaftung der Bodenressourcen	Wechsel in der Landnutzung *)	Wechsel im Landzustand *)	Grad der dezentralen Bewirtschaftung von Bodenressourcen
18 Schutz der Qualität und Quantität der Süßwasserressourcen	Jährliche Entnahme von Grund- und Oberflächenwasser	Grundwasserreserven	Dichte hydrologischer Netzwerke *)
9 Schutz der Erdatmosphäre	Emission SO_2	Kritische Belastungsgrenzen *)	Ausgaben zur Vermeidung der Luftverschmutzung

3 [illegible]

Wie gezeigt setzt die Konkretisierung des Leitbildes der Nachhaltigen Entwicklung in breitem Umfang auf räumlichen Daten auf. Diese werden heute in Geografischen Informationssystemen (GIS) erfasst, aufbereitet, analysiert und dargestellt. Der Begriff GIS wird homonym sowohl für GIS-Software, als auch für GIS-Projekte verwendet. Die GIS-Software ist dabei ein Werkzeug, mit dem Geodaten erfaßt, verwaltet, analysiert, fortgeführt und präsentiert bzw. ausgegeben werden können. Zu den wesentlichen Funktionen von GIS-Software zählt die Fähigkeit, räumlich refenzierte Objekte wie Punkte, Linien oder Polygone, aber auch Bilddaten mit einander in Beziehung zu setzen [7]. Über die Abbildung von Eigenschaftsdaten zu diesen Objekten in verknüpften Tabellen können nicht nur geometrische, sondern auch logische Fragestellungen bearbeitet werden.

Als GIS-Projekt wird alles bezeichnet, was für digitales raumbezogenes Arbeiten notwendig ist, also neben den funktionalen Eigenschaften der Software auch Daten und deren Organisationsform.

Dem Anwender werden GIS-Projekte meist in Fachschalen bereitgestellt, die ausgewählte Abfragen und Analysefunktionen anwendungsbezogen beinhalten. Häufig werden auch schon Datensammlungen wie z.B. das ATKIS (Amtliches Topographisch-Kartographisches Informationssystem der Landesvermessungsämter) als GIS bezeichnet.

GIS-Projekte können über den Anwendungsbereich unterschieden werden. Dieser reicht von der Vermessungstechnik über die Geo- und Biowissenschaften bis zur Kriminalistik. Ein weiteres wichtiges Unterscheidungsmerkmal ist der Zeitaspekt. Es werden zeitlich begrenzte Untersuchungsprojekte und Dokumentationsprojekte als Daueraufgabe bei Behörden und Versorgungsunternehmen unterschieden. Daneben werden GIS-Projekte über den Betrachtungsraum unterschieden. Sofern politische

(Verwaltungs-) Grenzen den räumlichen Rahmen bilden, werden kommunale, nationale und internationale GIS-Projekte unterschieden. Wird der Rahmen durch natür-liche Phänomene gebildet (Küstenlinien, Wasserscheiden) könen lokale regionale und globale GIS-Projekte unterschieden werden. Im Weiteren wird der Begriff GIS für GIS-Software im engeren Sinne verwendet.

Im Rahmen der Nachhaltigen Entwicklung werden drei Aufgabenfelder durch GIS abgedeckt:

Dies sind zum einen katastrale Aufgaben, also die Fortschreibung räumlicher Parameter über die Zeit. Auf kommunaler Ebene kann dies das Grünflächenkataster sein, auf nationaler Ebene ein Kataster der Waldflächen und auf internationaler Ebene die Verwaltung globaler Schutzgüter, wie z.B. des tropischen Regenwaldes. Auch soziale (Zugang zu sauberem Wasser) oder wirtschaftsgeografische Parameter (Dichte der Infrastruktur) sind mit Hilfe von GIS mess- und fortschreibbar und könen teilweise direkt als Nachhaltigkeitsindikatoren eingesetzt werden.

Die analytischen Möglichkeiten, räumliche Daten miteinander in Beziehung zu setzen und weitere Parameter oder auch Indikatoren zur Betrachtung der Nachhaltigkeit bereitzustellen, ist eine weitere Aufgabe von GIS. So etwa die Verschneidung von bodenkundlichen und klimatologischen Daten zur globalen Darstellung und Analyse der Bodendegradation [8].

Kommunikative Aufgaben bei der Integration von Anspruchsgruppen ist ein weiterer wichtiger Beitrag von GIS im Bereich der nachhaltigen Entwicklung. Bürgerinformationssysteme [9] sowie globale Informationssysteme über den Zustand weltweiter Ressourcen [10] greifen den Raumbezug auf, um Informationen anschaulich zu vermitteln.

4 [illegible]

Will man die Nachhaltigkeitsregeln auf metallische Stoffströme anwenden, so erhebt sich die Frage, welche Naturräume oder welches Naturkapital durch Aktivitäten des Stoffstroms tangiert werden. Die Definition von Regenerationsraten, Erneuerbarkeiten, Belastbarkeiten, und Reaktionsvermögen ist komplex angesichts großer Massenströme an einzelnen Standorten, länderweiten Recycling-Systemen sowie der teils länderübergreifenden Energiebereitstellung.

Besonders Prozesse der Primärproduktion, wo an einzelnen Standorten große Massenströme und Emissionen auftreten, lassen sich nicht durch einen globalen Referenzzustand vereinheitlichen. Hinzu kommt die unterschiedliche Quellstärke für einzelne Belastungen, die durch die unterschiedlichen Produktionsmengen und eingesetzten Techniken bestimmt wird.

Es erscheint daher sinnvoll, einzelnen Standorten das jeweilige Naturkapital als Sammelbegriff für die Eigenschaften des Naturraums gegenüberzustellen. Dazu wurde in der ersten Antragsphase (1997-1999) des SFB 525 ein Umweltinformationssystem entwickelt, in dem am Beispiel des Aluminiums Geodaten und Standortinformationen miteinander verknüpft wurden. In einzelnen Fallstudien wurden dann ausgewählte Parameter zu Indikatoren aggregiert und auf Teile des betrachteten Systems angewendet. Gegenwärtig wird innerhalb des SFB 525 an einem einheitlichen Indikatorensystem gearbeitet, welches sich mit Stoffstrom-, Sektor- und Produktindikatoren an dem Rahmenwerk der CSD orientiert [11].

5 [illegible]

Um die Zuordnung von Prozessen in den jeweiligen Naturraum zu ermöglichen, wurde ein Umweltinformationssystem konzipiert, welches als GIS-Projekt auf einem GIS aufsetzt. Dieses GIS-Projekt besteht aus drei Hauptkomponenten. Die Standort-datenbank, innerhalb derer Daten zu Standorten abgelegt werden, den Geodaten, die zu einzelnen Merkmalen flächendeckend raumbezogene Daten liefern, sowie Parametertabellen, in denen die Naturraumeigenschaften in der Umgebung der erfassten Standorte abgebildet werden.

Standortdaten

In der Standortdatenbank werden die Standorte der Primärmetallproduktion erfaßt Für das Beispielmetall Aluminium wurde für die Koordinatenfindung zunächst die vom U.S. Geological Survey herausgegebene Datenbank zu Standorten der globalen Rohstoffgewinnung und -verarbeitung ausgewertet [12]. Darüber hinaus wurden für weitere in der Literatur bezeichnete Standorte die Standortkoordinaten ermittelt [13-15] und innerhalb des SFB 525 abgestimmt.

Gegenwärtig sind 377 Standorte erfasst, davon 70 Gewinnungsstandorte, 93 erschlossene, aber nicht in Betrieb befindliche Lagerstätten, 75 Standorte der Aluminiumoxidproduktion und 139 Standorte der Aluminiumelektrolyse. Bis auf wenige Standorte in der Volksrepublik China und der Gemeinschaft Unabhängiger Staaten (GUS) ist diese Erfassung vollständig. Die Genauigkeit der Standortkoordinaten hängt von den Erfassungsgrundlagen ab und schwankt z.T. erheblich. Aus diesem Grund wurden die Daten einer einfachen Prüfroutine unterzogen, indem die erfassten Koordinaten auf höher aufgelöste digitale topographische Karten projiziert und manuell korrigiert wurden. Im Ergebnis ist davon auszugehen, dass die Abweichung vom tatsächlichen Standort überwiegend im Bereich von wenigen Kilometern liegt. Bei Standorten, über die nur wenige Informationen verfügbar sind, beträgt die Abweichung bis zu 20 km. Die Standortdatenbank ist für die Erfassung beliebiger Standorte auch anderer Metalle konzipiert.

Geodaten

Neben den Standortkoordinaten wurden unabhängig vom zu betrachteten Metall Geodaten in das GIS-Projekt aufgenommen. Für die zu bearbeitende Fragestellung müssen diese Daten bestimmten Anforderungen entsprechen. Zum einen müssen sie global flächendeckend für das Festland zur Verfügung stehen. Daraus ergibt sich, daß die Kartiereinheiten oder Merkmale in einem globalen Kontext auf einer vergleichbaren Erhebungsbasis bereitgestellt werden müssen. Um die Daten zusammenzuführen und für Einzelstandorte auszuwerten, müssen sie georeferenziert sein, das heißt, sie müssen über ein dokumentiertes Koordinatensystem verfügen. Neben der Dokumentation des Koordinatensystems müssen die Daten inhaltlich dokumentiert sein. Dazu zählen Angaben zur Genauigkeit, bezogen auf das betrachtete Merkmal und dessen räumliche Verbreitung.

Zu den derzeit abgebildeten Geodaten zählen großmaßstäbliche Vektordaten des digitalen Weltatlas (DCW - Digital Chart of the World) im Maßstab 1 : 1.000.000 mit topographischen Daten zu politischen Grenzen, Land- und Wasserverteilung, Besiedlung, Infrastruktur und Drainagenetz [16] sowie Vektordaten der FAO-Bodenkarte im Maßstab 1 : 5.000.000 mit Daten zur Verbreitung von Bodenarten und deren Eigenschaften [17].

Als Beispiel für großmaßstäbliche Vektordaten ist in Abbildung 1 ein Ausschnitt der Bodenkarte der FAO dargestellt.

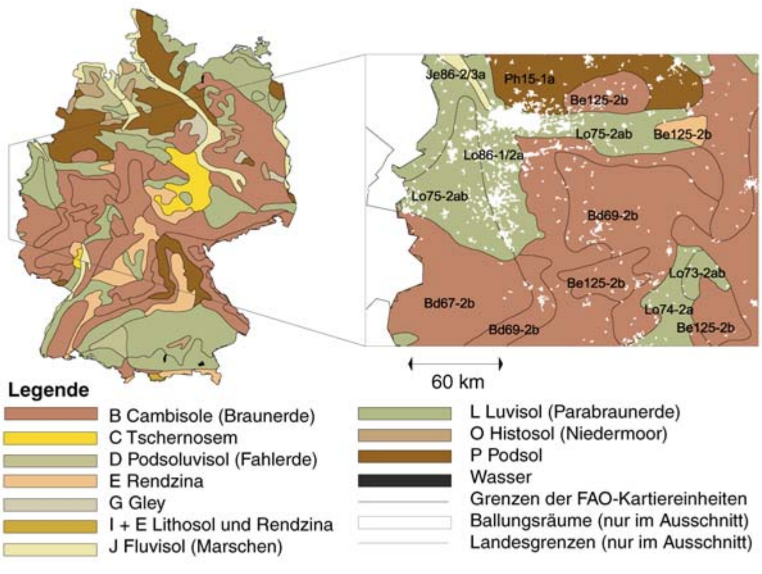

Abbildung 1: FAO-Bodenkarte Deutschlands mit einem Ausschnitt für Nordrhein-Westfalen; Flächentreue Lambert-Azimutal Projektion [18]

Auf der Basis multitemporaler Fernerkundungsdaten wurden auch hochaufgelöste Rasterdaten zur Landbedeckung mit einer Zellengröße von 30“ x 30“ geografischer Länge zu Breite (das entspricht einer Zellengröße von 1 km²) (GLCC - Global Land-cover Characteristics Data Base) [19] (Abbildung 2) sowie Rasterdaten zur Morphologie aus dem digitalen Geländemodell GTOPO30 des US Geological Surveys [20] in gleicher Auflösung aufgenommen. Zur Verdeutlichung dieses Maßstabsbereichs sind Ausschnitte aus der GLCC in Abbildung 2 dargestellt.

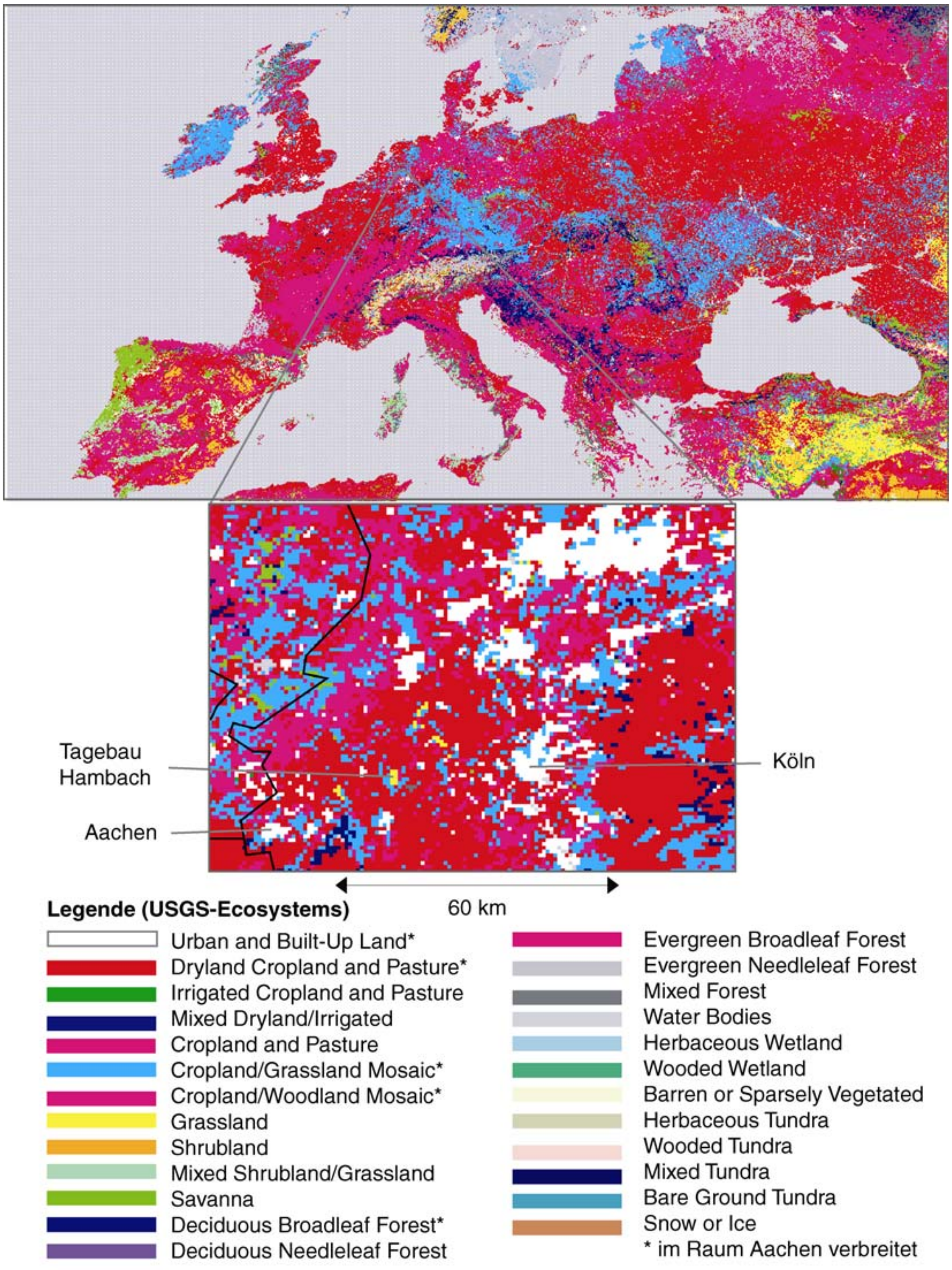

Abbildung 2: Globale Landbedeckungsdaten der GLCC (Global Land Cover Characteristics Data Base) für Europa und das westlicher Nordrhein-Westfalen, Flächentreue Goode-Homolosine Projektion [18]

Klimatologische Informationen stehen in grober Auflösung (zwischen 2° x 2° und 0,5° x 0,5° geografische Länge zu Breite) (CIDC- Climatology Interdisciplinary Data Collection) [21, 22] ebenso wie eine georeferenzierte Datenbank zur Bevölkerungsdichte und -verteilung [23] zur Verfügung.

Neben diesen Daten und ihrer Aktualisierung werden ständig weitere Geodaten in das GIS-Projekt eingepflegt. Dies sind in der Regel synthetische Daten, d. h. Daten, die aus anderen Daten hervorgehen wie bspws. die hydrologischen Daten des USGS [24], Daten zu ökologischen Belastungsgrenzen [25] oder Daten zu Evapotranspirationsraten [26]. In Abbildung 3 ist die räumliche Auflösung von berechneten Niederschlagsabflüssen in einem 1° x 1°-Raster dargestellt.

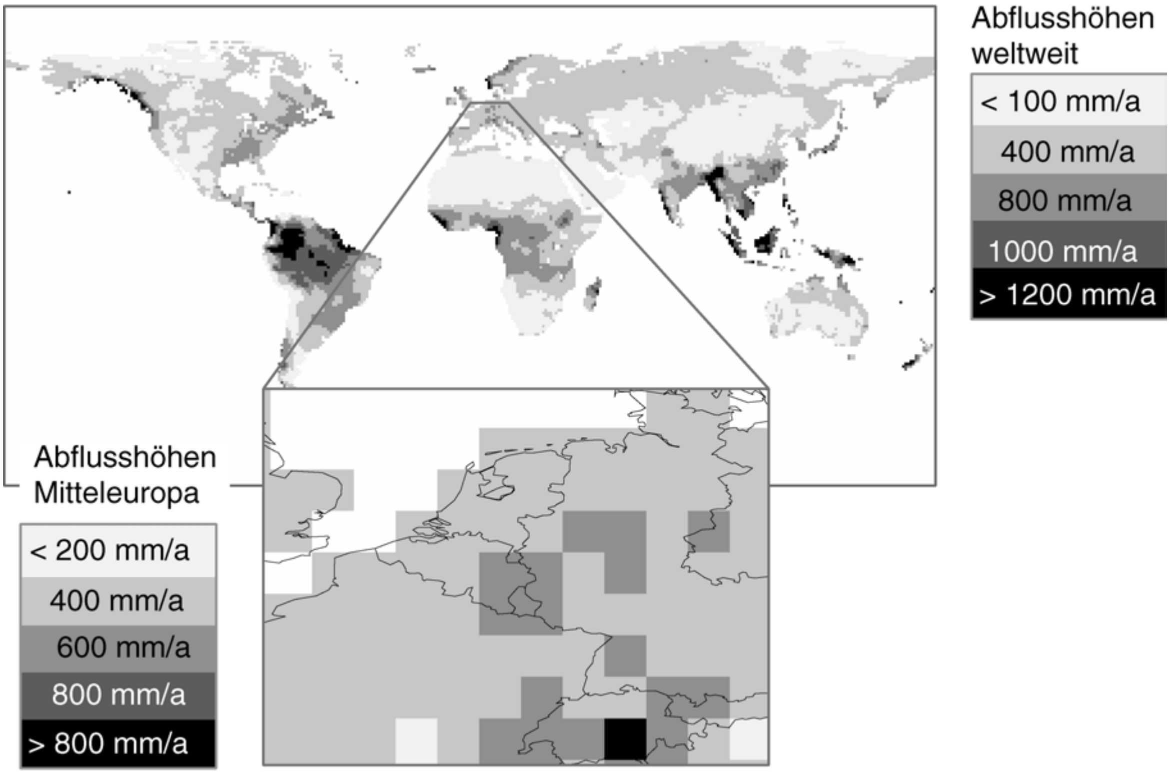

Abbildung 3: Abflusshöhen weltweit und für das westliche Mitteleuropa; Geografische Projektion [18]

Parametertabellen

Die erhobenen Geodaten stehen innerhalb des GIS zur Verfügung und können genutzt werden, um Einzelstandorte zu charakterisieren. Aufgrund unterschiedlicher Datentypen (intervallskalierte Daten, nominale Daten sowie diskrete Daten), unterschiedlichen Auflösungen bzw. Maßstäben und unterschiedlichen geometrischen Projektionen wurden für jeden Geodatensatz Routinen entwickelt, um die jeweilige Merkmalsausprägung des Naturraums in Tabellenform abzulegen.

Die Flächeninhaltsermittlung der Flächen in der Umgebung eines Einzelstandortes dient dazu, einen Wichtungsfaktor für die entsprechenden Merkmale (Landbedeckung, Bodenart) zu erheben. Als Arbeitsansatz wurde für die hochaufgelösten Daten ein Radius von 50 km um den Einzelstandort als Selektionsgeometrie festgelegt.

Der Radius begründet sich aus der beschriebenen Ungenauigkeit der Standortkoordinaten und der Großflächigkeit von Lagerstätten und Tagebauen. Bei den zur Verfügung stehenden Daten ist nicht in allen Fällen nachzuvollziehen, ob die angegebenen Koordinaten den geometrischen Schwerpunkt der Lagerstätte, das gegenwärtige Abbaufeld oder die Lage der Verladeeinrichtungen bezeichnen. Zwischen diesen Bestandteilen eines Standortes liegen z.T. erhebliche Distanzen. Ausgehend von möglichen Auswirkungen, die im Nahbereich über das Gelände eines Standortes hinausgehen, erschien es deswegen sinnvoll, den vereinbarten Radius von 50 km als Konstruktionsgrundlage für eine künstliche Erfassungsumgebung zu definieren. Diese Umgebung wird als Selektionsgeometrie genutzt, um die Raster, Linien und Flächeninformationen der Geodaten auszuwerten. Diese werden für den Einzelstandort in eine lokale Projektion zur Messung von Längen und Flächen überführt.

Für die gering aufgelösten Rasterdaten, für die die Auflösung geringer ist als die Genauigkeit der Standortkoordinaten, werden die Zellattribute (z.B. Niederschlag) dem Standort als Einzelwert zugewiesen. Zum Teil sind diese Daten nur auf dem Festland definiert. Aufgrund der geringen Auflösung werden kleinere Inseln und einzelne Kü-stenverläufe nicht abgedeckt. In diesen Fällen werden die benachbarten Zellen zur Auswertung genutzt. Neben diesen Analysetechniken können auch Distanzwerte bestimmt werden. Diese können in Einzelfällen je nach Fragestellung weitere Auswertungen ermöglichen. Im Folgenden wird nicht weiter auf diese Maße eingegangen. Ein Beispiel findet sich in [27]. In Abbildung 4 sind diese Analysemöglichkeiten illu-striert.

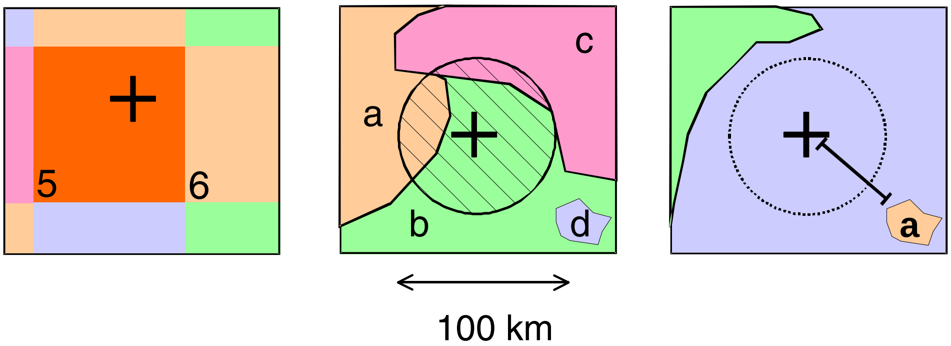

Abbildung 4: Eingesetzte GIS-Funktionen zur Bestimmung von standortspezischen Parametern (Identifikation, Flächeninhalte, Distanzen)

Die ausgewerteten Daten werden als Parameter themenbezogen abgebildet:

- Im Thema Topographie werden die Flächeninhalte der Land- und Wasserflächen mit einer Unterscheidung von Meeres- und Binnengewässern abgebildet. Diese werden zur Quantifizierung der Flächeneigenschaften in den Themen Boden und Vegetationsbedeckung benötigt. Das Verkehrs- und Gewässernetz sowie die Besiedlungsräume werden als Orientierungskarten und zur Plausibilitätsprüfung von Standortkoordinaten bereitgestellt. Das Thema Topographie wird ergänzt um die hydrografischen Derivate des GTOPO 30 Modells, die ein generisches Gewässernetz und Einzugsgebietsgrößen beinhalten;
- Im Thema Landbedeckung werden die Flächeninhalte der unterschiedlichen Landbedeckungsarten innerhalb der Erfassungsumgebung ermittelt. Dies erlaubt die qualitative Betrachtung einzelner Bedeckungsarten, aber auch die Aggregation unterschiedlicher Bedeckungsarten über Leistungsparameter;
- Analog zu den Daten zur Vegetationsbedeckung werden im Thema Boden die Flächeninhalte der Kartiereinheiten der FAO-Bodenkarte sowie deren Verknüpfung zu den Bodeneigenschaften bereitgestellt. Das Thema Boden wird ergänzt um die ökologischen Belastungsgrenzen;
- Im Thema Morphologie werden die Höhendaten des digitalen Geländemodells hinsichtlich der Reliefenergie ausgewertet und dargestellt. Die Informationen umfassen die statistische Beschreibung der morphologischen Verhältnisse über die Hangneigung und die Höhe ü. NN;
- Im Thema Bevölkerung wird die Bevölkerungsdichte (Stand 1990) angegeben;
- Informationen zu Niederschlag, Verdunstung, Temperatur und Windverhältnissen werden im Thema Klima bereitgestellt. Die kleinste Zeiteinheit in den Ausgangsdaten ist das Monatsmittel. Dieses wird als Zeitreihe über ein Jahr abgebildet.

Die auf diese Weise vorgenommene themenbezogene Parameterbestimmung bildet die Grundlage zur Analyse von Einzelstandorten sowie zur vergleichenden Betrachtung mehrerer Standorte. Über die Abbildung innerhalb einer relationalen Datenbank werden themenübergreifende Aggregationen und Abfragen ermöglicht. Die Parameter werden in dem Informationssystem des SFB 525 abgebildet und mit den tech-nischen Prozeßdaten sowie ergänzenden Standortinformationen verknüpft. In Abbildung 5 sind die Verknüpfungen einzelner Tabellen abgebildet.

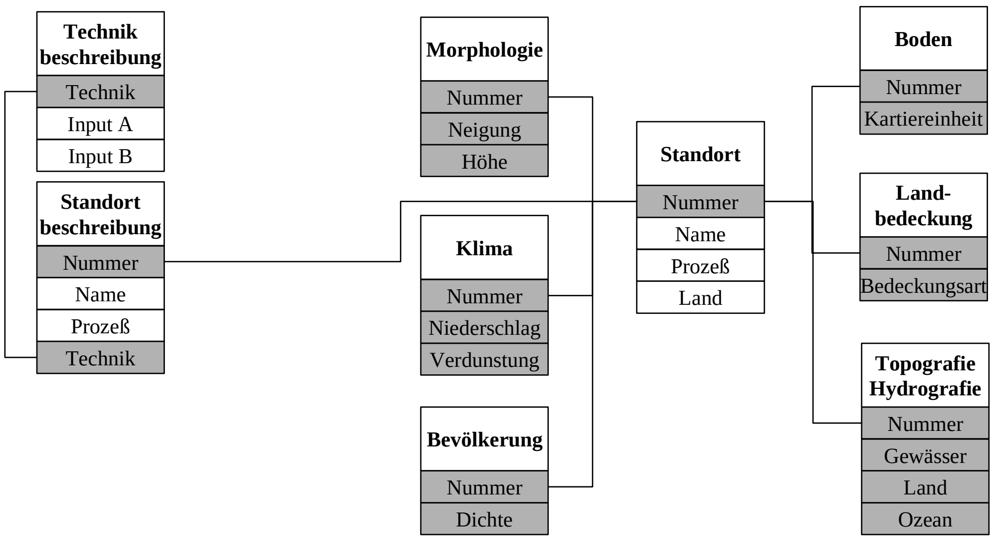

Abbildung 5: Verknüpfung der Parametertabellen mit den Technikbeschreibungen und Standortbeschreibungen im Gesamtinformationssystem des SFB

6 [illegible]

Die auf diese Weise zusammengestellten Parameter können nun zur Auswertung genutzt werden. Neben der Möglichkeit, qualitative Aspekte zu diskutieren, können die Parameter genutzt werden, um quantitative Indikatoren abzuleiten. Die Konstruktion der Indikatoren lehnt sich an die Wirkungsabschätzung der Produkt-Ökobilanz (LCA) nach den ISO 14040 Standards an [28]. Aufbauend auf der Sachbilanz folgt die Wirkungsabschätzung (LCIA - Life Cycle Impact Assessment), innerhalb derer unterschiedliche In- und Outputs über Äquivalenzfaktoren aggregiert werden. Diese ordnen den Beitrag eines einzelnen Flusses zu einem Schadensmechanismus in der Umwelt zu. Das Ergebnis wird als Wirkungspotenzial bezeichnet.

Für jede Kategorie wird dieser Wirkungsparameter nach der generellen Gleichung (1) [29] berechnet:

$$N_j = \sum_i M_{ij} * Q_i \qquad (1)$$

N = Wirkungspotenzial

M = Umweltintervention in Kategorie j

Q = Äquivalenzfaktor für die Intervention i

Ein bekanntes Beispiel ist das Versauerungspotenzial, welches die Menge an H^+ Ionen beschreibt, die von einer Emission an Wasser oder Luft abgegeben werden kann. Die Versauerungspotenziale werden in SO_2-Äquivalenten ausgedrückt. Die Stärke dieses An satzes ist es, dass über diese Äquivalenzfaktoren eine Vielfalt von emittierten Substanzen zu einer kleinen Anzahl Parametern oder Indizes zusammengerechnet werden können.

In der gegenwärtigen LCA wird nicht unterschieden, an welchem Ort die Belastung auftritt. Regionale Eigenschaften oder Sensitivitäten werden nicht berücksichtigt. Erste Regionalisierungen hinsichtlich der Versauerung und der Eutrophierung werden durch länderspezifische Äquivalenzfaktoren ermöglicht [30].

Um den Einzelstandort im metallischen Stoffstrom und seine standortspezifischen Wirkungspotenziale abzubilden, ist es erforderlich, die allgemeine Gleichung (1) um zwei weitere Faktoren zu erweitern. Dies ist zum einen die Quellstärke einer Bela-stung am Einzelstandort, um die Einzelergebnisse gewichtet aggregieren zu können und der Standort- oder landesspezifische Charakterisierungsfaktor als Maß für die jeweilige Tragekapazität.

Die generelle Gleichung (1) wird daher in Gleichung (2) eingebettet.

$$N_{jk} = \frac{\sum_{l=1}^{n_k} \left(\sum_{i=1}^{m_j} M_{ji} * Q_i \right) * Q_l * A_l}{\sum_{l=1}^{n_k} A_l} \qquad (2)$$

A = Quellstärke der Intervention am Standort *l*

k = Elemente in der Aggregation

n = Anzahl der Standorte für das Element k

m = Anzahl der Interventionen/Substanzen in der Kategorie j

Als Näherungswert für die Quellstärke wird im Falle von Raffinerien und Schmelzhütten die installierte Kapazität eingesetzt, da Produktionszahlen nicht für alle Standort zur Verfügung stehen. Für Bergbaubetriebe wird die Produktion in einem festgelegten Referenzjahr verwendet. Über diese Näherung können die auf diese Weise berechneten Indikatoren für Technikkategorien, Unternehmen, Länder oder Regionen bis hin zu globalen Durchschnittswerten aggregiert werden [31].

Anhand von zwei Beispielen sollen im Folgenden die Möglichkeiten und Grenzen des GIS-Einsatzes bei der Indikatorberechnung vorgestellt werden.

Fläche

Die Belegung und Transformation von Flächen ist auch bei metallischen Stoffströmen relevant. Kurz- bis langfristige Flächenbelegungen treten beim Bergbau und bei der Entsorgung von Produktionsabgängen und Abfällen besonders in Erscheinung und ist grundsätzlich mit der Transformation von Flächeneigenschaften verknüpft. Das integrierte Management von Bodenressourcen (Kapitel 18, Agenda 21) beinhaltet dieses Thema. In dem LCA ist Landnutzung (land use) eine eigenständige Wirkungskategorie. Die Nutzung von Flächen ist mit unterschiedlichen Wirkungspfaden verknüpft (Abbildung 6).

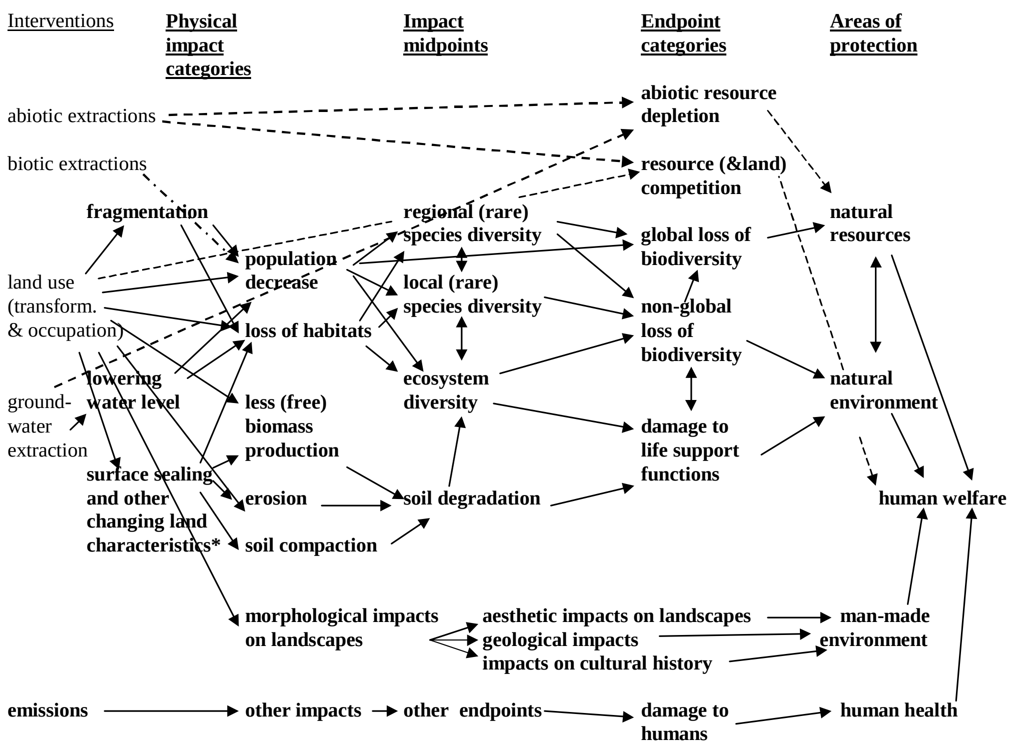

Abbildung 6: Wirkungspfade der Landnutzung und der Entnahme von Ressourcen [32]

Die von der Transformation und Belegung ausgehenden Wirkungen lassen sich in unterschiedlichen Kategorien zusammenfassen. Innerhalb dieser Kategorien treten verschiedene Effekte auf, die auf die betrachteten Schutzgüter bezogen werden können. Es wird deutlich, dass zur vollständigen Abbildung der möglichen Wirkungen sowohl im Sinne der Wirkungsabschätzung des LCA als auch im Sinne des dreispaltigen CSD-Ansatzes eine Vielzahl Indikatoren erforderlich wären.

Die im weiteren beschriebene Indikatorkonstruktion versucht stellvertretend für die Vielzahl an möglichen Wirkungen ein operables Maß für die Bela stung an einem Einzelstandort dazustellen.

Die Belegung als Belastung wird nach [32] in der Einheit [am²/t] quantifiziert. Durch die Einführung der Dauer werden kleinräumige und langfristige Belegungen mit großflächigen, aber kurzzeitigen Belegungen gleichgestellt. Damit wird indirekt auch die Folgenutzung berücksichtigt.

Um den Flächengebrauch eines Bergbauunternehmens abzuschätzen, werden die Abbauflächen über die Geometrie des Erzkörpers und des Deckgebirges ermittelt. Die Landnutzung für Infrastruktur wird aus einer Korrelationsfunktion abgeschätzt, die in sechs Feldstudien ermittelt wurde [33]. Die Dauer des Bergbaus wird aus eigenen Erhebungen und Literaturstudien abgeleitet [33]. Da nicht für alle Bergbaubetriebe gesicherte Angaben über die Dauer vorliegen, werden für Betriebe, für die eine Rekultivierung wahrscheinlich erscheint, 2 Jahre für die Flächenbelegung angenommen. Wo keine Rekultivierungsmaßnahmen anzunehmen sind, werden 10 Jahre angenommen. Produktionszahlen und Reserven werden für die Abschätzung der In-frastruktur genutzt [33].

Der Flächengebrauch der Tonerderaffinerien wird getrennt für die Rotschlammdeponierung und die Produktionsanlagen abgeschätzt. Der Betrag und die Dauer der Belegung durch die Deponierung wird vom Zustand des verbrachten Materials wesentlich mitbestimmt. Gegenwärtig können fünf Deponierungsarten unterschieden werden [34]. Für das Produktionsgelände der Tonerderaffinerien und Aluminiumelektrolysen werden aus Fallstudien erhobene Werte verwendet.

Mit der Landnutzung hängt kein unmittelbarer Schadensmechanismus zusammen. Jede Belegung erscheint gleichgewichtet in der Sachbilanz. Um unterschiedliche Tragekapazitäten zu berücksichtigen, können nun die Parameter aus der Parameterdatenbank genutzt werden, um Eigenschaften und darüber auch Charakterisierungsfaktoren abzuleiten.

Ausgehend von einer Ursache-Wirkungsanalyse für den Bauxitbergbau wurden fünf Faktoren ermittelt: Bodenerosion durch Wind, Bodenerosion durch Wasser, Verminderung der Grundwasserneubildungsrate, der Natürlichkeitsgrad und der Ökosystemindikator [35].

Der Natürlichkeitsgrad und der Ökosystemindikator sollen stellvertretend für die anderen auch wegen ihrer Relevanz für die subsequenten Prozessschritte vorgestellt werden. Der Natürlichkeitsgrad gibt als Indikator Auskunft darüber, zu wie viel die Standortumgebung bereits anthropogen genutzt wird, sei es für Landwirtschaft oder Besiedlung. Für diese Abschätzung wird das Landbedeckungsmuster der Standortumgebung in der Datenbank abgebildet. Die Charakterisierung der Landbedeckung erfolgt nach dem Land Cover Scheme des U.S. Geological Survey. Dieses Schema enthält bei einer übersichtlichen Klassenanzahl von 24 Klassen auch unterschied-liche landwirtschaftliche Nutzungsarten.

Mit den auf die Einheitsfläche mit dem Radius 50 km bezogenen Flächengrößen für die einzelnen Bedeckungsarten wird nun das Verhältnis von durch menschliche Nutzung gegenwärtig überprägten Flächen zu natürlichen Flächen gebildet. Das Verhältnis reicht von 0 bis 1, wobei 1 einen unbeanspruchten Naturraum indiziert [35].

Die Natürlichkeit ist weder mit einem besonderen Umweltschutzgut verknüpft, noch mit einem Umweltschadensmechanismus. Allerdings erlaubt er die Formulierung, in welchem Maße eine Störung natürlicher Ökosysteme wahrscheinlich ist.

Über Klassifikationstabellen kann der Natürlichk eitsgrad um eine Leistungsbeschreibung der jeweiligen Landbedeckungen erweitert werden. Durch die Quantifizierung der Netto-Primär-Produktion der Vegetation kann den unterschiedlichen natürlich Landbedeckungsarten der Umsatz an Biomasse zugewiesen werden. Dies ermöglicht die Unterscheidung bspws. von Wüsten, Tundren und Wäldern. Als Einheit wird Kilogramm Trockensubstanz angegeben, die durch die Flächenbelegung nicht akkumuliert wird [35]. Für beide Teilprozesse ist die Flächeninanspruchnahme, der Natürlichkeitsgrad sowie der Ökosystemindikator im globalen kapazitätsgewichteten Mittel abgebildet (Abbildung 7).

Es zeigt sich, dass der Flächengebrauch des Bergbaus das vierfache des Gebrauchs durch die Deponien beträgt. Der Natürlichkeitsgrad ist an den Bergbaustandorten leicht höher. Der Ökosytemindikator, der Auskunft gibt über die Produktivität der natürlichen Landbedeckung, beträgt das sechsfache im Vergleich von Bergbau und Deponierung.

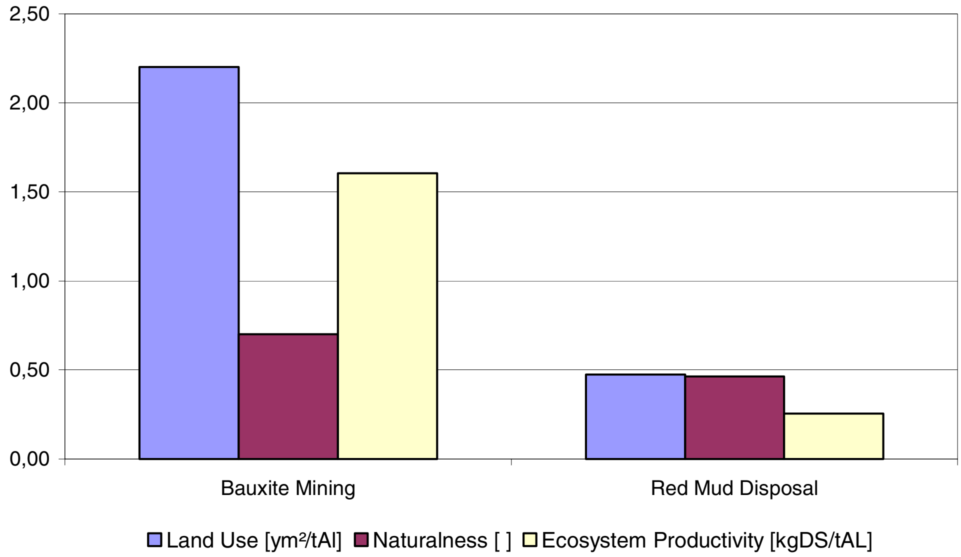

Abbildung 7: Flächengebrauch, Natürlichkeitsgrad und Ökosystemindikator für den Bauxit-Tagebau und die Entsorgung von Rotschlamm bei der Tonerderaffination [36]

Wasser

Süßwässer mit der Ausnahme fossiler Grundwässer sind erneuerbare Ressourcen, die jedoch in Qualität und Quantität stark zwischen einzelnen Standorten variieren. Der Wasserverbrauch wird in dem Kapitel 12 der Agenda 21 behandelt. Dieses Kapitel trägt den Titel „Schutz der Quantität und Qualität der Süßwasserreserven". In der Wirkungsabschätzung des LCA wird der Wasserverbrauch in der Wirkungskategorie „Erschöpfung abiotischer Ressourcen" angesprochen [32].

Im Vergleich zu anderen abiotischen Ressourcen kann Süßwasser sowohl als Fluß-Ressource, d.h. als konstante an einem Ort verfügbare Menge, oder auch als Natur-Kapital, d.h. als in einem Einzugsgebiet insgesamt verfügbare Menge betrachtet werden. Die Erschöpfung eines Flusses thematisiert die Wasserentnahme in einem Drainagenetz über die Regenerationsrate hinaus, die Erschöpfung des Kapitals bezeichnet eine Veränderung der Regenerationsraten selbst [32].

Effekte auf die Qualität, welche durch Emissionen oder die Einleitung von Abwässern verursacht werden, werden in anderen, dazu besser geeigneten Wirkungskategorien betrachtet. Der Wasserverbrauch wird im SFB 525 definiert als die Menge Wasser, die der lokalen Umwelt an einem Standort durch Verdunstung oder als Wassergehalt in Produkten und Abfällen entzogen wird. Der bezogene Schadensmechanismus ist die Erschöpfung einer Fluss-Ressource.

Wasserentnahmen in größerem Umfang sind für die Tonerderaffinieren kennzeichnend. Im engeren Rahmen werden Kühlwasserverluste und die Restfeuchte in den verbrachten Rotschlämmen angegeben. Der durchschnittliche technische Verbrauch wird mit einem technischen Minimum von 1 m^3/t alumina angenommen. Die Restfeuchte im Rotschlamm wird durch den verarbeiteten Bauxit und die Aufbereitung bestimmt. Sie variiert zwischen 30% und 50% und liegt zwischen 0,2 und 0,8 m^3/t alumina [34].

Die Herkunft des Süßwassers ist nur für einzelne Standorte bekannt und wird daher nicht im technischen Inventar abgebildet. Auch wenn Salzwasser oder Abwässer zur Substitution genutzt werden, kann dies nicht berücksichtigt werden.

Um eine spezifische Entnahme mit der Versorgungssituation zu gewichten wird ein Charakterisierungsfaktor über die Parameter des Informationssystems abgeleitet. Dieser Faktor ist das Verhältnis von Wasserbedarf und Wasserangebot und damit ein Indikator für eine Wasserknappheit am betreffenden Standort. Als Term für den Wasserbedarf wird der länderspezifische Verbrauch pro Kopf mit der standortspezi-fischen Bevölkerungsdichte multipliziert. Die Verfügbarkeit wird über die klimatologische Wasserbilanz, also die Differenz zwischen Niederschlag und Evapotranspirationsraten, abgeschätzt. Flüsse werden nicht berücksichtigt.

Der so gebildete Charakterisierungsfaktor beschreibt somit den Anteil des gebrauchten Wasser am jährlich wiederergänzbaren Wasserdargebot. Der Faktor beträgt 1, wo die Verfügbarkeit dem Verbrauchsverhalten der Bevölkerung entspricht.

Nach Kulshreshtra [37] wird bei einem Verhältnis > 0.8 [m³/capita a] der erneuer-baren Trinkwasserressourcen von einer ernsten Wasserknappheit gesprochen, unabhängig vom verfügbaren Wasser pro Kopf und Jahr.

Abbildung 8 zeigt den weltweiten kapazitätsgewichteten Durchschnittswasserverbrauch der Tonerderaffinerien. Dabei wurden Techniken unterschieden, bei denen Wasser zurückgewonnen wird, und Techniken, bei denen das Wasser im Rotschlamm verbleibt. Es zeigt sich, dass sich der Nettoverbrauch durch die Rückgewinnung geringfügig verringern lässt.

Generell wird der Wasserverbrauch über diesen Indikator scheinbar gegenüber dem tatsächlichen Verbrauch verringert. Im Vergleich der unterschiedlichen Techniken wird deutlich, dass die Verknappung bei den Standorten, an denen Wasser zurückgewonnen wird, trotzdem deutlich höher ist, als dort, wo keine Wasserrückführung im Deponierungsverfahren vorgesehen ist. Über das übergeordnete Nachhaltigkeitsziel Ressourcenschutz hinaus können auf diese Weise konkret Potenziale abgeschätzt und prioritäre Handlungsfelder festgelegt werden. Durch die Disaggregation dieser Mittelwertsbildung auf Länder- und Standortebene sind Präzisierungen bis auf das Verursacherniveau möglich.

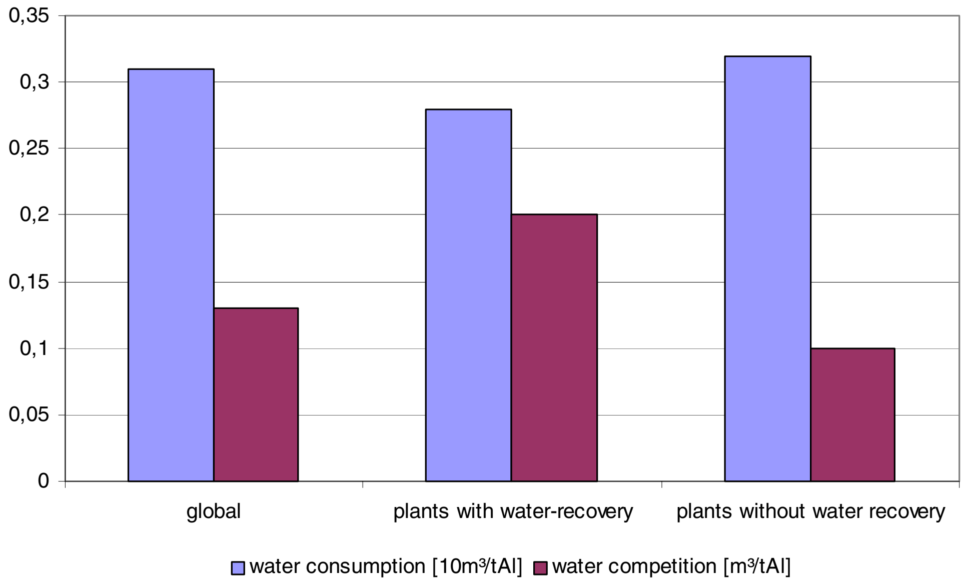

Abbildung 8: Wasserverbrauch an Standorten der Tonerderaffinerien [36]

7

In den Anwendungsbeispielen konnte gezeigt werden, dass die Nutzung von GIS zur Ableitung von naturräumlichen Parametern einen wesentlichen Beitrag zur Bildung von Nachhaltigkeitsindikatoren leisten kann. Die vorgestellte Indikatorenkonstruktion über den Einsatz von GIS ermöglicht die Identifikation von Herausforderungen für die einzelnen Akteure im Stoffstrom. Durch die Möglichkeit, unterschiedliche Aggregate zu bilden (Standorte, Techniken, Länder) können Hinweise darauf gewonnen werden, für wen wo welche prioritären Handlungsfelder relevant sind. Die entwickelten Routinen zur Ableitung von Parametern aus Geodaten erlauben eine fortschreitende Aktualisierung und Ergänzung des Parameterbestandes und die Ausweitung auf weitere regionale und lokale Umweltwirkungen. Durch die Möglichkeit, länderspezifische Faktoren mit zu berücksichtigen, können auch vernetzte Indikatoren gebildet werden, die bspws. soziale Gegebenheiten mit abbilden können.

Neben diesen Möglichkeiten gibt es jedoch auch Einschränkungen für den GIS-Einsatz bei der Indikatorkonstruktion. Als bedeutendste Einschränkung ist die Genauigkeit der einzelnen Geodaten anzuführen. Dabei ist der Begriff der Genauigkeit bei räumlichen Daten in zweierlei Weise relevant. Zum einen ist zu beurteilen, inwieweit die Geodaten die tatsächlichen Bedingungen vor Ort charakterisieren, zum anderen entscheidet die Präzision der Standortkoordinaten über den Ausschnitt der erfassten Geodaten. Unter diesen Vorraussetzungen sind die abgeleiteten Indikatoren eher als Potenziale im Sinne des LCA zu betrachten und nicht als konkrete Standorttypisierungen.

8

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TOWARDS SUSTAINABLE DEVELOPMENT INDICATORS OF THE GLOBAL ALUMINIUM FLOW*

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ABSTRACT

Most research activities on sustainability indicators are focused on the development of indicator frameworks at different local, regional and national levels. However, considering the process chain of primary and recycled metals, a complex global network of producers and consumers and therefore a multitude of ecological, economic and social interventions across national boundaries on different scales have to be taken into account. Thus a sustainable development indicator framework of material flows of metallic raw materials has been developed, taking aluminium as example. The focus of the paper is within the methodology used to derive the indicators.

KEYWORDS

Sustainable development, operationalisation, indicators, metallic raw material flow, aluminium

* Source: Hüttner, K. L.; Kuckshinrichs, W.; Bauer, C. (2001): Towards sustainable development indicators of the global aluminium flow. In: Chistiansen, S. (ed.): Proceedings of 1st International Conference on Life Cycle Management. Copenhagen, pp. 371 – 374.

1 Introduction

The 1990s have been marked by innumerable activities to verify the concept of sustainable development by suitable indicators at local, regional and national level [1]. The main activities, which consider the ecological, social, economic and institutional dimension of sustainable development, take place at the national level. They are especially encouraged by the Commission on Sustainable Development's (CSD) list of indicators [2].

Methods, however, linked to the level of material flows and to process chains, e.g. Life Cycle Assessment (LCA) and Material Intensity per Service Unit (MIPS), focus primarily on environmental issues within sustainable development. Nevertheless, a holistic consideration of a material flow demands the integration of the ecological, economic, social and institutional dimension.

The objective of this paper is to offer an approach developed within the Collaborative Research Centre 525. This approach includes indicators for every dimension and not single consolidated indicators. The study bases on the material flow of aluminium but can be adapted to other metallic material flows. The process chain of the investigated material flow of aluminium includes beneath auxiliary processes bauxite mining, the processing to primary aluminium, its use as intermediate in the processing to final products and the following reuse, recycling and/or disposal. At first a short overview of the examined aluminium material flow and its link to the four dimensions of sustainable development is given. In section III, research targets related to the construction of a multi-dimensional indicator list are demonstrated. Section IV outlines indicator-based methods, necessary to incorporate all sustainability dimensions into a comprehensive consideration of the aluminium flow. Conclusions are drawn in the last section.

2 The global aluminium flow

Production of each good within the process chains spreads all over the world. The distribution of processing is caused mainly by geological (allocation of deposits) and economic factors (costs, regional centres of consumption). Bauxite deposits are concentrated in tropical and sub-tropical regions.

Large electrolysis capacities are installed where base load power stations are available. Products and alloys are demanded mainly in the Far East, North America and Europe.

The exploitation and processing of bauxite to primary aluminium is linked to several environmental impacts. At the local scale major impacts are related to land use and the occurrence of large quantities of solid wastes during alumina refining. Considering regional environmental impacts the emission of acidifying substances during electricity production and the electrolysis is particularly important. At the global scale emissions of greenhouse gases (GHG) due to fossil fuel combustion for electricity generation are of major concern. Environmental impacts of the secondary aluminium production are linked to the different recycling systems. In the use phase aluminium may contribute to the reduction of induced material flows due to its mechanical and physical properties.

Within the economic dimension the material flow is linked both to direct and indirect flows of income (wages, taxes, subsidies), which are essential to the society the material flow is embedded in. In the intersection between the economic and social dimension the material flow produces goods, which are of central meaning to the satisfaction of human needs.

There are several possible impacts to the social dimension directed to the processing of aluminium. These are reaching from working conditions of employees to treatment both of legitimate property rights of indigenous and local communities and legitimate rights of neighbourhood of the site. These impacts are often prejudiced as negative ones. One must also recognize that the material flow offers compensatory measures to reduce possible negative social impacts as expenditures to occupational safety, support to local communities suffering from diseases and environmental problems not necessarily caused by the aluminium flow. Also the material flow gives assistance to building up local infrastructure in weakly developed regions.

In Political Science, polity covers the institutional dimension of politics, while policy covers the thematic dimension and politics the process dimension. The global aluminium flow can be characterized as one original policy field. Institutions represent the polity aspect of the global aluminium flow wherein decisions relevant to the social, economic and ecological dimension are made. Organisations assigned to civil society like non-governmental organisations and associations as well as governmental, intergovernmental and international organisations are engaged in the global aluminium flow. Therefore their decisions and institutional decision-making processes have to be regarded within a comprehensive consideration of the global aluminium flow.

3 Research targets

The goal of any sustainability indicator system should be to provide a tool not directed to an isolated representation of one dimension but towards an integrative representation of for example a whole material flow. An approach, which depicts different regions all over the world, must take into account the heterogeneity of related features.

The countries involved in the global material flow of aluminium have different preference structures and thus distinct environmental policies and laws, different economic policies and different political cultures. Given particular ecological, economic, social and institutional indicators this leads to the necessity of comparative examination of these aspects of social systems, the material flow is particularly affected with.

This generally leads to different values of indicators. In this connection one has to take into consideration the variability of local, regional and national conditions the global aluminium flow meets with also in the north-south context. This variability implies that the global aluminium flow can generally not be characterized as unsustainable or sustainable due to the missing or fulfilment of northern benchmarks. Rather the material flow and sustainable development have to be regarded in different spatial and temporal perspectives. The proposed indicator framework enables this consideration.

4 Method

Compared to traditional indicator systems, which are adjusted to a politically or geographically determined single area, the integrative presentation of the global material flow of aluminium with indicator sets contains specific challenges. Aspects exclusively at the level of processing as well as aspects embedded in a social environment are to be considered. To enable an integrated consideration an indicator framework is constructed which distinguishes between material flow indicators, sector indicators and product indicators [4].

Material flow indicators represent ecological, economic and social factors based on the process chain. They are exclusively linked to technical processes and are standardized to a specific unit of input or output of the system. Due to causes of compatibility we prefer the output-unit, which in our case is a ton aluminium. Material flow indicators are transformed to different areas of influence according to their ecological, economic and social mechanisms. Material flow indicators are suitable for decision support on the operational level to reflect effects of technological development and operational management.

Sector indicators are a second group of indicators for material flows. Sectors are used in economy and politics to monitor the performance of similar industries and to reflect ecological, economic, social and institutional dependencies within and across sectors. Sector indicators as defined in the current study represent relevant features of the main process chain within regarded political and/or economic areas. With regard to the global aluminium flow this means that the aluminium sector is regarded. Sector indicators are suitable for decision support on company level and within political strategy development.

Product indicators characterize intermediate goods and final goods (investment goods and consumption goods). Intermediate goods serve as input to the production of other products. The general use of products takes place in the use phase wherein is differentiated between investment goods and consumer goods. These goods are usually made of several components and only in single cases composed of one unique metal, which is central to their ecological, economic and social assessment. Indicators of investment goods and consumer goods are related to the social, ecological and economic function of these products e.g. aesthetic appeal and lightweight construction. Product indicators of final products are relevant for product design, material selection and customer decisions.

This leads to a general distinction of material flow indicators, sector indicators and product indicators. System boundaries divide social, economic and ecological circumstances caused by the material flow from external circumstances evident in the environment. Based on this framework, indicators that are of central importance to a sustainability evaluation of the global aluminium flow are enumerated.

The indicators chosen are the result both of a bottom-up and a top-down approach. They are identified and consolidated by using methodology sheets similar to those developed of CSD. In order to guarantee a comprehensive sustainability consideration the chapters of Agenda 21, which beside the Brundtland-Report is the most important document of sustainable development, are chosen as a starting point and were filled with content where a relation to the material flow of aluminium is evident. General aims of sustainable development are ecological integrity, economic stability and social equity. They are discussed in content and different weighting within several research activities all over the world. What is special in the proposed approach is that the general aims are grouped to sub-aims and criterions. The classified indicators demonstrate the performance of the relevant circumstances of the global aluminium flow described and can be interpreted with regard to sustainable development.

Within the ecological dimension impact categories of current LCIA practice are used. To address different scales and actor levels additional impact categories are introduced. In the economic dimension, indicators, which are generally identified as representative pointers to the economic system, are transformed to the economic consideration of the material flow of aluminium. Referring to the proposed criterions the indicators give information about the future abilities of the global aluminium flow with regard to his present economic configuration and meaning. The social dimension takes into account results of the social indicators research activities that followed the quality of life discussion of the 1970s. This means that both subjective indicators directed to the perception of environmental conditions as well as objective indicators are represented. To guarantee the dependence on the material flow, social indicators outside a plant are basically related to the term neighbourhood used in (German) environmental law as a plant's spatial sphere of influence. Institutions assigned to civil society like non-governmental organisations and associations as well as governmental, intergovernmental and international organisations are regarded. With the chosen indicators it is possible to identify to what degree institutional changes, executed to deal with decision-making relevant to sustainable development, take place.

5 Conclusions

The integration of economic, social and institutional aspects beside traditional Life Cycle Management is necessary to come to an overall assessment of the global aluminium flow. As the global aluminium flow is embedded in different social, economic, ecological and institutional conditions, general statements concerning sustainable development of the material flow are not possible. The proposed approach to take into account indicators of all dimensions and to reflect local, regional and national features therefore is a necessary further methodological step to realize a systematic evaluation. In the short-term lack of data might limit an overall quantitative assessment in detail. Independently first qualitative criterions and indicators are already identified.

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SOCIAL SUSTAINABILITY: CONCEPTUAL ISSUES OF THE ALUMINIUM SECTOR AND HOST NATION STATES*

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ABSTRACT

The paper discusses participation and quality of life as topics of central relevance to social sustainability. Participation is divided into formal participation in decision-making and substantial participation in value added. Quality of life as a recently discovered element of social sustainability includes objective topics e.g. material and physical well-being as well as subjective topics as emotional well-being and interpersonal relations. The paper presents lack of social sustainability, upcoming social sustainability, restricted social sustainability and excellent social sustainability as general combinations of social sustainability between nation states and industrial sectors. In this regard, it is taken into account that both nation states and industrial sectors are integrated in a multilevel system of international institutions as well as governmental and non-governmental actors. The second part of the paper focuses on the aluminium industry as one specific industrial sector of material flows of metallic raw materials. Such industrial sectors are of special interest to social sustainability issues. Although corporate social responsibility as an instrument for increasing social sustainability is more than the usual in-company social responsibility it should not act as an isolated replacement for the responsibilities of nation states. Built on cooperative and well-defined responsibilities, possible measures to increase social sustainability on the part of nation states and the aluminium sector are developed. The paper is intended as conceptual and can be transferred to industrial sectors with similar characteristics.

KEYWORDS

Social responsibility, metals sector, host nation states, cooperation in multi level systems

* Source: Greening of Industry Network (ed.): Proceedings of the 10th International Conference of the Greening of Industry Network, Gothenburg, 2002 (http://www.informtrycket.se/gin2002sql/pdf/010026Hüttner.pdf)

1 Introduction

The concept of sustainable development is gaining increasing scientific and political importance since the Rio summit in 1992 and intensifying activities with regard to the Rio+10 Summit in Johannesburg in August 2002. In the meantime, the multidimensional character of sustainable development as characterised in Agenda 21 is broadly accepted. As the concept emerged of the dualistic ideas of environmental protection and economic growth, the initial orientation towards the ecological and economic pillar seems to be plausible.

Recently, the discussion has increasingly focused on the social sustainability pillar. The following paper discusses participation and quality of life as topics of central relevance to social sustainability. Responsibilities for realising social sustainability are not solely assignable to single national actors, as the sovereignty of nation states is limited in practical politics. Nevertheless nation states, together with industrial sectors, play a crucial role with regard to increasing social sustainability. The division of the responsibility of social sustainability within the area of conflict of industrial sectors and nation states has not been adequately debated so far. Therefore this article discusses the general interdependencies between industrial sectors and nation states in the context of social sustainability. In this connection, a distinction is made between lack of social sustainability, upcoming, upcoming social sustainability, restricted social sustainability and excellent social sustainability.

Of special importance to a consideration of social sustainability are industrial sectors operating in the field of metallic raw materials. Deposits and the directly following processing steps are mainly located in low-income and middle-income countries. The processing of alloys and the use of metal-based products predominantly takes place in industrialised countries. These characteristics apply among other things to the material flow of aluminium. On this account, basic elements of the corporate social responsibility of the aluminium sector are presented that are of significance concerning the increase of social sustainability. It is demonstrated that corporate social responsibility as a crucial strategy of social sustainability does not end at perimeter of plants and is more than the usual in-company social responsibility. Possible measures to increase social sustainability are subsequently developed differentiating between responsibilities of the aluminium sector and host nation states. The paper is intended as conceptual one and can be transferred to industrial sectors of similar characteristics. It is planned to carry out empirical studies in the future.

2 Social Sustainability

2.1 Participation

Not surprisingly, participation is recognized as an important aspect of social sustainability. Indeed, participation is not an invention of the sustainability discussion. Participation in political decision-making has been subject of discussion in political theory and the political history of ideas for several centuries and is especially linked to theories of forms of government. The most evident reference of participation to parliamentary democracy as a specification of representative democracy is to be found in the enlightened liberalism of John Stuart Mill [Göhler 1993]. The idea of participation consists of several dimensions. In the following a distinction is made between political participation and substantial participation.

Normally, political participation is defined as the behaviour of single or voluntarily associated citizens with the aim of influencing political decisions. This influence can be targeted at one or several levels of political systems. The behaviour can take on different forms. The most common way of influencing political decisions is participation in elections. However, participation can take on a variety of further modes. These generally range from the mere election of representative bodies, to consultation processes and legally defined participation and empowerment in particular political decisions, as for example public participation in project approval.

Applying a broader concept of politics, political participation goes beyond influencing the political decisions of national institutions. Political participation could therefore also be interpreted as behaviour by stakeholders intended to influence corporate policies of private and state-owned enterprises.

Within the in-company dimension, political participation by employees can generally be realised by the election of employee representatives. Pursuant to legally defined rights, these representatives are integrated into the formulation, implementation, monitoring and enforcement of corporate policies. In addition, surveys, direct consultation of employees and direct participation are further instruments to create possibilities of participative approaches. Within the external dimension, special attention is to be paid to adjacent communities of plants as it is widely recognised that these are among the most important direct stakeholders in production activities. Approaches of political participation most obviously exist with respect to public participation in licensing procedures. However, this approach is limited to participation in the construction, fundamental change and closure of plants. A continuous acceptance of production activities becomes more and more important. It is also required of other stakeholders, like national agencies and especially consumers, all over the world. Appropriate instruments of continuous participatory approaches are transparent information events concerning ongoing activities as well as discursive processes of consultation.

In addition to a rather formal character of political participation, participation also contains a substantial character. In this regard, the appropriate and equitable distribution of costs and benefits, associated with economic activities is of particular interest. Substantial participation applies both to subunits of nation states and supranational institutions as well as to individuals living in nation states. Generally it is the task of the nation state to ensure that every citizen, within the scope of his abilities and the capacity of nation states, has the opportunity of participating in value-added-processes and the creation of wealth. Citizens are not only formally legitimated in participating in decision-making processes but are also entitled to appropriate substantial participation in the way of monetary and non-monetary partnership.

Within the discussions of corporate social responsibility and global governance increasing attention is being paid to the effective cooperation of both national actors, business actors and actors of the civil society [Commission of the European Communities 2001]. Of special relevance is the responsibility of business actors like industrial sectors in the context of corporate social responsibility.

Again, a distinction is to be made between an in-company dimension and an external dimension. Within the in-company dimension the substantial share in business value added by employees is important. Within the external dimension the substantial share of the adjacent neighbourhood in business profits is of relevance. This is of particular interest if the operational activities are connected with significant adverse environmental and social impacts. To what extent participation by the adjacent neighbourhood should take place directly or indirectly is particularly dependent on the institutional legitimacy and capacity of national bodies.

2.2 Quality of Life

The concept of quality of life has its origins in the discussion of the limits to growth that has been under consideration since the publication of the report of the same name by the Club of Rome. The fundamental idea of the concept is that human happiness is not solely determined by material well-being. Human happiness also includes immaterial factors such as social relations and the individual perception of social and environmental conditions.[1] Such considerations also reflect the fact that gross domestic product as a synonym for economic prosperity includes positively monetarised environmental and social damage.

Preliminary operationalisations of the concept have been taking place within social indicator research activities since the middle of the 1970s. In practice, it has proved very difficult to measure quality of life. However, general agreement has been reached referring to the consideration of both subjective and objective topics. Those topics include emotional well-being, interpersonal relations, material well-being, personnel development, physical well-being, self-determination, social inclusion and rights.

Especially with regard to industrial countries the concept of quality of life ties with the sufficiency strategy of sustainable development. This strategy implies an environmentally friendly change of con-

[1] In this context the quality of life discussion takes up considerations that are discussed by John Stuart Mill in the Principles of Political Economy.

sumption patterns leading to lower consumption of products and services harmful to the environment. As mentioned, human happiness is not only defined by material consumption. Therefore, in spite of lower material consumption higher quality of life can be achieved. Such estimation is primarily relevant to industrial countries. However, developing countries still face an undersupply of basic needs. Therefore priority is given to remedying this lack. Nevertheless, in the long term the concept of quality of life within a common global commitment can also become relevant to developing countries as it enables the realisation of an economic development that contains not solely quantitative but also qualitative measures. With regard to the external dimensions of production activities, quality of life is targeted to adjacent communities both in industrial as well as in developing countries.

3 Industrial sectors and nation states

3.1 Industrial sectors

The determination of industrial sectors within economics is not well defined. Historically, structuring follows a temporal and systematic classification into primary sector (agriculture and forestry), secondary sector (manufacturing industry) and tertiary sector (trade, banking, insurances etc.). In national accounting economic institutions are aggregated as sectors in order to represent their economic activities within accounting. As national accounting is historically linked with nation states, a variety of different sector determinations exist, which are partially harmonised at present. In order to offer a universal determination the presented paper defines industrial sectors according to material flow analyses of aluminium. These analyses distinguish between main process chains and auxiliary process chains. The main process chain consists of mining, refining to produce alumina and electrolysis to produce aluminium metal. Further elements are the use of aluminium-based products, the scrap industry and secondary smelters. Auxiliary process chains like the energy supply deliver necessary inputs into the main process chain and are themselves connected to social impacts. In this connection, segments of the main process chain located in one country could be logically regarded as an aluminium sector. On the basis of this summations requirements with respect to socially responsible cooperation of the industrial sector and national bodies can be developed.

3.2 Nation states

Nations rest upon common fundamental characteristic of their individuals, especially common language, culture, religion, race, territory history and traditions. The linkage of nation and state within the nation state represents a gain in national legitimacy. The state integrates the citizen not only formally but also as part of his identity and legitimates the former to take responsibility in domestic and foreign policy. One fundamental principle of international law is the sovereignty of nation states independently of real economic, military or political power. However, considering different policies and political decisions there are predominant factors in political and economic power weakening this principle. In addition to horizontal interactions of nation states with different political and economic power, a vertical dimension of interaction developed increasingly after World War II. This is due to the increasing economic and political integration of nation states and the creation of supra- and international institutions and organisations. Within such multilevel systems[2] single actors lose part of their decision-making sovereignty. A compensation of this lost is the possibility of influencing and determining decisions at other levels of the multilevel system, then applying to all actors involved in the system. Taken together the sovereignty of nation states is restricted by horizontal and vertical interactions.[3] Nation states have the task of fulfilling sovereign functions, especially when these functions are not offered via the market. Resources that are used have to be acquired by taxes and charges. Beside the provision of

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[2] In political science a multilevel system is defined as a cooperation of political and social actors within institutional integration at the sub-national, national and supranational level.

[3] In this context the role of the civil society is not regarded. However, the civil society has increasing possibilities of exercising influence in nation state policies, as for example in human rights and environmental protection. As possibilities of the civil society influencing national politics and corporate policy increase the sovereignty of all nation states declines. The relative weakening of some nation states is therefore accompanied by the absolute weakening of all nation states.

infrastructure that falls within the allocation function of nation states redistribution of funds in favour of underprivileged citizens is a constitutional characteristic of nation states.[4]

3.3 Interdependencies within the context of social sustainability

In the following, four social sustainability related reciprocal relationships between industrial sectors and nation states are distinguished. The reciprocal relationships differ between the particular reputation of the nation state and the industrial sector operating in this nation state. With regard to social sustainability (the sum of participation and quality of life) the possible relationships can be distinguished between lack of social sustainability, upcoming social sustainability, restricted social sustainability and excellent social sustainability.

Figure 1: Social Sustainability Matrix

Nation State Reputation	Sector Reputation: low	Sector Reputation: high
high	Upcoming social sustainability	Excellent social sustainability
low	Lack of social sustainability	Restricted social sustainability

3.3.1 Lack of social sustainability

Regarding a lack of social sustainability, the reputation of both the nation state and the industrial sector is undeveloped. The nation state does not possess enough resources to train and to acquire agency staff, necessary for the formulation, legislation, implementation, monitoring and enforcement of social topics. The lack of personnel capacity is often associated with an increased danger of corruption and embezzlement. Consequently the institutional capacity of such nation states is also rudimentary.

Simultaneously, the institutional and personnel capacity of the industrial sector is underdeveloped. The industrial sector uses the personnel and institutional weaknesses of the nation state either actively or passively. Actively implies that the sector tries to take advantage by corrupting representatives of national bodies or tries to undermine existing social standards. Passively implies that the sector is not willing to strengthen activities in corporate social responsibility on its own initiative and ignores standards formulated by national legislative bodies or supranational institutions. As a consequence both participatory approaches by adjacent communities as well as workforce issues are not dealt with adequately[5].

In the short-term there is no sign of moving from a lack of social sustainability to upcoming or restricted social sustainability.

3.3.2 Upcoming social sustainability

[4] It is generally accepted that nation states have a distributional function. As a consequence of different principles of justice (equity of ownership, equity of achievements and equity of needs) a neutrally defined redistribution cannot exist. The concrete distribution chosen is dependent on the available resources and particular opinion-forming and decision-making processes.

[5] However, it is to be taken into account that taxes paid by companies in a sector could be used for purposes that are counterproductive for social sustainability, as for example the funding of weapons during civil wars.

With upcoming sustainability the nation state is in the phase of formulating, legislating and implementing social standards, orientated towards social sustainability within the concerned sector. The personnel and institutional capacities of the national bodies are especially high. Transparency and adequate use of legislation is realised. However, in the case of upcoming social sustainability the industrial sector is not yet concerned with aspects of social sustainability. Due to the high personnel and institutional capacity of national bodies in the short-term a spillover of social sustainability issues could be realised. This is especially the case with regard to the assumed openness of the nation state towards the internal and external diffusion of social sustainability aspects either horizontally or vertically. In this context, the nation state creates the general framework for social sustainability by social legislation and regulation, subsequently also enforced by industrial sectors.

3.3.3 Restricted social sustainability

Restricted social responsibility could be characterised by low personnel and institutional capacities of the nation state as also included in the case of lack of social sustainability. However, the sector recognises its responsibility to actively manage social impacts resulting from its industrial activities. As the capacities of nation states are low within restricted social sustainability these activities are likely to be focused directly on the adjacent neighbourhood of plants, possibly with the collaboration of non-governmental organisations or local pressure groups. The initiative could come from aluminium sectors within advanced nation states or consumers who demand a socially acceptable production of aluminium-based products.

3.3.4 Excellent social sustainability

Excellent social sustainability is characterised by both high national and sector reputation. The nation state has created the personnel and institutional capacities to formulate, legislate, implement, monitor and enforce measures oriented to improve social sustainability. Transparency and high institutional abilities ensure the ongoing institutional modernisation necessary to deal with social changes both with respect to substance and social construction. On its part, the industrial sector possesses the necessary capacities to formulate, implement, monitor and modify policies in terms of corporate social responsibility including relevant social supply chain management. In the long term this ensures social sustainability both in-plant and externally.

3.3.5 Evaluation

Social sustainability in the context of industrial sectors and nation states is placed in a difficult position within the field of lack of social sustainability and restricted social sustainability. This is especially due to the limited resources of nation states in personnel and institutional capacities. It is questionable whether the nation states concerned are able to initiate substantial and institutional reforms and innovations on their own. Therefore the horizontal diffusion of knowledge and policies by advanced nations states takes on an important function. By an exchange of information, agreements concerning the permanent training of agency staff and temporary employment of skilled employees in the respective nation states their capacity can be increased. With regard to ongoing globalisation of economic activities and the still increasing trend towards multinational companies, also horizontal policy learning within the industrial sector includes a high potential for incorporating social sustainability into national and sector policies.

Similarly, the vertical diffusion of knowledge and policies takes on an important function. Supranational institutions can initiate further training and support institutional reforms both organisationally and financially. Also they can act as a moderator between nation states and industrial sectors. Therefore they can make sure that the basic conditions are created that are in turn necessary for increased consideration of social sustainability. Last but not least, vertical influence can be exerted from supranational institutions on industrial sectors for example by means of social requirements as part of sureties and loans in conjunction with large industrial projects.

4 Aluminium sector and social sustainability

4.1 Integration of the aluminium sector in different nation states

The aluminium industry is composed of two principal producing segments, the primary industry and the recycling industry. The primary aluminium industry consists of mining, refining to produce alumina and electrolysis to produce aluminium metal. The recycling industry consists of the scrap industry and secondary smelters. Fabrication of aluminium metal into marketable products is essential for both sectors of the industry. The main process chain of the aluminium flow additionally contains the use of metal-based products. Auxiliary process chains like energy supply are elements of other industrial sectors that deliver the necessary inputs into the main process chain and are themselves connected to ecological, economic and social impacts.

Large deposits of bauxite occur within a tropical and subtropical belt north and south of the equator. Other than in Australia, bauxite deposits are located mainly in low- and middle-income countries as for example Guinea, India or Jamaica. However, Australia dominates the worldwide mining of bauxite with a 43 % share in 1998. In absolute terms, nation states like Guinea (approx. 15 %), Jamaica (approx. 11 %), Surinam (approx. 4 %) and Venezuela (approx. 5 %) are less important, although bauxite mining is of relatively high economic importance to those nation states [World Bureau of Metal Statistics 1999]. The share in the bauxite world market of the above-mentioned countries is about 78 %. In spite of a growing demand for aluminium since World War II, the magnitude of bauxite resources is sufficient to meet projected needs for the 21st century [U.S. Geological Survey 1997].

Regarding the downstream activities of the aluminium flow, it is noticeable that a relocation of processing stages is taking place in favour of industrialised countries. As electrolysis requires enormous amounts of electricity, smelters have often been installed where cheap electricity sources are available. Given basic conditions of electricity supply and electricity supply policies, smelters have mainly been installed in industrialised countries like the United States, Russia, Canada and the People's Republic of China.

Industrialised countries like the United States, Japan, Germany and the United Kingdom are the most important demanders with regard to fabrication of semi-manufactured products and aluminium-based products.[6] Recycling of aluminium requires only about 5% of the energy necessary for the refining of primary aluminium. It is associated with lower resource requirements and emissions [Bringezu 2001]. Recycling activities are also concentrated in industrialised countries because scrap and new areas of application accumulate mainly in these countries and costs for recycling are not high enough to initiate an international scrap trade. Due to excellent recycling potential the demand for primary aluminium is partly compensated by recycling activities.

Obviously, aluminium sectors operate in nation states with different political, cultural and institutional structures. Bauxite mining and alumina production are largely concentrated in developing and transformation countries. The subsequent value-added process is mainly located in industrialised countries. Essentially, economic development standards are compatible with the reputation of nation states concerning the problem-solving capacity of the respective political system.

4.2 Sector-related dimensions of social sustainability

4.2.1 Internal dimension

Based upon the principle of social equity the stakeholders of the internal dimension of social sustainability are employees and workers within the aluminium sector. The sector has to accept responsibility for the employees and workers. Consequently, this firstly concerns compliance with general and sec-

[6] The use of aluminium-containing products satisfies several consumer needs. Areas of application extend through traffic engineering (both aviation, rail traffic and automotive engineering), the building industry (aluminium beams and window frames) to products of everyday life like packages, ladders or bicycles.

tor-specific health and safety regulations both at the operational and administrative level. Taking the outlined cases of upcoming and excellent social sustainability, these regulations are of national origin. However, taking into account the globalisation of the economy and politics, even national regulations often have their origin in supranational institutions and in intergovernmental bargaining. As a matter of fact, conventions of the International Labour Organisation (ILO) are of special importance with regard to social legislation. Compliance with social legislation - as far as it exists - is a necessary but not sufficient condition for realising in-plant social sustainability. Substantial requirements of legal requirements differ from nation to nation. Therefore compliance with primarily national social legislation should be interpreted only as a minimum for social sustainability. The relevant regulations standardise only central facts and are often targeted at directly averting danger. Further, it is not possible to apply sanctions in cases where ILO Conventions are not ratified or implemented.

Additionally, requirements that are optional from the legal point of view are important elements of in-plant social sustainability. Programmes like vocational training, continuation of payment to sick employees and measures of accident prevention within risk-intensive operating areas going beyond legal requirements could act as benchmarks. Those measures are not to be exclusively regarded as additional costs but as investments in human capital. In addition to objective factors, the subjective perception of working place conditions from the point of view of employees is of particular relevance to social sustainability. Such a consideration takes into account the outlined elements of quality of life, namely that human happiness is not exclusively linked to material consumption of goods and services. With regard to working conditions this means, that job satisfaction must be realised and sustained. Only in cases of degrading conditions outside direct areas of operations due to the lack of infrastructure or socio-political deviations does sector responsibility expand to the external working conditions of employees. Nevertheless, the aluminium sector and if necessary other sectors are not obliged to compensate national deficiencies completely but should coordinate their measures with national bodies in order to guarantee overall consistent support.

4.2.2 External dimension

The external component is concerned with the social impacts of aluminium sector activities on stakeholders in general. Of particular interest are social impacts on communities adjacent to sector plants. The central issue concerns the question of how to deal with social impacts.

First of all, social sustainability in terms of formal participation requires the inclusion of stakeholders' interests. With regard to adjacent local communities this is basically ensured by possibilities of public participation in the construction, fundamental change and disclosure of plants.[7] Additionally, consultation processes and discursive processes are instruments for supporting formal participation.

The identification of the interests of the adjacent communities affected by aluminium sector activities is a central condition for taking into account the respective interests, identifying social costs and benefits and realising their appropriate distribution. In essence, social sustainability demands a maximisation of the balance between positive and negative social impacts and a socially appropriate distribution of this balance.

In cases, where negatively interpreted social impacts are inevitable, adequate support and compensatory mechanisms must be made available. If support and compensatory mechanisms are not suitable adequately to take into account the legitimate rights and objects of protection of affected adjacent owners, activities of the sector are not legitimated with regard to social sustainability. Vice versa, this means that the aluminium sector, insofar as it meets the social responsibilities by means of sufficient monetary and non-monetary prevention, support and compensatory measures, is not responsible for negatively interpreted social development and disruptions in adjacent communities. A non-discriminatory and continuous participation especially by adjacent stakeholders authorises the industrial sector and prohibits an apportioning of blame in the immediate environment of sector activities. Indeed, it could also be the result of non-discriminatory participation that the exhaustion of ore and its processing at a certain location is not optimally operated or a plant is not built due to cultural, eco-

[7] In practice, also participative processes between national agencies and the industrial sector are of special importance in order to initiate at an early stage probably necessary adjustment policies to the disclosure of plants.

nomic, social or historical reasons. Taken together, the objective of the external dimension of aluminium sector activities with regard to social sustainability consists of maintaining and increasing the quality of life of adjacent communities, either directly or in cooperation with national bodies.

5 Increasing social sustainability: Assignment of responsibility between the aluminium sector and host nation states

Both nation states and the aluminium sector have special responsibilities with regard to increasing social sustainability in aluminium production. The following chapter discuss the basic factors that contribute to enhanced social sustainability. Especially with regard to a lack of social sustainability it is taken into account that nation states and industrial sectors are mutually integrated in a multilevel system of nation states and non-governmental actors that can support social sustainability.

5.1 Increasing capacities of nation states

5.1.1 Training

Training of agency staff is the most direct way to increase the capacity of the political and administrative system also with regard to the aluminium sector. Technical skills previously dominated the training programmes. However, with regard to social sustainability, it is also necessary to increase capacity in governance, including regulation, administration and enforcement of laws. The regulation of safety and social issues is comparatively new and relatively expensive. Therefore the training of staff represents a challenge, especially with regard to developing countries. The finding of means is of central importance. One possibility of raising money for capacity building consists in obliging private companies to contribute to social training programmes both financially and by training officials. Provided that coordination is ensured, horizontal and vertical assistance in training can also play an important role in training agency staff. With respect to horizontal assistance, nation states that have a wide range of experience concerning the regulation, administration and enforcement of social standards in the raw material sector should support nation states with a lack of capacity either bilaterally or multilaterally. In the case of aluminium production this could mean that a country like Australia with a well-trained agency staff could offer assistance to a country with a less developed agency staff, for example Guyana.

Simultaneously, considering the vertical dimension of multidimensional systems, supra- and international institutions and organisations may be of significant assistance to nation states with regard to the skills of agency staff. In this context the United Nations Conference on Trade and Development (UNCTAD) has developed a structured learning programme called “Mining, Environment and Development” for senior-level government officials responsible for mineral policy and related sustainable development issues. The main components of the course are global issues, country and resource-sector level issues, and mine-site and local community issues [Rosenfeld Sweeting, Clark 2000]. Vertical and horizontal assistance can support the transition from lack of social sustainability to upcoming social sustainability and is also of continuing relevance to restricted social sustainability and excellent social sustainability.

5.1.2 Institutional reforms

Beside personnel capacities, institutional frameworks are of central importance for the controlling capacities of political and administrative systems. This also applies to nation states with regard to the aluminium industry as one particular industrial sector. Several factors are of importance in this context. The functions and responsibilities of national institutions must be ensured as a matter of principle. This task is of basic importance to cases of a lack of and restricted sustainability and could be achieved by continuous vertical and horizontal assistance. It is to be recognised that institutions generally evolve successively and self-dynamically and can be precisely controlled only within close limits. In further institutional reforms it is to be ensured that the functions and responsibilities of the national institutions are coordinated and integrated in a harmonised way. This of particular relevance to cases of upcoming and excellent social sustainability as the high personnel capacities of national bodies may lead to a conflict of powers between different institutional areas of authority. Explicit assignment and restrictions of competence prevent blockades of implementations of social regulations that are the consequence of frequent shifts or ambiguities with respect to the functions and responsibilities of national institutions [Rosenfeld Sweeting, Clark 2000].

5.2 Social legislation, implementation, monitoring and enforcement

Generally, social legislation represents a condition for the maintenance of social regulations and, implicitly, for the maintenance of social sustainability. Social standards will not discourage reputable companies as long as the regulations are realistic, clear and consistent. On the contrary, the absence of clear social standards could be problematic since this results in an uncertainty of investments in terms of responsibilities and liabilities. The absence of social standards and socially irresponsible behaviour on the part of companies also undermines the existence of corporate social responsibility activities.[8]. While many countries have environmental regulations, the laws very rarely fully address the requirements of community relations programmes.[9] Therefore social legislation should be enacted covering topics such as the integration of social and environmental factors in project approval, information sharing and consultation, social assessment, support of community development, and reclamation plants.

National bodies need to effectively and consistently monitor compliance with social regulations and enforce sanctions if those laws are violated. Legislative bodies may pass the most advanced social standards, but without consistent and credible enforcement any social standards will be widely ineffective. Deficits in enforcement exist both in developing and in industrialised countries. Improving monitoring and enforcement requires an increase in the numbers, capacity and coordination of staff committed to this area.

Monitoring should involve the regular inspection of sector facilities subject to authorisation. The aim must be to identify social violations and also to predict and prevent problems before they happen. The institution of project audit requirements also stimulates effective monitoring. In this context, a social audit is a systematically documented, periodic and objective evaluation of social performance. Audits help to monitor compliance and safeguard a company against legal risks. Increasingly, companies could exercise social environmental audits to ensure compliance with national regulations and their own operating principles. Whereas such audits are internal to the company and are not made public, they act as a basis for public-orientated social reporting by companies. In order to support internal audits, external audits by independent experts to verify compliance and performance of social standards should be required. National auditing requirements can contribute to identifying levels of risk, providing a measure of performance and clear and comprehensive information to both the public and to governmental and legislative bodies.

In addition to monitoring activities, legislative and governmental bodies should implement effective punishment and remediation mechanisms when violations concerning social standards are discovered. Enforcement and any sanctions should be applied consistently and equally across companies and should be public and transparent. In order to avoid conflicts of interest, an independent administration department not identical with departments that promote industrial activities of the sector should carry out enforcement. A way to ensure that regulations are taken seriously is to criminalise violations of social statutes, and to enforce sanctions against companies or individuals. Legal liability for the facility sites should extend for a certain period of time after closure to ensure that reclamation has been thorough and effective.

In addition to direct interventions by governmental and legislative bodies, an effective way of promoting compliance with and enforcement of regulations is to allow citizens to recourse to legal action in case of violations of law. Empowering citizens to sue in order to compel compliance in cases of human rights and social statutes violations will increase companies' potential liability and therefore their

[8] Of special importance is the green paper by the Commission of the European Communities "Promoting a European Framework for Corporate Social Responsibility, the OECD Guidelines for Multinational Enterprises, and the Mining, Minerals and Sustainable Development (MMSD) Project.

[9] These issues are discussed in detail within social impact assessments.

incentives for good social performance. Again, horizontal and vertical assistance is of crucial importance.

5.3 Financial instruments

5.3.1 Taxes and charges

In addition to traditional income, profit and production taxes and royalties, legislative and governmental bodies can institute environmental taxes that encourage pollution control and waste reduction. Financial instruments should only be used where command and control approaches ensure direct averting of danger. Government and legislative bodies can impose a tax on levels of pollution produced, amounts of waste generated, or quantities of resources used in order to provide incentives to reduce resource use and pollution. The prospective reduction of pollution could increase the quality of life of the neighbourhood. Accordingly, financial penalties or sanctions for violations are another way of encouraging compliance with social statutes within the aluminium sector. With regard to a socially acceptable distribution of costs and benefits of sector activities, a precise percentage of taxes should be paid to local administrative institutions for communities affected by sector activities. Such earmarking is of special importance in cases of upcoming social sustainability, where the capacity of national bodies is adequate. Earmarking could also be integral part of excellent social sustainability. However, if other local areas are underdeveloped excellent social sustainability could also be realised by lower taxation for underdeveloped regions.

5.3.2 Funds

A further possibility for national bodies to ensure social sustainability within sector activities is the regulation of funds directed to the support of employees and adjacent communities. These funds could have different time perspectives and generally require a corresponding financing mechanism. The purposes of the funds can range from bridging imminent cyclical unemployment to the construction of local infrastructure and post closure-related projects of adjustment policy. The fund could be financed by an allocation from the sector and with the potential cooperation of employees, local communities and national bodies. In this regard local national bodies act as trustees and guarantee the appropriate application of funds. Doubtlessly, national bodies should fulfil this task only in cases of upcoming social sustainability or excellent social sustainability.

5.4 Responsibilities of the aluminium sector

5.4.1 Stakeholder participation

As mentioned, participation is of crucial importance to social sustainability. Therefore it must also be an objective of the aluminium sector to enforce and sustain ongoing participation during operating activities in-plant and external. Participative approaches are to be utilised according to the intervention intensities of operation activities. Information and consultation processes are adequate for impacts of low intensity. Within the in-plant dimension this particularly concerns issues of working hours and the implementation of legislative requirements. Within the external dimension this applies especially to issues of everyday operations to create acceptance and reliance within the adjacent community. Both are of special relevance to upcoming social sustainability and excellent social sustainability.

Additionally, employees and adjacent communities should be empowered in issues that are of essential relevance to their future. This concerns especially employment policies and occupational health and safety issues within the in-plant dimension. Within the external dimension this concerns particularly planning for closure participation and participation in strategic issues of central relevance to the adjacent community. An adequate method to ensure ongoing participation is a written agreement between sectors and adjacent communities. The more intensive participative approaches are of special relevance to the currently lacking of social sustainability and presently upcoming social sustainability.

5.4.2 Social programmes

In order to ensure acceptability of sector activities an important element is the development of social programmes, both in-plant and external. These programmes are a precise indicator of the sector commitment towards social sustainability. Additionally, they can go beyond the formal sector – community agreements ensure substantial consideration of both employee and community interests. An integral part of social programmes is the recognition of land rights and the reduction of adverse social impacts of operating activities independently of economic compensation.

Social programmes are of special importance with regard to the continuity of local development beyond sector activities. Within upcoming social sustainability and excellent social sustainability continuity could be ensured by the structural policy of national bodies. However, in cases of restricted social sustainability social programmes initiated by the aluminium sector could act as a reasonable substitute for national structural policy.

5.4.3 Social assessment and monitoring

For a long time, social impacts of aluminium sector activities, especially concerning bauxite mining and metallurgy, were neglected or ignored. As a consequence of determining social sustainability, social impact assessment (SIA) is recognised as a useful method for assessing the social impacts of projects, also in the aluminium industry.[10] As the methodology is generally independent of existing laws, SIAs could be either undertaken in a self-contained manner or in cooperation with environmental impact assessments. However, the implementation of SIAs for projects of the sector subject to authorisation is an important precondition for ensuring social sustainability of sector activities. SIAs contribute to the identification of social impacts both positively and negatively and are therefore helpful with regard to the distribution of social costs and benefits. In this regard, SIAs are central as a basis for social programmes and as a basis for local acceptance of sector activities. SIAs have special importance in areas of restricted social sustainability where a lack of national capacity is to be compensated, whereas the absolute contribution of voluntary SIAs with regard to upcoming social sustainability and excellent social sustainability could be regarded as relatively low.

5.4.4 Economic compensation and support

On condition that sector activities at special locations are not unacceptable due to cultural, social or economic reasons, special attention must be paid to economic compensation and support. Economic compensation applies to the direct lost of assets possibly associated with the lost of traditional way of life and also with the lost of traditional income. In this regard, economic compensation may be not sufficient. Additionally, support should be provided with regard to social adjustment to new social conditions. This could be realised by employment of the affected residents and the organisation of social support for older and/or needy residents. Another way of offering support in a more general direction lies in the creation of direct economic benefits by taking supply contracts to local and regional companies. Again these mechanisms are applicable to the areas of restricted social sustainability and understated in the area of upcoming social sustainability.

6 Conclusions

Participation and quality of life are essential elements of the social sustainability pillar. Consequently, the cooperation of industrial sectors and nation states has to focus on these two important elements. Considering the general interdependencies of industrial sectors and nation states within the context of social sustainability four specifications are presented, namely lack of social sustainability, restricted social sustainability, upcoming social sustainability and excellent social sustainability. Considering the aluminium industry with regard to social sustainability, participation and quality of life are in the focus in-plant and externally. The best possible social sustainability is only to be achieved by both national and sector activities. In different circumstances it is questionable whether sectors and nation states are capable of initiating reforms directed to the long-term objective of excellent social sustainability. In

[10] In 1993 the Interorganizational Committee on Guidelines and Principles for Social Impact Assessment developed the guidelines and principles for SIA as a first systematic and interdisciplinary statement to assist government agencies and private sector interests in using SIA to make better decisions under NEPA and related authorities.

such cases, both sectors and nation states rely on horizontal and vertical assistance of advanced countries and sectors in other countries as well as international institutions and organisations. In any case, the aluminium sector should not argue that the host nation state does not create the general institutional framework for realising social sustainability. Restricted social responsibility is also widely possible without nation state cooperation. However, corporate social responsibility of sectors should not generally be seen as a substitute for regulations or legislation concerning social rights. In countries where social regulations do not exist, efforts should focus on putting the appropriate regulatory and legislative framework in place and establishing adequate implementation, monitoring and enforcement mechanisms [Commission of the European Communities 2001]. With respect to the increase of information services and consumer demands, social supply chain management becomes increasingly important. Socially acceptable and sustainable extraction of bauxite, processing, smelting of alumina, manufacture of semi-finished products and recycling of products is therefore at the centre of an ongoing valuation process. In this context, responsibilities are to be distributed between nation states and the aluminium sectors according to particular circumstances and capabilities with adequate horizontal and vertical support.

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SUSTAINABLE DEVELOPMENT INDICATORS OF MATERIAL FLOWS OF METALLIC RAW MATERIALS: THE CASE OF ALUMINIUM*

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ABSTRACT

Following the Rio Summit of 1992 research activities are concerned with sustainability indicators. Most activities are focused on the development of indicator frameworks at different local, regional and national levels. Considering the process chain of primary and recycled metals, a complex global network of producers and consumers and therefore a multitude of ecological, economic and social interventions across national boundaries on different scales have to be taken into account. Thus a sustainable development indicator framework of material flows of metallic raw materials has been developed, taking aluminium as example. The material flow of aluminium and its impacts are embedded in different ecological, economic, social as well as institutional basic conditions. To take this into account, the identified indicators are methodologically differentiated into material flow, sector and product indicators. Additionally, different spatial and temporal dimensions of the impacts are considered. A special feature of the indicator set is that system boundaries are determined according to different actor levels and decision contexts. This enables the determination of sustainable development-orientated recommendations particularly addressing different actors of the material flow of aluminium as well as the material flow of metallic raw materials in general.

KEYWORDS

Sustainability indicators, metallic raw material flows, holistic indicator set, decision-making

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1 INTRODUCTION

The concept of sustainable development is gaining increasing importance on different analysis levels. Considering the preparations by national governments, scientific advisory councils and other non-governmental organisations for the earth summit in Johannesburg in August 2002 one notices that both developing and industrialised countries deal with the concept of sustainable development.[1] Also taking into account numerous activities within Local Agenda 21 it is obvious that most activities are on political and administrative levels. Considering products, life cycle assessment (LCA) was originally designed to estimate the ecological impacts of the production, use and disposal of goods. In the meantime, LCA is being increasingly used within the ecological context of sustainable development to evaluate the sustainability of products.[2] The Collaborated Research Centre "Resource-orientated material flow of metallic raw material" operationalises the concept of sustainable development within the context of material flows of metallic raw materials, taking aluminium and copper as examples.[3] It is characteristic for material flows of metallic raw materials to be connected with several ecological, economic and social impacts. Simultaneously, metal-based products are indispensable for satisfying the needs of today's society. For this reason, the consideration of the material flow of aluminium with regard to sustainable development is of particular interest.

Sustainability indicators take a crucial part in terms of operationalising sustainable development and in terms of decision-making towards a more sustainable future. Therefore, the following article discusses sustainable development indicators of the material flow of metallic raw materials taking aluminium as an example. Subsequently, an associated indicator set is represented which takes into account holistic characteristics of the global material flow of aluminium as well as the complex multi-level network of producers and stakeholders. Consequently, the indicator set can act as a basis for sustainability-orientated recommendations in different decision-making contexts.

2 Characteristics of the global material flow of aluminium

2.1 Process chain of primary and recycled aluminium

The aluminium industry is composed of two principal producing segments, the primary industry and the recycling industry. The primary aluminium industry consists of mining, refining to produce alumina and electrolysis to produce aluminium metal. The recycling industry consists of the scrap industry and secondary smelters. Fabrication of aluminium metal into marketable products is essential for both sectors of the industry. The main process chain of the aluminium flow additionally contains the use of metal-based products. Auxiliary process chains like energy supply deliver necessary inputs into the main process chain and are themselves connected to ecological, economic and social impacts.

Large deposits of bauxite occur within a tropical and subtropical belt north and south of the equator. Other than in Australia, bauxite deposits are located mainly in low-income countries and middle-income countries as for example Guinea, India or Jamaica [2]. In spite of a growing demand for aluminium since World War II, the magnitude of bauxite resources is sufficient to meet projected needs for the 21st century [3].

Regarding the downstream activities of the aluminium flow it is noticeable that a relocation of processing stages is taking place in favour of industrialised countries. As electrolysis requires enormous amounts of electricity, smelters have often been installed where cheap electricity sources are available. Given basic conditions of electricity supply and electricity supply policies, smelters have

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[1] The website of the summit gives a broad review of the wide range of activities. (http://www.johannesburgsummit.org/)

[2] At the moment discussions are taking place to expand life cycle assessment to life cycle management, including besides traditional ecological aspects also economic and social considerations [1].

[3] For more information see http://sfb525.rwth-aachen.de/sfb525.

mainly been installed in industrialised countries like the United States, Russia, Canada and the People's Republic of China [2].

Industrialised countries like the United States, Japan, Germany and the United Kingdom are the most important demanders with regard to fabrication of semi-manufactured-products and aluminium-based products [4]. The use of aluminium-containing products is concerning several consumer needs. Areas of application extend through traffic engineering (both aviation, rail traffic and automotive engineering), the building industry (aluminium beams and window frames) to products of everyday life like packages, ladders or bikes.

Recycling depends on the residence time of the products in technosphere. Whereas packages have a short life cycle, producer goods are integrated into the use phase over a longer time before recycling or disposal takes place. Recycling of aluminium takes only about 10% of the energy necessary for the refining of primary aluminium. It is associated with lower resource requirements and emissions [5]. On this account, recycling of aluminium is profitable both ecologically and economically. Recycling quotas vary from country to country. However, recycling activities are also concentrated in industrialised countries because scrap and new areas of application accumulate mainly in these countries and costs for recycling are not high enough to initiate an international scrap trade.[4]

2.2 Distinctive network of producers and stakeholders

The material flow of aluminium is embedded in a multi-level system of actors within different institutional frameworks on the local, national and international scale.

The main actors to be taken into consideration on the production side are companies associated with the main process chain. These include companies of the business segments of bauxite mining, alumina producing, metallurgy, manufacturing of semi-finished products, manufacturing of aluminium-based products, recycling and disposal activities. Companies of the main process chain are integrated in an international network of suppliers and purchasers. This is due to the disparity between the location of bauxite deposits and the main consuming countries. With regard to production activities from bauxite mining to manufacturing of semi-finished products, vertical and horizontal mergers are frequently the case. Different products demand special machinery and equipment as well as skilled workers. For this reason a division of labour leads to a multitude of suppliers and purchasers upstream of the aluminium flow. The complexity of the network of producers and stakeholders is therefore increased by the plurality of different applications of aluminium products. Companies continuously interact with the society they are operating in and the customers. With regard to production activities, relations with legislative and executive bodies are of central significance. Generally, these interactions concern environmental legislation and environmental monitoring, accounting legislation and social legislation as well as compliance with formalities.

Social actors in relation to companies are summarised as stakeholders. Consequently they include actors of civil society as well as governmental actors. Heterogeneity among stakeholders implies different perceptions and demands on companies of the material flow of aluminium.[5] The workforce has, for example, special demands concerning security of employment, adequate payment and satisfying working conditions. Communities adjacent to plants are interested in a socially acceptable way of manufacturing and have legitimate demands on participating in business profits. On another level governmental and legislative and also judicial bodies are especially interested in company and sector characteristics that are relevant with regard to their special powers and functions. Apparently, the ecological, economic and social performances of companies and industrial sectors represent the origins of associated environmental, economic and social administrative decisions, legislation and court decisions. The aims of governmental, legislative and judicial bodies are sometimes different.

[4] Scrap trade in other metals is also restricted by international environmental legislation. For example, although severely criticised, copper scrap is one subject of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal.

[5] Within the scope of this article it is not possible to detail the multitude of stakeholders and associated perceptions. An excellent overview is given in Carroll 1996 [7].

Politicians are mostly interested in the contribution of industrial sectors to the economic and social well being of the economy, including tax payments as well as the creation and maintenance of jobs. In contrast, judicial bodies are interested in the application of rules within legislation. This can lead to conflicts of interest considering, for example, regulations on subsidies and competition.

Consumers can potentially be regarded as one of the most powerful stakeholders. The selling of products is essential to the existence and economic wellbeing of companies. Consumer demands on products are diversified around price policy, product policy, promotion policy and place policy [6]. Consumers are an inhomogeneous group. Whereas one group of consumers might have preferences for cheap aluminium products, others are more interested in sophisticated aluminium products. One group of consumers may pay most attention to environmentally sound production and use of products whereas others are more interested in a socially acceptable supply of goods and services. It is also possible that consumers are exclusively interested in the design of products due to physical properties of this material.

In buyers' markets sales of products is looked upon as a bottleneck for companies. Therefore, marketing activities are of crucial importance for companies and their products. Generally, consumers are becoming increasingly aware of social and environmental concerns.[6] With regard to the material flow, companies are also obliged to communicate with consumers about the advantages their products offer as well as social and environmental impacts and costs associated with the production of these products.

2.3 Survey of ecological, economic and social impacts

Impacts of the primary aluminium and recycling process chains occur in different spatial and temporal dimensions. On the local scale major ecological impacts are related to land use for mining and the occurrence of large quantities of solid wastes related to alumina refining. Considering regional environmental impacts, the emission of acidifying substances during electricity production (auxiliary process chain) and electrolysis (main process chain) is particularly important. Of major concern on the global scale are emissions of carbon dioxide (CO_2) due to fossil fuel combustion for electricity generation (auxiliary process chain) and process-related emissions of CO_2, hexafluoromethane (CF_4) and tetrafluoroethane (C_2F_6) (main process chain) during electrolysis. Environmental impacts of recycled aluminium production are linked to different recycling systems. In the use phase aluminium may contribute to the reduction of induced material flows due to its mechanical and physical properties, taking lightweight construction of automobiles as example.

Regarding the economic dimension, companies and industrial sectors of the material flow of aluminium operate within the borders of political and administrative areas. On the local level associated flows of income as a result of wages and suppliers payments are especially relevant. On the federal, national and regional level aggregated economic interactions like tax payments, subsidies and import duties on minerals and metals, as well as questions of competition policy and competition law, are of concern. Considering products as the economic objects of production activities, impacts are related to the associated value added.[7]

Within the social dimension of the material flow of aluminium, special attention has to be given to the internal and external behaviour of facilities. A central role in the internal dimension is taken by working conditions comprising wages and occupational health and safety. The external dimension is formed by the relation between operators of facilities and neighbouring communities. Topics to be regarded in this context are assistance in building up local infrastructure in weakly developed regions and complaints concerning environmental problems. Additionally the satisfaction of society's needs by the use of aluminium-based products can be interpreted as a social impact within the entire material flow.

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[6] Generally, for Western European society changes in values have been identified. Whereas materialism determines human happiness as a result of consumption of goods, emerging postmaterialism describes self-realisation as the central value. Self-realisation implies a more independent and potentially a more critical attitude on the part of consumers [8].

[7] With regard to trade of primary aluminium details can be found in Kuckshinrichs, Poganietz [9].

3 Material flow of aluminium and sustainable development indicators

3.1 Sustainable development in the context of material flow of aluminium

In a bottom-up approach the material flow of aluminium has to be regarded within a multidimensional concept of sustainable development as it is characterised by ecological, economic and social impacts. Even though emphases vary between different actors the material flow of aluminium shows impacts in all sustainability dimensions. Following the Agenda 21 passed at the Rio Summit of 1992 sustainable development should incorporate ecological, economic, social and institutional aspects in order to be sustainable at all. Analogically, also following a top-down approach, the material flow of aluminium is to be regarded as multidimensional.

The overall objectives of sustainable development within the material flow of aluminium are, therefore, to realise ecological integrity, economic stability and social equity. In this context, ecological integrity comprises the maintenance of management rules concerning non-renewable resources, renewable resources and carrying capacity of natural systems [10]. Economic stability demands a continuous development within the economic dimension of sustainable development in consideration of ecological and social concerns, as for example the internalisation of external environmental costs. Social equity within the material flow of aluminium concerns the social responsibility of operators of a plant within a neighbourhood as well as their general social responsibility with regard to the whole society they are operating in. Material flow activities are not responsible for social distortions that are loosely linked to the material flow only [11].

In fact, such multidisciplinary definitions are too abstract to be directly transformed into a decision-making context. Therefore, disaggregation of the overall objectives of ecological integrity, economic stability and social equity is necessary. This disaggregation leads to several sustainability issues and associated criteria. Thus indicators act as specifications of the criteria and should finally present concrete associated empirical parameter values.

3.2 Requirements on indicators

Indicators are the subject of intensive investigations and studies. Some authors describe methodologies to develop sustainability indicators and define ideal requirements on indicators [12;13]. Other authors and initiatives are more interested in transforming indicators of traditional environmental, economic and social reporting into sustainable development reporting [14]. Certainly, existing indicators can have the same relevance to measure sustainable development as newly designed sustainability indicators. However, it is necessary that sustainability indicators are clearly defined and not solely determined from existing reporting systems. An acknowledged method of guaranteeing the sustainability relevance of indicators of the material flow of aluminium is the creation of methodology sheets.[8] Further, methodology sheets contribute to the fulfilment of indicator requirements as they point out strengths and weaknesses of indicators. A basic orientation towards Agenda 21, as the most important document of sustainable development, is a guarantee that international project frameworks are taken into account more intensive than currently.[9] On the one hand, orientation to international project frameworks implies the consideration of multidimensional features of the material flow. On the other hand, conceptual weaknesses of international frameworks must be examined critically.[10] Also, since different constellations of actors are to be regarded, it is not appropriate to aggregate parameters into one overall single indicator. A set of indicators is more adequate whereas the fundamental idea of the indicator pyramid is to be taken into account [15]. According to the indicator pyramid a successive condensation of scientifically-based indicators by

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[8] The most popular methodology sheets have been developed by the United Nations Commission on Sustainable Development (CSD) (http://www.un.org/esa/sustdev/indisd/english/english.htm).

[9] Henseling, Eberle and Grießhammer rightly point out that indicator initiatives should refer more closely than at present to international frameworks of sustainable development [16].

[10] This may be the case with regard to the Driving Force-State-Response framework used by CSD. This framework has proven as unworkable in several indicator projects.

selection and or aggregation should take place towards indicators for decision-making and indicators for public communication. Thus, the indicator pyramid supports the idea of core indicators for decision-making.

3.3 Indicator differentiation

Developing a set of indicators for the material flow of aluminium is different from indicator sets developed at political and administrative levels. The latter are marked by aggregated data. Political and economic borders predetermine system boundaries. On the contrary, in developing an indicator set for the material flow of aluminium it is to be taken into account that a multitude of ecological, economic and social interventions within and across national boundaries exist. To enable a holistic consideration of the global aluminium flow a distinction of possible indicator specifications has been developed covering material flow indicators, sector indicators and product indicators. These specifications vary depending on particular questions, actors and associated system boundaries.

- Material flow indicators represent ecological, economic and social values based on the main process chain and auxiliary process chain. They are exclusively linked to technical processes and are standardised to a specific output unit of the main process chain. Material flow indicators are suitable for decision support on the operational level to reflect effects of technological development and operational management. Examples of material flow indicators are global warming potential per tonne of aluminium and process-specific health hazard per tonne of aluminium.
- Sector indicators are a second group of indicators relevant to material flow analysis. Sectors consist of companies operating in the same business segment. Sector indicators as interpreted in the current contribution therefore represent values of the main process chain within administrative and economic areas. With regard to the global aluminium flow this means that the aluminium industry is represented according to site composition. Sector indicators are especially useful for decision support on the company level and within political decision-making and court decisions. Examples of sector indicators are employment trend of the sector and vocational level of training.
- Product indicators take into account the fact that products are the target figure of material flow activities. As a matter of fact, products have to be regarded with respect to their production-related ecological, economic and social impacts. As products serve to satisfy human needs these impacts are to be connected with the ecological, economic and social function of products in the use phase, e.g. aesthetic appeal and lightweight construction. Product indicators have a multitude of different addressees. They are, for example, relevant for product design and material selection at operational levels. To the same extent they are relevant for customer decisions and are increasingly important for environmental legislation and decision-making.[11] Examples of product indicators are ozone depletion potential per functional unit and eutrophication potential per functional unit.[12]

3.4 Sustainability indicator set of the global aluminium flow

A number of scientists criticise the indefiniteness and vagueness of the concept of sustainable development [19]. Without doubt this is problematic as a multitude of different actors could try to incorporate the concept in favour of their particular interests. Therefore concretisation of the concept of sustainable development is crucial for the ongoing discussion. Within the following indicator set concretisation is guaranteed by listing different sustainability issues holistically. Further, documentation of relevance to the material flow of aluminium as well as construction of associated indicators contributes to the operationalisation of the concept. Table 1 contains a preliminary synopsis of the indicator set being developed in the collaborative research project. The indicators are structured

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[11] Of special importance are the activities of the Commission of the European Communities with regard to integrated product policy [17].

[12] The functional unit is the quantified performance of a product system for use as a reference unit in a life cycle assessment study [18].

by the four main categories and grouped according to key issues of Agenda 21. Emphasis is put on the translation of national sustainability issues to specific aspects of metallic raw material flows. The outlined differentiation of indicators in material flow, sector and product-indicators are different views of this comprehensive table.

Issues related to the ecological dimension include protection of the quality and supply of freshwater resources, protection of oceans, seas and coastal areas, protection of land and associated carrying capacities, protection of the atmosphere as well as protection of natural raw materials. Indicators of the ecological dimension are derived from widely accepted impact categories from life cycle assessment (LCA) (ISO 14040). LCAs offer a comprehensive, science-based account of environmental impacts along the lifecycle of a product and are also suitable for material flows. By formulating characterisation factors a multitude of substances and environmental interventions can be aggregated in defined categories.

Issues represented within the social dimension are divided into three parts. Two issues are orientated to plant-related sustainability and plant-outdoor-related sustainability, respectively. The third issue is orientated to basic social conditions of sustainable development with regard to material flows of metallic raw materials. It makes the social conditions in the vicinity of material flow activities the subject of discussion. Indicators of the social dimension take into account results of social indicator research activities following the quality of life discussion of the 1970s [20]. Both objective as well as subjective indicators associated with the social dimension of aluminium production activities are considered [10]. A standardisation of social indicators equivalent to LCA accepted worldwide has not been developed yet.[13]

Sustainability issues represented within the economic dimension are listed according to the main themes general economic development of the industrial sector, market distortions, market structure and regulation and use of resources. Indicators representing the economic system are obviously adapted to the material flow of aluminium within the context of sustainable development. In this regard the indicators give information about the economic sustainability of the material flow of aluminium in the respective social context.

The institutional dimension as reflected by the Rio Summit of 1992 is recognised as fourth dimension of sustainable development. Institutional indicators give information about the extent of institutional changes, both relevant and necessary for sustainable development. Institutional indicators in the set are concentrated on the surroundings of plants operated within the aluminium flow.

Table 1: Synopsis of the preliminary indicator set[14]

Category: Environment	**Relevance to material flow of metallic raw materials**	**Indicators**
Sustainability issue		
Protection of the quality and supply of freshwater resources	Reduction of qualitative and quantitative impacts of natural aquatic systems as the cause of discharge of wastewater and water consumption	• Water use • Water scarcity • Waste water
Protection of oceans, seas and coastal areas	--	--
Protection of the resource of land and associated carrying capacity as well as maintenance of biological diversity	Reduction of interventions in terrestrial ecosystems as the cause of industrial and mining-related land use	• Land use • Ecosystem indicator
Protection of the atmosphere	Reduction of air pollutant emissions	• Global warming potential (GWP) • Ozone depletion potential (ODP) • Acidification potential (AP) • Eutrophication potential (EP) • Dust • Formation potential of photo-oxidation (summer smog) • Exceeding critical loads of AP und EP
Quality and volume-related protection of natural raw materials	Reduction amounts of waste Increased use of secondary raw materials	• Waste to be deposited • Waste to be utilised • Resource-orientated recycling quota

[13] At the moment a feasibility study by the International Standardisation Organisation is being compiled to construct a framework of corporate social responsibility. Indicators will most likely play a crucial part.

[14] It is the purpose of the project to develop general characteristics of material flows of metallic raw materials taking aluminium and copper as examples. Terms and definitions of the indicator set are therefore used neutrally and can be applied to aluminium.

Category: Social	Relevance to material flow of metallic raw materials	Indicators
Sustainability Issue		
Plant-related sustainability	Increase of occupational safety and industrial safety	• Process-specific health hazard • Expenditures on industrial safety and health protection
	Compliance with social standards	• Ratified ILO-Conventions
	Increased internal level of qualification	• Demand for skilled workers • Level of vocational education • Programmes of further occupational training
	Securing material and immaterial supply of goods	• Pay • Job satisfaction
Sustainability related to plant vicinity	Incorporation of stakeholder interests into construction, fundamental restructuring and closure of plants	• Complaints about environmental problems • Resettlement • Conflict potential of local land use and water use • Compensatory services • Public participation in licensing processes
Basic social conditions of sustainable development with regard to material flows of metallic raw materials		• Access to health care • Regional unemployment rate • Net migration rate • Metal consumption per capita • Sector employment share in total regional employment
Category: Institutions	**Relevance to material flow of metallic raw materials**	**Indicators**
Sustainability Issue		
Institutional framework of a material flow of metallic raw materials related to sustainable development	Institutionalisation of relevant aspects within political and administrative systems of the material flow of metallic raw materials	• Institutionalised public participation in licensing processes • Realisation of environmental impact assessments • Realisation of social impact assessments • Representation of ethnic minorities and indigenous segments of the population • Representation of important social groups
Category: Economy	**Relevance to material flow of metallic raw materials**	**Indicators**
Sustainability Issue		
General economic development of the sector		
a) Production	Growth-orientated development	• Sector share in GDP • Metals consumption per unit GDP
b) Work	Increased competitiveness (productivity)	• Employment trend of the sector • Employment intensity (man hours per tonne)
	Growth-orientated employment level	• Annual metal production in relation to capital expenditure (productivity)
c) Investment	Protection / upgrading of facilities	• Sector net investment • Share of sector replacement investments in gross investments • Share of sector investments in total investments of a region
d) Exports	Share of metal sector in maintaining and increasing international competitiveness of a nation state	• Share of metal export revenues in total export revenues of a national economy
	Share of metal sector in integration of a nation state within world economy	• Metal export +metal import divided by gross value added
e) Price	Continuous price trend	• Development of the real price of the raw material • Development of the real intermediary product price of energy • Development of the real metal price
f) Costs	Reduction of costs	• Running costs • Installation costs
g) Research and development	Improvement of future competitiveness	• R&D expenditures proportionally to turnover
Market distortions, market structure and regulation		
a) External effects	Price representation as signal of scarcity	• Emergence of positive and negative external effects • Internalisation rate of external effects
b) External costs and benefits	Internalisation of external costs and benefits	• Avoidance of cost of damage to the environment • Level of external costs • Internalisation rate of external costs and benefits
c) Trade restrictions	Reduction of market distortions	• Import duties on minerals and metals
d) Taxes / Subsidies	Reduction of market distortions	• Existing taxes / subsidies of the sector under consideration
	Significance of sector to national finances Reasonable taxation of raw material annuity Reduction of tax and fee payment	• Sector share in regional tax revenue • Royalty (raw material tax) • Development of taxes proportionally to return
e) Market power	Guarantee of competition	• Sector degree of concentration
Usage of resources		
a) Non-renewable resources		
aa) Mineral resources	Duration of maximum possible usage of resources	• Range of coverage of proven reserves of raw materials • Output • Range of coverage of proven reserves of raw materials (according to quality characteristics)

ab) Metallic resources	Reduction of use of specific primary raw material	• Recycling quota
ac) Energy resources	Reduction of energy intensity	• Static life expectancy of reserves of a non-renewable energetic resource • Energetic transformation efficiency of non-renewable energy resources • Input intensity of a non-renewable resource
b) Renewable resources		
ba) Metallic resources	Increase of significance of renewable resources	• Output • Recycling quota
	Dematerialisation of production	• Metal consumption per unit GDP
bb) Energy resources	Increase of significance of renewable energy sources	• Energetic transformation efficiency of a renewable energy resource • Input intensity of a renewable energy source

4 Application of the indicator set

The set in the previous section meets the requirements of the multidimensional demand for sustainable development within the material flow of aluminium. According to the indicator pyramid it represents a scientifically orientated indicator set. With regard to the future development of the material flow, the presentation of a holistic set is an important but not sufficient step.[15] Additionally, with regard to decision-making and addressing relevant actors of the material flow of aluminium, a scientifically based indicator set seems to be too complex and conflicting since stakeholders have different sustainability targets.

For this reason, the important thing is that connectivity of the indicator set is provided within relevant social subsystems and decision makers in the particular segments of the material flow of aluminium. Consequently, indicators of special interest to particular actors and indicators which are directly linked to the role the actors play in the material flow of aluminium are to be determined in concrete cases.

At the operational level of companies, it might be especially important to optimise the ecological impacts induced by processing activities. An isolated optimisation of processes related for example to air-pollutant emissions might cause disproportionate deteriorations of other issues, for example, the occurrence of a large volume waste. Therefore an integrated optimisation of processing activities with the help of the listed environmental indicators is necessary. In order to apply equivalent valuation standards, indicator standardisation as a material flow indicator is appropriate.

Due to the integration of the aluminium flow in political systems, policymakers are important stakeholders. Legislation and implementation can have significant influences with regard to choice of location and relocation. Policymakers are especially interested in the sector contribution to the economic wellbeing of the country as a whole or to a subnational area. Therefore, policymakers might take indicators as a basis, which compare the ecological, economic and social performance of the aluminium flow with other material flows. These indicators can include employment shares, tax shares but also shares in greenhouse gas emissions (GWP) or sulphur dioxide emissions (acidification potential) as well as social indicators like resettlement or compensatory payments. In this context, policymakers can balance reasons with regard to stronger environmental, economic or social legislation targeted at the aluminium sector. Within the scope of benchmarking, decision-making with regard to structural change and conservation of locations of aluminium industry is supported.

Also consumers can revert to the indicator set. It is evident that ecological, economic and social characteristics associated with the manufacture of products are important purchasing factors. In addition to basic benefits and additional benefits of products these factors are relevant for buying decisions. For this reason, indicators of the set can be interpreted with regard to buying decisions. The indicators offer information about products with regard to the ecological, economic and social performance and impacts. Corporate social responsibility of companies becomes more important in

[15] With regard to a possible social call for action the definition of threshold values indicating social call for actions is an important future task. With regard to policy options it is also of significance to weight indicators according to their relative relevance to sustainable development. Also, multidimensional indicators are to be selected for scenario analyses. Such analyses give information about the future compatibility of the material flow of aluminium with the concept of sustainable development. Consequently, these analyses can be used to identify social call for action.

the recent discussion of social sustainability [21]. Therefore, also companies operating within the global material flow of aluminium have to document the origin of manufactured products and the associated ecological, economic and social impacts. As a matter of fact, product indicators will also become increasingly important.

However, the examples show that precise configuration of the material flow of aluminium cannot be predetermined top down by a few actors. In contrast, realising sustainable development of the material flow requires relevant indicators to be chosen as decisive factors in different decision-making contexts and as a basis for decision-making. If this is achieved the sum of single decisions will lead to a more sustainable material flow of aluminium.

5 Conclusions

Operationalisation of the concept of sustainable development in the context of the material flow of aluminium follows both a bottom-up approach and a top-down approach. However, sustainability indicators of the material flow of aluminium are different from indicators at the political and administrative level. The differentiation of indicator types into material flow indicator, sector indicator and product indicator is the logical consequence. Taken together one gets a holistic representation of the material flow of metallic raw materials within the context of sustainable development. However, due to a multitude of factors, adverse effects and uncertainties one runs the risk of being caught in a trap of complexity. This is especially the case when trying to take the scientific indicator set as basis of policy options. Therefore, as suggested, representation of a scientifically based holistic indicator set is only one step with regard to an evaluation of the present configuration of the material flow of aluminium and recommendations towards its precise future formation. The selection of indicators in different decision-making contexts (specific core indicators) as well as the identification and determination of threshold values are important subsequent steps. At the moment the indicator set can be used to differentiate qualitative sustainability-orientated recommendations according to the functions producers and stakeholders have within the material flow. For the future it will be possible to deduce policy options based on quantitative data.

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A SET OF SUSTAINABILITY INDICATORS FOR METALLIC RAW MATERIAL FLOWS - A DECISION SUPPORT APPROACH -*

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ABSTRACT

Metallic raw material flows are characterized by a complex global network of producers and consumers, as well as by a multitude of ecological, economic and social impacts across national boundaries and on different scales. This leads to the need to develop methodologies which allow to identify obstacles that prevent metallic raw material flows to contribute to sustainable development.

From a scientific point of view CRC 525 has developed an holistic indicator set consisting of approximately 80 different indicators. This set is taking into account the multidimensional character of sustainable development. Moreover the indicators reflect different system boundaries according to different actor levels and decision contexts.

The full indicator set is important in scientific considerations and suitable for scientific awareness creation. However, to fulfil the function of a decision support approach for political and economic decision-makers some modifications are of central concern. At first a reduction of the full indicator set by selection of core indicators enables decision-makers to deal with complex issues of contrary economic and societal protection targets. Secondly, as thresholds of indicators justify societal call for action, they are discussed against its political or scientific origin.

KEYWORDS

Sustainable development, metals, aluminium, sets of indicators, core indicators, decision support

* Source: Agioutantis Z. (ed.): Proceedings of Milos International Conference "Sustainable Development Indicators and the Mineral Industries", 2003, Milos Island, Greece

1 Sustainable Development

1.1 The concept

The concept of Sustainable Development is multi-dimensional taking into account ecological, economic, social and institutional aspects. According to this concept, the overall objectives are to realize ecological integrity, economic stability and social equity. In this context, ecological integrity comprises the maintenance of management rules concerning non-renewable resources, renewable resources and carrying capacity of natural systems. Economic stability demands a continuous development within the economic dimension in consideration of ecological and social concerns, as for example the internalisation of external environmental costs. Social equity concerns the social responsibility of operators of facilities within their vicinity as well as their general but differentiating social responsibility with regard to the whole society they are operating in.

The Plan of Implementation of the World Summit on Sustainable Development recognizes the important role of mining, minerals and metals for many countries and modern living.[1] The relevance of sustainable development to metallic raw materials is also demonstrated by the Mining, Minerals and Sustainable Development Project (MMSD, 2002).

1.2 Sustainable development indicators

Indicators are a common method for the simplification and visualisation of circumstances not accessible to human perception directly. The word indicator means to present something, which is not observable immediately.

Indicators are the subject of intensive investigations and studies. Some authors describe mainly methodologies to develop sustainability indicators and define ideal requirements on indicators (Livermann et al., 1988) Indeed, other authors are interested in transforming indicators of mainly traditional environmental, economic and social reporting into redefined sustainable development reporting and developing sustainability indicators (Michalos, 1997). Further initiatives are developing indicators based on stakeholder perception (Kuhndt et al., 2002). Certainly, existing indicators can have the same relevance to measure sustainable development as newly designed sustainability indicators. However, it is necessary that a full set is not solely determined from existing reporting systems and that sustainability indicators are clearly defined .

Unlike existing reporting systems it is unique to indicator sets for sustainable development to reflect dimensional interdependencies. Efforts to optimize the ecological dimension may have

[1] http://www.johannesburgsummit.org/html/documents/summit_docs/2309_planfinal.htm

economic and social impacts. Sets of indicators for sustainable development need to reflect this inter-dimensional mechanisms.

An acknowledged method to clearly define indicators is the creation of methodology sheets.2 They support to treat the discussion objectively by introducing a kind of standardization for indicators. The standardization procedure includes e.g. a clear description of the indicator, measurement rule, measurement unit, description of interlinkages, and so on. Further, methodology sheets contribute to the fulfilment of indicator requirements as they point out strengths and weaknesses of indicators.

2 Metallic Raw Materials Flows

Metallic raw material flows result of activities of the primary and the recycling industry. The primary industry consists of mining, mineral processing and metallurgy. The recycling industry consists of the scrap industry and secondary smelters. Fabrication of metal into marketable products is essential for both sectors of the industry. The main actors to be taken into consideration on the production side are companies associated with the main and auxiliary process chains. These include companies of the business segments of mining, metallurgy, manufacturing of semi-finished products, manufacturing of metals-based products, recycling and disposal activities as well as suppliers of auxiliary products, like electricity companies.

The main process chain of metallic raw materials and auxiliary process chains are connected to ecological, economic and social impacts. These impacts occur in different spatial and temporal dimensions. On the local scale major ecological impacts are related to land use for mining and the occurrence of large quantities of solid wastes which affect soil and subsoil water in medium-term.

Considering regional environmental impacts, the emission of acidifying substances during electricity production (auxiliary process chain) and electrolysis (main process chain) is particularly important. Of major long term concern on the global scale are emissions of carbon dioxide (CO_2) due to fossil fuel combustion for electricity generation (auxiliary process chain) and process-related emissions of greenhouse gases (main process chain) during electrolysis.

Environmental impacts of recycled metals production are linked to different recycling systems. Hereby, recycling depends on the life time of the products in technosphere. Whereas packages for example have a short life time, window frames are integrated into the use phase over a longer time before recycling or disposal takes place. Recycling is associated with lower resource requirements and emissions (Bringezu, 2001). It takes much less of energy than necessary for

[2] The most popular methodology sheets have been developed by the UN Commission on Sustainable Development (CSD) (http://www.un.org/esa/sustdev/indisd/english/english.htm).

the refining of primary metals. On this account, recycling of metals is profitable both ecologically and economically. Recycling activities are concentrated in industrialised countries because scrap and new areas of application accumulate mainly in these countries.3 Indeed, production activities take place where cheap electricity supply is available, mostly independent from the main centres of consumption.

Regarding economic and social features, companies of metallic raw material flows operate within political and administrative areas at local, regional and national level. On the local and regional level associated flows of income as a result of wages and suppliers payments are especially relevant. On the national and regional level aggregated economic interactions like tax payments, subsidies and import duties on minerals and metals, as well as questions of competition policy and competition law, are of concern, bearing for example in mind that vertical and horizontal mergers are frequently the case.

Within the social dimension attention has to be given to the internal and external behaviour of facilities. A central role in the internal dimension is taken by working conditions comprising wages and occupational health and safety. The workforce has special demands concerning security of employment, adequate payment and satisfying working conditions. The external dimension is formed by the relation between operators of facilities and vicinity. Topics to be regarded in this context are assistance in building up local infrastructure in weakly developed regions, resettlements at the local level and complaints concerning environmental problems. Communities adjacent to plants are interested in a socially acceptable way of production activities and have legitimate demands on participating in business profits.

It is to be considered that the ecological, economic and social performances and developments of companies and industrial sectors represent the origins of associated environmental, economic and social administrative measures, legislation and court decisions. The measures which are based on environmental legislation and environmental monitoring, accounting legislation and social legislation as well as compliance with formalities in general are drawn to guarantee that societal targets are fulfilled adequately. As a precondition for deriving social "call for action" these societal targets as well as the performance of the material flow have to be identified to evaluate a possibly existing distance to target. Taken together, these characteristics which can only be drafted within this paper have to be taken into account when developing and applying a set of sustainability indicators of metallic raw materials.

[3] Scrap trade can also be restricted by international environmental legislation. For example, although severely criticised, copper scrap is one subject of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal.

3 Holistic Indicator Set

Bearing in mind the special features of metallic raw material flows, an indicator set covering the multidimensionality of Sustainable Development has been developed within CRC 525 (Hüttner; Kuckshinrichs; Bauer, 2002). The set rests upon scientific considerations. The indicators of the different dimensions are allocated to sustainability-relevant topics and are connected to related specific sub-goals. The indicators are developed to cover the whole life cycle of metallic raw material flows, thus beginning by exploration of mines and ending with recycling and disposal activities. In order to meet the requirements of scientific completeness, the indicator set spans 80 indicators.

The indicators differ in its standardization level. As the majority of studies on material flows have been focusing on ecological aspects eco Bearing in mind the special features of metallic raw material flows, an indicator set covering the multidimensionality of Sustainable Development has been developed within CRC 525 (Hüttner; Kuckshinrichs; Bauer, 2002). The set rests upon scientific considerations. The indicators of the different dimensions are allocated to sustainability-relevant topics and are connected to related specific sub-goals. The indicators are developed to cover the whole life cycle of metallic raw material flows, thus beginning by exploration of mines and ending with recycling and disposal activities. In order to meet the requirements of scientific completeness, the indicator set spans 80 indicators.

The indicators differ in its standardization level. As the majority of studies on material flows have been focusing on ecological aspects ecological indicators have reached a high standardization level. Standardization procedures already established by ISO 14040ff for life cycle analysis (LCA) had a significant influence. For the economic, social and institutional dimension the standardization procedure has not come to this level.

Table 1: Representative extract of the indicator set

Sustainability dimension	Relevance to metallic raw material flows	Indicators
Ecological		
Topic: Protection of the atmosphere	Reduction of air pollutant emissions	• Global warming potential • Acidification potential • …
Social		
Topic: Sustainability related to plant vicinity	Integration of stakeholder concerns	• Resettlements • Public participation in licensing processes • …
Economic		
Topic: Price	Continuous price trend Price as signal of scarcity	• Development of real raw material price • Development of real metal price • …
Topic: Costs	Minimisation of costs	• Operating costs • Installation costs • …
Institutional		
Topic: Institutional framework of metallic raw material flows	Institutionalisation of relevant features within administrative systems	• Implementation of environmental impact assessments • Implementation of social impact assessments • …

4 Decision Support

4.1 Reduction of the Set

To evaluate overall sustainable development based on the indicators, a quantitative or at least qualitative weighting of indicators seems as a coherent methodological procedure. However, beside the fact that a lack of data for several indicators complicates an objective evaluation it is also to be taken into account that the sustainability discourse outreaches scientific considerations. Science has to make contributions to the concretisation of sustainable development in order to derive social call for action. In this context sustainability research is more often different to other research activities, as it is connected to the strong emphasis of social action outreaching scientific knowledge increase.

However, sustainable development is a social construct and varies with the social perception of favoured development paths. Therefore, the distinction between "unsustainable" and "sustainable" takes place in a social discussion inevitably. The exact boundary between the two extremes can and should be scientifically based but is nevertheless dependent on the social construction of reality and the willingness to be considerate of succeeding generations.

The inclusion of social considerations and the growing aim to offer policy advice in a social context advises the addressee-oriented application of the indicator pyramid. The indicator pyramid has been originally developed by Braat (Braat, 1991). Following the indicator pyramid, a successive condensation of scientifically-based indicators by selection and or aggregation should take place towards indicators for decision-making and indicators for public communication.

In few words, the basic concept of applying the indicator pyramid is an appropriate preparation of indicators suitable for different actors and stakeholders. Thus, the indicator pyramid supports the idea of core indicators for decision-making considering the limited problem solving capacity of decision-makers. Fig. 1 shows an adaption of the pyramid concept.

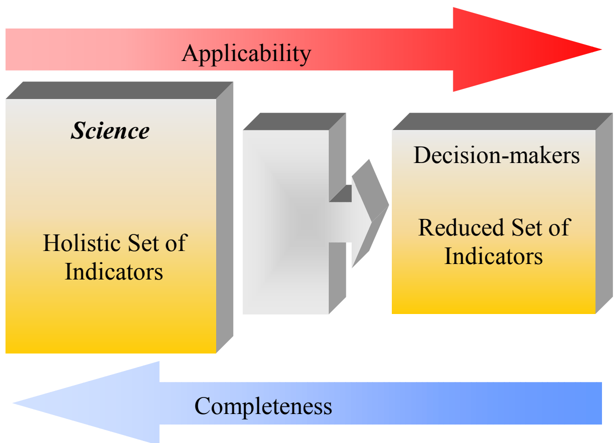

Fig.1: Reduction of the indicator set for decision support

Ecological, social and economic impacts are complex and generally characterised by differentiated impact mechanisms. Thus, the aggregation of parameters into one overall single indicator is not appropriate as important information is lost by aggregating. Also, when different constellations of actors and polluters are addressed, it might not be appropriate to aggregate parameters into one single indicator as responsibilities are obliterated and potential measures are identified hardly. Indeed, in a decision-support approach, a set of indicators is more adequate (cf. Gilgen, 2001).

At present, a generally accepted methodological approach to select core indicators is not available. Such an approach ought to reconcile individual preferences of different stakeholders, which in its nature are shaped by subjective value judgements. Nonetheless, in any case the used approach for indicator selection, e.g. expert judgement, stakeholder perception and so on, should be clearly stated.

4.2 Addressee oriented indicators and system boundaries

It has been discussed before that metallic raw material flows are embedded in a distinctive network of actors and stakeholders at different levels. As a consequence, different decision-making powers and responsibilities determined by public and civil law but also shaped by actual conditions are existent. Simultaneously, stakeholders are acting in different contexts of interest due and according to the social environment they are belonging to and they are constructing. The different responsibilities and decision contexts of actors of the main and auxiliary process chain are associated with the type of environmental, economic and social impacts within different system boundaries as well as social demands.

Thus, independently of the complexity of the system, it is evident that a static indicator set is not flexible enough to represent and respond to the variety of impacts occurring along the process chain of metallic raw material flows. Taking for example Global Warming Potential which as one overall indicator conceals the single contributions of greenhouse gases caused by fossil-fuel based energy supply and CF_6 as well as C_2F_6 during electrolysis of alumina.

To integrate the aspects of decision-making capability and contexts into the indicator framework a methodological distinction of indicators has been developed within CRC 525. It is distinguished between material flow, sector and product indicators. These are based on the generation of local parameters and are addressing different actors and stakeholder of the metallic raw material flow. Material flow indicators can be used at an aggregated level to give an overall impression of the environmental, economic and social impacts of the material flow. For example, the material intensity per ton systems output gives a hint to an overall environmental impact. However, the indicator itself does not take into account possible hot spots occurring at different stages of the process chain. The main benefit of the indicator is in awareness creation.

Sector indicators are taking into account the embedding of metallic raw material flows in political and economic systems. They can be used to support decision making at sector level (self commitments) as well as policy level (legislation, case law). Taking for example the degree of vertical and horizontal concentration of a metals sector is of special importance to antitrust agencies.

Product indicators are focusing on product characteristics as bundle of reasons leading to satisfaction of consumer needs. Beside physical and aesthetic properties consumers pay increasing significance in buying decisions to ecological, economic and social facts. Product indicators, for example LCA-based, are therefore of use with regard to buying decisions at consumer level and the responding and preliminary product development.

4.3 Threshold identification

As it is the case with indicators, the discussion of thresholds is inherent to the concept of sustainable development. With regard to carrying capacities of the natural system and maintainable stress of the, economic and social system, thresholds for indicators are necessary to divide "sustainable" from "unsustainable" development. Impartial existence of thresholds would make decision-making more plainer and on equal terms easier. Indeed, the identification of thresholds is accompanied by uncertainties and different individual perceptions of actors. Among scientists there are still many uncertainties about the respective thresholds to be applied, depending on the different positions with regard to the substitution of natural capital, real capital, human capital and social capital. Things are even getting more complicated with regard to societal discourse and political decision making. Legitimate individual interests of different actors are taken into account and are to be balanced in the context of political bargaining. As a result, thresholds due to scientific considerations, and thresholds due to political considerations can differ significantly.

This applies for example to thresholds for the reduction of CO_2 emissions. Scientists require to cut these emissions by 80% until 2050 compared to 1990 levels. However, international climate negotiations reached consensus to cut greenhouse gas emission of Annex B countries of the Kyoto Protocol leading to an overall Annex B reduction in the commitment period from 2008 to 2012 of at least 5% compared to 1990 levels (Oberthür; Ott, 1999). Even provided a continuation of reduction commitments in following periods in all likelihood the scientific thresholds will not be reached until 2050. Indeed, it is not possible to characterise the different thresholds as sustainable or unsustainable as they rests upon different considerations and practical constraints.

4.4 Scenarios

Scenario based analysis enables the projection of current developments of metallic raw materials under determined assumptions and general set-ups. Applying scenarios to different indicators enables forward-looking interpretation of possible developments. This is the founded basis for giving options for action. Especially after having identified potential thresholds, scenario analysis admits conclusions about "sustainable" and "unsustainable" developments of metallic raw material flows.

There are numerous studies on possible future trends. But they mainly look on one dimension, i.e. ecology. Therefore, it is very useful to link the indicator discussion with an in depth analysis of the interlinkages between different dimensions, taking into account the forward-looking approach of sustainable development by using scenario techniques (Poganietz; Kuckshinrichs; Hüttner, 2003).

5 Conclusions and Perspective

Sustainable development is recognized as challenge to the minerals and metals sector worldwide. By means of indicators it is possible to concretise the relevant components of the different sustainability dimensions. With regard to a detailed science oriented analysis a rather distinguished set of indicators is appropriate. However, to enable decision making a reduced set consisting of core indicators is of central importance.

Due to scientific uncertainty and the societal embedding there is no unique impartial perception of the sustainability concept. This is inevitably reflected in the identification of possible thresholds, separating "sustainable" from "unsustainable" development. Indicator related application of scenarios will provide deeper information about the sustainability of metallic raw material flows. Eventually, it is to be taken into account that the perception of what is accounted as sustainable or unsustainable will vary with the individual preferences of actors of metallic raw material flows as will the thresholds.

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SITE-SPECIFIC ENVIRONMENTAL PARAMETERS –A BASELINE FOR THE DEVELOPMENT OF TAILORED INDICATOR APPROACHES FOR METALLIC RAW MATERIAL FLOWS–*

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ABSTRACT

In order to analyse and quantify distinct environmental properties in the vicinity of sites, the Site-Specific Natural Resources Information System (SARIS) has been developed based on a Geographic Information System (GIS).

SARIS is one of the fundamental databases of a collaborative research programme aiming at the resource orientated analysis of metallic raw material flows with aluminium and copper serving as exemplary case studies. The spatial database incorporates all present production sites of ore extraction, refining and smelting. Environmental data for each location were derived from global digital survey data covering land cover, soils, morphology, climate, topography and population density. The main application of this database is the characterisation of environmental safeguard objects which may be affected by the activity of concern.

This site-specific environmental impact assessment is used to determine the relevance of environmental issues based on the distribution pattern of sites in a global framework. The derived results are used to suggest a tailored indicator approach to measure progress and performance of industrial developments relative to the predetermined site-specific conditions.

KEYWORDS

Bauxite, mining, SDI, sustainable development, rainforest, wilderness

* Source: Agioutantis Z. (ed.). Proceedings of Milos International Conference “Sustainable Development Indicators and the Mineral Industries”, 2003, Milos Island, Greece, p. 141 - 149, Milos, Greece

1. INTRODUCTION

In recent years operational indicators and questionnaires have been developed to monitor the environmental performance as well as the sustainability of companies (GRI, 2002). Especially for metals, which are of inevitable importance for modern economies a focus has been put on mining activities which are always associated with a broad variety of environmental impacts (GRI supl, 2001).

Many potential environmental impacts considered in such indicator frameworks vary considerably depending on different economic, ecologic and social conditions at single locations. Particularly mining, which is generally associated with large concentration processes at single locations is covered insufficiently in such generic inventories.

The specific environment of a deposit is a fixed component which means mining activities have to take such location-specific elements into consideration. Therefore, it is helpful to use sustainable development (SD) indicators for monitoring the appropriateness of technologies in a broader sense prior to the performance itself. Thus, a tailored indicator approach encompassing the regional specificities of metal mining is necessary.

This proposal is based on a site-specific environmental impact assessment as part of the research undertaken by the Collaborative Research Centre 525 (CRC 525). The aim of this interdisciplinary initiative is to develop an integrated management approach for a resource sensitive supply of metallic raw materials. It is based on a diversified analysis of issues along the aluminium and copper production chain (CRC 525, 2002). One instrument is an indicator set which is the overarching framework of this paper (Hüttner et al., 2002).

2. SITE-SPECIFIC ENVIRONMENTAL PARAMETERS

The original goal and scope for the methodological development of site-specific environmental indicators was to enable an impact assessment including specific characteristics of the environment. Most currently available methods describing physical flows and technological systems, such as process chain analysis or Life Cycle Assessment (LCA), show a lack of integration of site-specific conditions, which have a large influence on environmental, but also social or economical impacts. The recognition of specific conditions in such analyses is difficult due to the lack of representative studies with a sufficient level of detail. Thus the main target for the methodological enhancement of the impact assessment was to reach a 100 % coverage of operations.

In order to derive site-specific characterisation factors it is obligatory to collect and manage a plethora of environmental data. To quantify distinct environmental properties in the vicinity of any producing site the environmental information system SARIS (Site-Specific Natural Resources Information System) has been developed based on a Geographical Information System (GIS). Latter is used to structure the information for the regionalised environmental impact assessment in a spatio-temporal database.

2.1 Environmental Information System

The environmental information system SARIS can be considered as an organised information infrastructure for spatial data, analytical routines and structured parameter tables.

At present, the major categories of the spatial database are land cover, soils, climate, water, morphology and population density. For each data source separate routines and models were developed to derive characteristic parameters for any location with importance for the primary metal production. The site data comprises coordinates, capacities and important technological specifications. Currently 360 sites of the primary aluminium production (bauxite deposits, alumina refining, electrolysis) and 920 sites of the primary copper production (mining processing and refining) are incorporated in the system. The reported production figures of these sites correspond to 100% of the known world primary production of aluminium in 1997 and of copper in 2000, respectively.

Most environmental parameters are estimated as average values for an unit circle with a radius of 50 km, which is due to the precision of location data and the small scale of the spatial data between 1:1.000.000 and 1° x 1° longitude - latitude. A subset of the estimated parameters has been classified, combined and aggregated resulting in characterisation factors within the relational database.

Examples for the application of SARIS to assess land use impacts, water consumption and the emission of acidifying substances along the primary aluminium production have been published previously (Bauer, 2002; Sliwka et al., 2001; Sliwka & Bauer, 2000; Martens et al., 2000, Hausberg et al., 1999). Furthermore essential findings have been discussed with experts in a workshop organized by the German Aluminium Association (GDA), the European Aluminium Association (EAA), the International Aluminium Institute (IAI) and the CRC 525.

3. TOWARDS A TAILORED INDICATOR APPROACH

The environmental impact assessment within the raw material flow analysis has an analytical character by nature, because the central subject is treated in a "snap-shot" for a given reference year. In contrast the principle of SD requires continuous improvements and therefore procedural indicator approaches.

In order to use the results of previous case studies for the design and the layout of an indicator set, a clear and straightforward road map has to be developed. Such tailored indicator approach must consider the specific distribution pattern of sites and present SD-issues.

3.1 Methodology

The development of indicators follows the definition given by the Organisation for Economic Cooperation and Development (OECD) for environmental indicators. According to the OECD an indicator is "*a parameter, or a value derived from parameters, which points to, provides information about, describes the state of a phenomenon/ environment/area, with a significance extending beyond that directly associated with a parameter value*" (OECD, 1994). In order to suggest parameters and their transformation to indicators, a procedure has been developed comprising four phases (Bauer, 2003):

1. definition of the rationale
2. description of the situation
3. estimation of future developments
4. suggestion of indicators

The initial **definition of the rationale** aims at the definition of the issue or the SD-theme. Within this phase, coherences between different stakeholders and safeguard objects have to be predefined. Following the terminology of Life Cycle Impact Assessment (LCIA) the coherence of cause or intervention and effect or impact is named "environmental mechanism". According to the complexity of cause-effect chains it is crucial for all subsequent phases to define this mechanism as well as a valid approximation. Land use e.g. as intervention can be associated with numerous impacts from soil degradation to habitat disruption. Potential approximations are linear or proportional if the size of the potential impact correlates with the intervention. Non-linear or non-proportional mechanisms address e.g. disturbances in "no go" – areas for which it is not advisable to distinguish different scales of interventions for an industrial operation. Once the rationale has been defined, suitable data or parameters have to be identified allowing a quantification within the specified theme to the greatest possible extent. These parameters are used to **describe the current situation**. Following this description, potential **developments** have to be considered to enclose potential actions and challenges for different stakeholders. Future trends can be both environmentally and industrially influenced. Latter includes e.g. new ore deposits or changes in technology. Within this specified corridor of challenges **indicators** can be suggested which serve to monitor the transition of production processes towards more "sustainability". At this stage, a revision of the preceding phases may be advised. In any case all simplifications and assumptions during the definition process have to be assessed in relation to the outcomes.

3.2 Application

The outlined procedure has been tested for linear and non-linear environmental mechanisms and for different segments of the primary aluminium production (Bauer, 2003). How SARIS can be utilised for the suggestion of a tailored indicator framework is illustrated by the following example.

The example depicts the impairment of tropical rainforests by bauxite mining representing a classical conflict area between mining and environmental safeguard objects. Particularly this issue has been treated extensively in scientific literature, however, a common consensus has not been reached to date.

Due to their geological and mineralogical genesis, large bauxite deposits occur in the subtropical and tropical belt. Although the aluminium industry has developed appropriate standards for rehabilitation measures, this intimates an endangerment of tropical ecosystems. Therefore this example illustrates the predetermination of specific threats due to the distribution pattern of deposits.

The **rationale** for the impairment of the tropical rainforest by mining activities is the disturbance of an ecosystem, which itself has the international status of a safeguard object due to its unique and, in many cases, still unexplored values.

“Disturbance”, as environmental mechanism, is a broad term including not only the deforestation itself but also all indirect impacts like fragmentation due to e.g. the exploration, development and operation of a mine. Especially in developing countries secondary effects by migration of the population are presumingly larger than those effects caused by the operation. Since many potential impacts are not proportional to the size of the operation, a non-linear mechanism is chosen.

In order to **describe the current situation** the land cover parameters in SARIS can be used. The most actual, publicly available global data about land cover characteristics is based on a multi temporal remote sensing campaign (EROS, 1997). The resulting map reveals land cover types inheriting a resolution of one square kilometre per cell value. In order to derive characteristic and representative parameters, a unit circle with the radius of 50 km is used to characterise the land cover pattern for each location within SARIS. Even if the quality of this information is rather insufficient, the indicative character is preserved.

To determine whether an operation is situated in an area where tropical rainforest may be impaired, this specific pattern is extracted from the database. Figure 1 reveals the preliminary results.

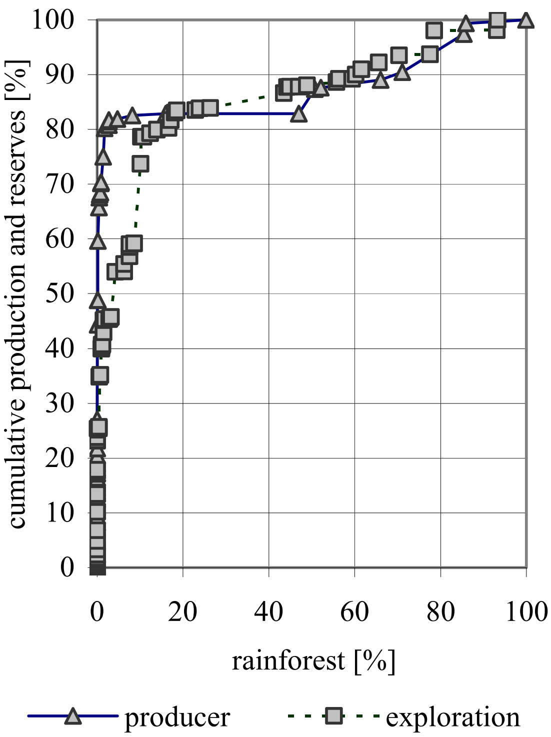

Figure 1: Cumulative bauxite production and reserves and tropical rainforest within the site vicinity

The amount of this land cover pattern is given in percent of the total land area. The share of each producer in the total production (reference year: 1997) is used to emphasise the importance of each operation. To determine whether a disturbance is likely or not the threshold percentage has to be determined. The precision of the underlying data justifies the assignment of a high disturbance potential to those sites operating in areas with more than 50 % rain forest. This classification has been verified using field reports and data from scientific literature. The figure illustrates that nearly 17 % of the worlds bauxite production (140 million tonnes in 1997) took place at 8 locations within tropical rain forests[1].

Table 1: Bauxite mining and reserves in areas with tropical rain forest.

Country	Intervention		Safeguard object	
	Prod. [miot] in rain forest	Res. [miot] in rain forest	Rain-forest [mio. km²]*	Protect. forest *
Brazil	5.7 83 %	854.7 50 %	3.012	6.9 %
Guyana	1.7 100 %	1.9 100 %	0.178	1.3 %
Suriname	1.6 100 %	104.6 100 %	0.132	4.0 %
Venezuela	2.2 100 %	99.1 76 %	0.556	59.0 %
Indonesia	0.3 100 %	51.6 100 %	0.887	20.9 %
Costa Rica	-	151.8 100 %	0.014	44.8 %
Panama	-	29.5 100 %	0.037	30.9 %
Malaysia	-	78.0 53 %	0.130	11.7 %
world	55 20 %	5,000 16 %	14.07	11.7 %
* source WRI, 1999				

Potential **future developments** have to be taken into account to develop an indicator scheme which incorporates this predetermined situation. Therefore, it would be desirable to know how both safeguard objects and mining activities develop. Though, no data is available to determine continuous trends adequately. However, the mining activities are bound to the reserves which have been explored to date.

These, together with the current operations are the corridor in which bauxite mining can develop. Using the same parameter the reserve situation can be analysed similar to the operation case (Figure 1). As result 14 % of approximately 14 billion tonnes of bauxite are explored at 15 locations within tropical rain forests.

Based on this assessment further aggregations are used to suggest an indicator framework. Aggregations beyond the site level may address different stakeholders e.g. companies or national bodies. Table 1 depicts the results of this preliminary analysis aggregated by country. Exclusively those countries were depicted for which the impairment of tropical forests is likely. The numbers representing production are given in the amount of alumina which is recoverable from the mined bauxite. This allows the estimation of the value of the bauxite for further down stream processes. Also, the percentage of a countries production within such areas demonstrates the importance of these operations within one country.

On a national level, further parameters are introduced, illustrating to which extent the safe guard object is present and which portion is protected within each country.

The table reveals very different settings in different countries. The ratio of protected tropical rainforests varies as much as the dependencies on these mines among countries. Future enterprises may impair rainforest in countries which have not been involved in this particular issue.

This kind of analysis enables a specific contribution to the development of a tailored indicator framework. It is inevitable at this stage that the given parameters are based on literature studies only. Given production figures and reserve es-

[1] This generic value can be indirectly verified by case studies. The Second Bauxite Mine Rehabilitation Survey of the International Aluminium Institute (IAI, 2000) reports that 14.5 % of the overall pre-mining land cover is tropical rain forest considering 73 % of the worlds' bauxite production in 1998. A survey of the Federal Institute for Geosciences and Natural Resources Germany (BGR, 1998) revealed that 18 % of the mined area is covered with tropical rain forest considering 79 % of the worlds' bauxite production in 1994. The area of deforestation amounts to 2.4 km² which is small compared to 154000 km² of annually deforested rain forest in 1994 as reported from the Rainforest Action Network (RAN, 2002).

timates might not accurately express realistic conditions.
Therefore, underlying data has to be validated before introducing specific indicators. The addressee for this task is the producing industry. Once "real" figures have been introduced and validated a continuous monitoring with specific **indicators** can be suggested. As a fallback position the parameters given in table 1 might be updated continuously. This would fully support the "Driving Force – State – Response" indicator approach from the United Nations Commission on Sustainable Development (CSD, 2001). In this case the intervention would be a driving force, the state corresponds to the land cover pattern and the response is the level of protection of the safeguard object. Considering the national aggregation level, targets can be derived for each country separately. Following the report on the world summit of sustainable development in Johannesburg (UN, 2002) recommendations include actions to "*support efforts to address the environmental, economic, health and social impacts and benefits of mining, minerals and metals throughout their life cycle, including workers' health and safety, and use a range of partnerships, furthering existing activities at the national and international levels among interested Governments, intergovernmental organizations, mining companies and workers and other stakeholders to promote transparency and accountability for sustainable mining and minerals development*".
The given parameters imply a different level of preparedness for such actions. For countries like Suriname, where protected areas are still small, companies might encourage the implementation of national protection strategies as suggested in the Mining, Minerals and Sustainable Development Report (IIED, 2002). For countries, where protection is guaranteed in larger scales, companies might be involved in specific protection and management tasks.
Different levels of involvement could be pursued in a parallel manner. Indicators for "beginners" could monitor areas which are collaboratively managed and where the operating companies contribute to the establishment of an integrated land management. Indicators for "professionals" could be success-indicators for rehabilitation and technology transfer.

4 DISCUSSION

The suggested procedure to design tailored indicator approaches for specific SD-issues based on the distribution pattern of sites combines numerous advantages supplementary to universal indicator approaches.
One strength of this generic approach is that 100 % of operations can be considered in this framework. In combination with the production figures, the relevance of issues can be determined and specific addressees can be identified. This screening relies on publicly available scientific data and can therefore be introduced to establish a baseline in the dialogue among various stakeholders. Reaching far beyond universal indicator frameworks this tailored baseline might reflect specific contentious issues for a specific distribution pattern of sites. Transparency and inclusiveness as overarching principles of any reporting initiative (GRI, 2002) can benefit from this compilation of information.
The introduced procedure also has a couple of disadvantages which are not only related to data deficiencies but also to the methodology. Data deficiencies of both environmental and technical nature restrict the specificity of parameters. The combination of generically determined parameters with national statistics, like the parameters of the World Resources Institute (WRI), inherits an additional variety of pitfalls in the interpretation.
Tailoring is very sensitive towards value choices. The definition of the rationale and of the environmental mechanism shows that a multitude of aspects might have to be considered equally. Considering the complex interdependencies between causes and effects within the SD-framework a consequent introduction of site-specific conditions may jeopardise any indicator approach. The reduction of possible parameters to a manageable set of operational indicators is an inevitable challenge for a continuous dialogue among stakeholders. Ideally, this reduction should focus on interlinkages between environmental, social and economic aspects.

The introduced methodology serves as stimulus for this discussion.

5. CONCLUSIONS

The design of tailored indicator approaches for metallic raw material flows is justifiable as environmental conditions are predetermined due to the distribution pattern of deposits. The developed methodology illustrates how findings of analytical studies may be utilised in the design of a continuous monitoring scheme.

By the application of this scheme for the impairment of tropical forests by bauxite mining exemplary indicators on a country level are derived. These indicators address different levels of maturity of the stakeholders within the development process.

The effort to derive specific indicators from a set of parameters is challenging and the rationale has to be chosen carefully to maintain the advantages of a tailored approach. Thus, a prior aim should be to depict themes with a high spatial dependency and a high significance within all three SD-dimensions.

Further discussion should focus on deposit specific issues and the development of monitoring structures which utilise and condense available information prior to collect new data in isolated initiatives.

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A MODEL-BASED QUANTIFICATION OF SUSTAINABILITY INDICATORS: THE CASE OF PRIMARY ALUMINUM*

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ABSTRACT

Since the adoption of Agenda 21 in 1992, many indicator sets have been constructed considering the four dimensions of sustainable development. The on-going discussion on appropriate indicator sets reveals some crucial points. Though sustainability indicators are incorporated in dimension-overlapping considerations, analyses of the interdependences of indicators representing different dimensions are not well developed. Furthermore, keeping in mind the forward-looking concept of sustainable development, the focus of those studies on possible future developments is placed rather on ecological assessments, leaving the other dimensions more or less aside.

The objective of this paper is to link the indicator discussion with an in-depth analysis of the interlinkages between different dimensions, taking into account the forward-looking approach of sustainable development. The analysis is based on a model which recognizes the interdependences of economic demands, ecological consequences, and the impact on the social dimension. The global primary aluminum material flow is taken as an example. In the paper, the impact on selected indicators of an increasing global demand for primary aluminum in the current decade will be discussed.

KEYWORDS

Sustainable development, indicator, primary aluminium, process-based partial equilibrium model, economic dimension, ecologic dimension, social dimension, investment, income, energy demand, emissions, lifetime

* Source: STE-preprint 17/2003

1 Introduction

In Agenda 21, the international community of states demanded the development of a set of indicators which recognizes the four dimensions of sustainable development (UN 2003: para. 40.4). These are ecology, economy, social dimension, and institutional setting. In the aftermath of the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992, where Agenda 21 was adopted, many indicator sets were constructed, aiming primarily at administrative units like countries (e.g. OECD 2000). In the on-going discussion it became apparent that sustainable development should not only be on the agenda of governments, but that it should be of comparable importance for non-governmental stakeholders. Furthermore, focusing on administrative units could be misleading, in particular in globalized markets. Consequently, in the last few years, indicators sets for sectors, firms, and products have been developed, e.g. COMPASS (Kuhndt and Liedtke 1998), whereas indicator sets for global material flows are still rare.

However, the on-going discussion on appropriate indicator sets reveals some crucial points:

1. Sustainability indicators are incorporated in considerations covering several dimensions and they do not just represent a sub-system focusing on, for example, ecological aspects. Nevertheless, many indicators have their origins in traditional indicator systems assessing for example the state of an economy.

   There are numerous studies analyzing the interlinkages between different dimensions of sustainable development. This is in particular true of the relationship between ecology and economy (e.g. van den Bergh 1996). Though the relationships between sub-systems of different dimensions are analyzed in some depth, combining these analyses with the indicator discussion is in its infancy.

2. Sustainable development is per se a forward-looking concept. That means, it is important to know

   - how a system will proceed in the future,
   - how to react if the development is not desirable, and
   - how chosen policies influence the path of the system.

   Consequently, there is an important role for forecasting in the indicator discussion (Linton and Yeomans 2002).

There are numerous studies on possible future trends. But the focus of the studies is placed more on an ecological assessment of the development, leaving the other dimensions more or less aside (Deutscher Bundestag – Enquete Kommission 2002).

The objective of this paper is to link the indicator discussion with an in-depth analysis of the interlinkages between different dimensions, taking into account the forward-looking approach of sustainable development thus filling a gap in the literature on indicators.

The analysis is based on a model which recognizes the interdependences of economic demands, ecological consequences, and the impact on the social dimension. A modeling approach demands a thorough investigation of the interdependences between different sub-systems or dimensions. Additionally, modeling calls for a focus on central aspects of the analyzed system. Consequently, an implicit selection of indicators is made, however, without losing the opportunity of an integrated analysis of the system.

Another advantage of a model-based discussion leads to the forward-looking feature of sustainable development. Based on scenarios the possible development of the system or impacts of policy measures can be evaluated with respect to their influence on sustainable development.

In the following, the global primary aluminum material flow is taken as an example. Like most other metals, primary aluminum is globally traded, with the main mining regions to be found in the "South" – with the exception of Australia –, and with the main processing facilities and demand centers in the "North". Likewise, in the same way as other metals, processing aluminum is accompanied by environmental impacts, e.g. greenhouse gas emissions and land use. Aluminum shows also some specific characteristics, as for example the emission of perfluorinated hydrocarbons, with their high global warming potential.

In this paper, the impact on selected indicators of an increasing global demand for primary aluminum in the current decade will be discussed. The scenario is computed by a process-based partial equilibrium model of the global primary aluminum material flow (GlobAl), depicting the process of mining bauxite, refining of alumina, and smelting of primary aluminum. The GlobAl model recognizes the interdependences of technical constraints, economic demands, and ecological consequences, considering some impacts on the social dimension of sustainable development.

2 Sustainable development indicators and metallic material flows: Selection of indicators

By taking primary aluminum as an example, the idiosyncrasies of metallic material flows have to be considered in the discussion of an appropriate indicator set.

Since the adoption of Agenda 21, the conceptualizing of sustainable development within different subject areas has taken place. This also holds for the mineral and metal industries (Stern 1995, Legarth 1996, Sanchez 1998, Schwarz 1999, Shinya 1998, MMSD 2002). The main challenges these industries have to face are the high (specific) energy demand for mining and processing the metals and the necessity for resettlement due to the extensive use of land, for example, for open-cast mining. Furthermore, the extraction of non-renewable as well as the demand for renewable resources leads directly to the question of sustainable usage.

Despite the fact of an intensive dispute concerning nearly all aspects of sustainable development and its relevance for the mining and metal industry, indicators are not included to an adequate extent. Although several projects have taken up the indicator discussion (EU Commission 2000), with one exception (Kuhndt et al. 2002), they have not yet presented their final reports.

To fill the gap, within the Collaborative Research Center (CRC) 525, a temporary joint research unit of the Aachen University of Technology and Research Center Juelich, a holistic indicator set containing eighty indicators has been developed for the material flow of metallic raw materials taking aluminum as an example. The set covers the ecological, economic, social, and institutional dimensions of sustainable development, differentiating between local, regional, and global points of reference (Hüttner et al. 2002).

The indicator set recognizes the special features of metallic material flows. The two most important features are discussed in the following with respect to primary aluminum:

- Regional dispersion of mining and processing units (spatial area): Primary aluminum is a globally traded material. Mining of bauxite is tied to regions with natural deposits, whereas the production of primary aluminum is related to regions with sufficient quantities of cheap electricity. The proximity of the processing facilities to demand centers is of equal importance. As a result, the ecological, economic, and social impacts of the material flow differ in their spatial point of reference and thus it could be misleading to focus on administrative units. For example, red mud disposal – a non-desired but unavoidable output of refining alumina – generates local effects. In contrast, greenhouse gas emissions (carbon dioxide and perfluorinated hydrocarbons) have global effects, irrespective of the geographical source.

- Extraction of non-renewable raw materials and their processing: Primary aluminum is based on natural resources (bauxite), but in itself it is an intermediate good to be used for the production of final goods. The value adding chain consists of technical processes. Consequently, indicators should be linked to these processes, either as inputs to technical processes or as outputs. Besides these process-based indicators, a wide range of, mainly social and institutional, indicators are independent of the technical characteristics of a material flow, i.e. not process-based; for example, forced and voluntary migration of indigenous peoples (Hüttner and Kuckshinrichs 2002).

Taking the special features into account, a set of indicators for a model-based quantification has been selected. The chosen indicator set consists of six indicators representing the economic, ecological, and social dimensions, leaving aside the institutional setting. Thus, a multidimensional analysis is possible. The economic dimension consists of investment, primary energy use, and static lifetime. The ecological dimension is represented by greenhouse gas (GHG) emissions, while value added and labor income stand for the social dimension (cf. Table 1):

- Investment in capital stock is necessary to preserve the capability for production and, thus, to generate income in the long run.

- Primary energy use is an important indicator as the production of primary aluminum is energy-intensive requiring a high level of non-renewable energy resources. In the case of renewable energy resources, building up capacities to meet the energy demand could have ecological and social impacts.

- A widely used indicator to reveal the economic relevant amount of resources is static lifetime. The static lifetime corresponds to the number of years before a mine is exhausted considering the amount of known reserves and the current volume of mined ore. Reserves are dependent on economic conditions, but also on technological and geological constraints, which means the different variables could have opposing effects.

- Greenhouse gas emissions are the only globally relevant threat from the material flow. Other activities stress the "local" environment and are thus bound to the sites, such as red mud as an outcome of refining. The material flow emits mainly carbon dioxide and the perfluorinated hydrocarbons (PFC) tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6).

- Value added generated by the material flow captures the financial potential of the government to support social development (via taxes) and involved enterprises.

- Labor income influences the individual's opportunities in his/her efforts to enhance his/her social position.

The last two indicators, grounded in the economic system, have strong interlinkages to social development. Both indicators describe the financial basis for social development for different stakeholders. The emphasis of both indicators lies on ability, but not willingness. This means that an increase in income raises the ability to enhance social development, by, for example, providing more expenditure for vocational training. But whether this will be done cannot be concluded from a change of the indicator's value. However, the indicators give information on whether the chances of enhancing social development will grow or, in contrast, whether a decrease in financial support is likely.

All selected indicators belong to the indicator set, specified within the CRC 525 for metallic material flows. Furthermore, they are process-based, and therefore quantifiable in the modeling context.

Irrespective of that, the indicator set considers the characteristics of the material flow of primary aluminum, though most of the chosen indicators are of equal relevance for other metallic material flows. Of general importance are the indicators of investment, static lifetime, value added, and labor income.

The indicator of greenhouse gas emissions consists of carbon dioxide and perfluorinated hydrocarbons. PFC emissions are unique to the primary aluminum material flow. According to Harnisch et al. (1999), more than half of anthropogenic PFC emissions arise from primary aluminum smelters. PFC has a high global warming potential, reaching in the case of CF_4 6,500 units of CO_2 and in the case of C_2F_6 9,200 units of CO_2 (Grubb et al. 1999).

The last indicator, primary energy use, is in principle not specific to primary aluminum. However, the huge demand for the smelting process justifies a special consideration (cf. Table 1).

The regional coverage of the indicators corresponds to the global material flow, though a regional breakdown will be performed. In the model discussion, regions correspond to selected countries.

Table 1: Selected indicators

Sustainability dimension and topic	Indicator	Spatial center of reference	Unique characterizing point
Economic			
Economic growth potential	Investment	Regional	
Usage of resources	Primary energy use	Global/Regional	x$^{1)}$
	Static lifetime	Regional	
Ecological			
Protection of the atmosphere	Greenhouse gas emissions	Global	x$^{2)}$
Social			
Support of social development	Value added	Regional	
	Labor income	Regional	

Notes: 1) Due to relevance of energy demand.
2) Due to PFC emissions.

3 Processing of primary aluminum

Aluminum is the third most abundant element on the Earth's surface. Only oxygen and silicon are more common. The Earth's crust to a depth of 16 kilometers contains 8% aluminum. Aluminum has a strong tendency to combine with other common elements and therefore rarely occurs in nature in the metallic form.

Bauxite, worldwide the main raw material for processing aluminum, contains aluminum oxide, which has to be broken down. In Russia nepheline is used instead of bauxite. To break down aluminum oxide, crushed bauxite is digested by caustic soda and thermal energy, extracting aluminum hydroxide. In a further step aluminum hydroxide is calcinated. There are three digestion techniques (high- or low-temperature autoclaves, and also tube reactors) and two calcination techniques (rotary kiln process and fluidized bed process). On a world average, tube reactors offer the best values regarding energy requirements and consumption of caustic soda, followed by low-temperature autoclaves. The superior calcination technology is the fluidized bed process with respect to energy efficiency .

To produce primary aluminum, the aluminum and oxygen in alumina must be separated by electricity in the reduction process. This reduction takes place in carbon-lined cells through which direct electric current is passed. The bottom of each cell acts as a cathode. Carbon is used in the cell to serve as an anode. Inside the cell, alumina is dissolved in a bath of molten electrolyte, composed mainly of cryolite. The electric current passing from the anode to the cathode separates the oxygen from the alumina, which reacts with the carbon anode to form carbon dioxide, while the aluminum metal settles to the bottom of the cell to be siphoned off. If the separated alumina concentration of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, the so-called anode effect. Anode effects cause carbon from the anode and fluorine from the molten cryolite bath to combine, producing significant quantities of perfluorinated hydrocarbons. Additionally, carbon reacts with the dissolved oxygen to carbon dioxide (Gagnier and Berthoud 1999).

Five technologies for processing primary aluminum can be distinguished: vertical stud Söderberg (VSS) and horizontal stud Söderberg (HSS) technology, side-worked pre-baked (SWPB), center-worked pre-baked (CWPB) and point-feeder pre-baked (PFPB) technology. Both Söderberg technologies use anodes, which will be self-baked during the process; the other three use pre-baked anodes. The main advantage of pre-baked anodes is their homogeneous structure. This leads to a lower electrical resistance and lower specific consumption of anodes compared to self-baking anodes. Pre-baked technologies differ in their way of feeding the smelter with alumina. Point feeding is the most advanced technology. New alumina is added in small proportions that ensure the optimal concentration of alumina in the smelter. Therefore, PFPB smelters should use less energy compared to other technologies.

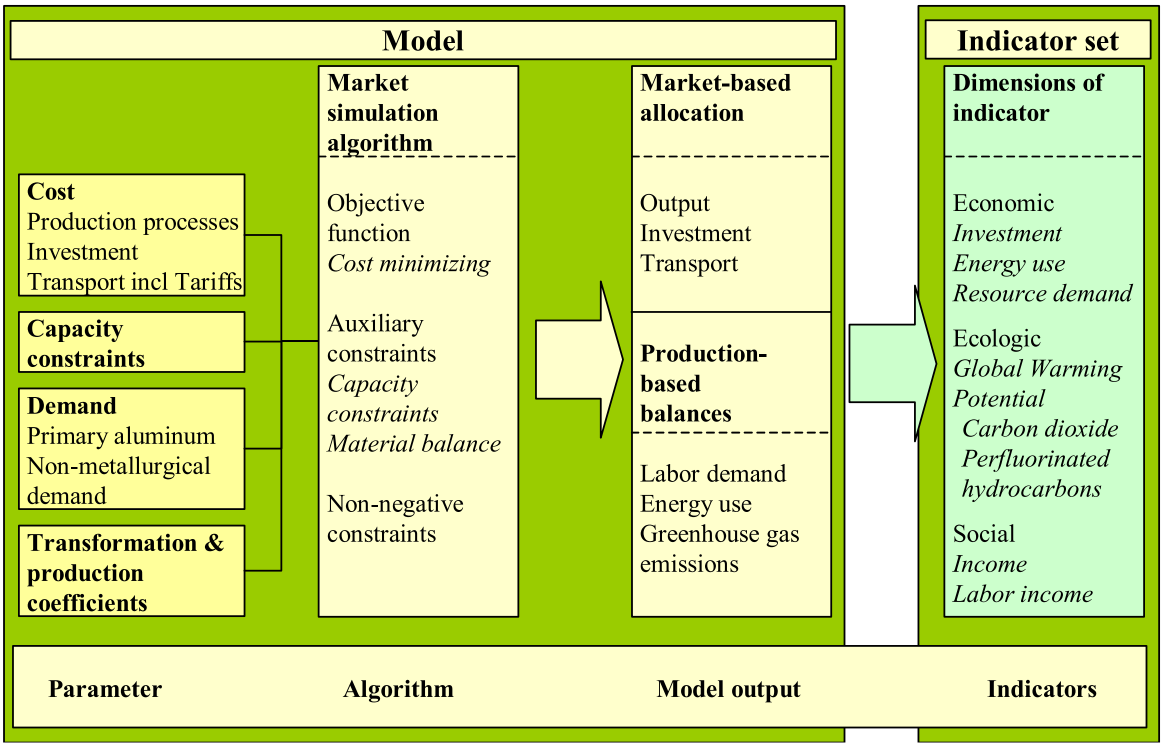
4 The Global model

The scenario presented below is computed by the GlobAl model. GlobAl is a process-based partial equilibrium model. The model depicts the process chain of primary aluminum in three process steps: mining, refining, and smelting. In the model, the three steps constitute the main chain of the analyzed material flow. As a complement to the process steps, the generation of electricity, caustic soda production, anode baking – in the following the auxiliary chain – and transport are recognized in the model (Poganietz 2001).

The version used is a slightly revised variant of the model developed by Schwarz (1999, 2000). The model is based on work by Brown et al. (1983), Nichols et al. (1992) and Manne et al. (1994). A detailed description of the model is given by Schwarz (2000) and Poganietz (2001).

The model is described by a set of parameters which can be divided into four groups (cf. Figure 1). The first group consists of all cost parameters for processing, investment, and transport, including tariffs. The model differentiates between labor, energy, and residual costs for each technique at each process step. Furthermore, a distinction is made for each technique regarding costs as they were in the reference year, i.e. 1995, and as they will presumably be in the final year, i.e. 2010, .

Figure 1: Structure of the model and its link to the chosen indicator set

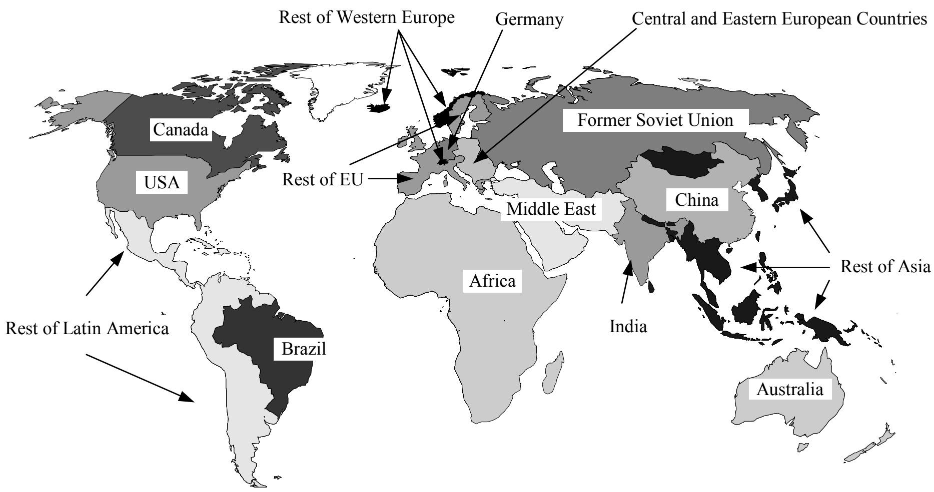


Investment costs are differentiated according to the type of investment, i.e. upgrading, brownfield, and greenfield investment. In the case of transport costs, the type of transport carrier is considered, i.e., conveyor belt, truck, diesel and electric railway, inland and deep sea ships, and, thus, different cost parameters are implemented.

The second group of parameters contains capacity constraints, as they were in 1995 and as they will presumably be in 2010. The data for 2010 were taken from the literature. The third group of parameters is demand parameters. The demand for primary aluminum as well as the non-metallurgical demand for bauxite and alumina is given to the model. The last group of parameters pools technical transformation and production coefficients. In the same way as cost parameters, production coefficients are differentiated according to the techniques as well as the year under consideration, i.e., 1995 and 2010.

Each parameter is not only distinguished according to technique and year of consideration, but also in respect of each modeled region. The world is divided into 15 regions (*cf.* Figure 2).

Figure 2: Regions of the model



By minimizing the total costs of processing, investing, and transporting the model calculates the production of bauxite, alumina, and primary aluminum in each region as well as the trade flows between regions. The optimization calculus is restricted by auxiliary constraints, i.e. capacity constraints and the material balance, and by the non-negative constraints. Irrespective of this, the model is demand-driven. That means, the total output of each good is determined by demand for this good. Demand for primary aluminum is completely non-price-elastic and exogenously given. The chosen objective function implies profit maximizing economic agents. Since perfect competition is implemented in all markets in all regions , in equilibrium supply always equals demand.

The model output has to be differentiated between a market-based allocation and a production-based balancing of numerous variables (cf. Figure 1). A market-based allocation is performed for production at each process step and for investment in each region as well as transport services within the regions and between regions for the different transport carriers. Production-based balancing is performed for several inputs, such as energy, and greenhouse gas emissions. The model balances emissions of carbon dioxide (CO_2) and of the perfluorinated hydrocarbons tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6) of the entire process chain. Emissions resulting from transport, caustic soda production, and anode production as well as from power generation are assigned to the material flow of primary aluminum.

5 Scenario

Looking at the medium-term development of the global material flow, a scenario reflecting different assumptions concerning demand was computed. In the scenario, the driving force of the development of global aluminum material flow is a change of regional demand for primary aluminum up to 2010. Within the scenario, two cases are differentiated, with diverging projections regarding the regional demand for primary aluminum. Two cases are analyzed to get an idea of the sensitivity of the findings in respect to the most important variable of the model.

Regional demand for primary aluminum depends basically on income, the aluminum intensity of the entire output of an economy, and the primary aluminum intensity of aluminum products in each region. To obtain only the effects of different demand levels on the indicators, leaving aside possible structural changes in the demand for primary aluminum, in both cases the projections regarding the two intensities are the same. Thus, the cases differ solely with respect to the assumed development of income up to 2010. According to our estimations, in both cases global demand will increase while the regional growth rates differ considerably (Table 2; Poganietz 2001).

Table 2: Demand cases

		1995	2010	
			Base case	High demand case
Primary aluminum demand	m t	20.2	27.9	31.1
Average growth rate	%/year	-	2.2	2.9
Range of growth rate	%/year	-	0.6[1)] – 5.5[2)]	1.0[3)] – 7.4[4)]

Notes: 1) Australia.
2) China, India.
3) Germany, Rest of European Union, Rest of Western Europe.
4) China.

Case-invariant assumptions

The projected development of all other exogenous variables does not differ between the two cases. It can be characterized as follows. Prices of commodities converge between regions, leaving the world price of each input constant. Regional wages will converge by 5%, electricity price by 10%, thermal energy price by 30%, caustic soda price by 50%, and lime price by 20%. Regarding transport tariffs, a decrease of 10% is assumed. Tariffs will fall by 20% (Schwarz 2000).

Technical progress is revealed by a kind of learning-by-doing without changing the setting of the plant, but also by modernizing existing facilities and installing new ones. At mines, input requirements per tone of bauxite will decline by 20% between 1995 and 2010. The productivity of existing refineries and smelters will approach the worldwide best level, without reaching it. Plants at the efficient edge in 1995 will not experience any technical progress.

In the case of modernization and installment of new facilities, it is assumed that all modernized and new plants will make use of the latest technology known in 1995. Investment in refineries means the installation of rotary kiln process and tube reactors; the smelter technique always chosen in a new technology setting is PFPB. This kind of technical progress does not occur in mining.

Upper limits for brownfield and greenfield investments were set exogenously. The limits differ regarding region, process step, and investment type and are based on forecasts in the literature (Schwarz 2000).

6 Discussion of the results

6.1 Selection of regions

The analysis will focus on the global material flow as well as on five selected countries/regions. The USA and the EU are the most important demand centers of primary aluminum worldwide. At the same time, both regions are leading producers worldwide, although their production capacities do not meet their own demand. Australia is the most important supplier of bauxite and alumina worldwide. Brazil and India are two important countries in the "South" with diverging development strategies. India follows an inward bound policy with high import tariffs. In contrast to India, Brazil is more outward-looking with tariffs corresponding to the world average.

6.2 Remarks on selected indicators

Before discussing the results, some technical remarks regarding a few indicators are necessary.

For the quantification of investment of the total material flow, investments in mining, refining, and smelting were aggregated. Investment is defined as the difference between projected capacities in the main chain in 2010, and the actual capacity in 1995 at each process step in terms of value. Before summing up, the investment costs at all process steps were converted to tones of primary aluminum.

To analyze the sustainability of resource demand the chosen indicator is static lifetime, as mentioned above. Since development of known reserves is not implemented in the model, the calculated mining output in 2010 is combined with the known reserves in 2000. Due to this attempt, proven changes are recognized. Nevertheless, the results give at least some clue to the possible development of static lifetime.

The emissions of GHG are calculated on the basis of the 100-year direct global warming potential.

Value added generated by the main chain of the material flow equals sales less input less depreciation. Due to lack of data, it is assumed that the value of depreciation in 2010 equals that in 1995, in 1995 prices. However, this is no heroic assumption. Sensitivity analysis revealed no considerable change in the findings.

Labor income is derived from labor demand and wage rate. The wage rate is linked to the change in labor productivity. However, regional wage rates converge, following unit labor costs.

6.3 Results

The following figure 3 sums up the results of the computation. The values display the change of the indicators between 1995 and 2010, in percent. The results are normalized as follows. A positive growth rate is seen as a trend towards sustainable development. A positive value regarding investment, static lifetime, value added, and labor income means an increase of the respective figures. The opposite is true in respect of primary energy and greenhouse gas emissions. A positive figure indicates a decrease of primary energy demand and GHG emissions, which is regarded as positive.

6.3.1 Global material flow

Following the computations, in neither case can a unique trend of the global material flow towards (or away from) sustainable development be identified. This is true irrespective of the chosen case.

In the base case, the capacity of the global material flow is enhanced, while GHG emissions will drop. The former is the result of the increase in demand for primary aluminum which leads to a growing production of primary aluminum and consequently of alumina and bauxite. The increase of production at all process steps will exceed production capacities in 1995, leading to a positive global net investment. Global capacities will rise by 26%; the annual growth rate would be 1.6%.

The decrease in GHG emissions by 9% from 336m t CO_2-equivalents is mainly brought about by a cutback in PFC emissions. As CO_2 emissions go up by 3.2%, PFC emissions drop by 59%. Specific carbon dioxide emissions will fall by 28%, specific PFC emissions by 71%. Though the drop in specific emissions is mainly due to technical progress especially in smelting technology, the rate of technical progress and the ability to make use of technical progress differs between process steps, and also regarding the generation of electricity (Poganietz 2001).

Both indicators, investment and greenhouse gas emissions, indicate a trend towards sustainable development. But increasing investment is at the expense of energetic and non-energetic resources. Demand for primary energy increases by 6%, from 4EJ in 1995, as static lifetime drops by 25%, from about 200 years in 1995.

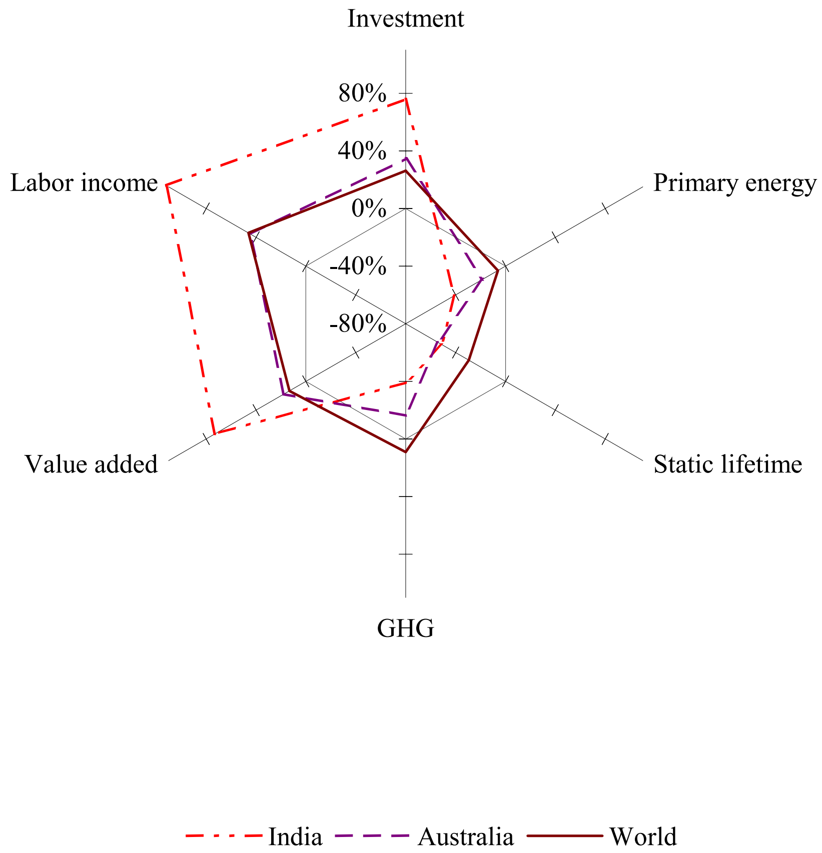
The low increase of primary energy demand, compared to the development of the output, results mainly from higher efficiency of fossil-fueled power plants and technical progress in smelting technology, leading to a drop of specific primary energy use by more than 22% from 158GJ/t PAl in 1995.

The divergent trend of the indicators will be intensified in the case of high demand. Due to the large increase in production, which leads to an edging up of production capacity by 40% – i.e. 2.2% p.a. –, GHG emissions will increase slightly by 1.2%, outstripping ecologically relevant technological progress in smelter technology and power generation. Furthermore, the exhaustion of resources will intensify: primary energy demand will increase by 18% and static lifetime will drop by 35%.

Irrespective of the chosen case, value added and labor income generated by the material flow increases in real terms. Regarding value added, an increase of 13% (base case) and 41% (high demand case) can be expected, i.e. an annual growth of 0.8% and 2.3%, respectively. In both cases, the value added increase is below the predicted GDP figures.

World labor income in 1995 prices will increase by 46% and 60.5%. The labor income growth is driven by the change in labor productivity as the demand for labor decreases by more than 50% in either case. That means even though the financial potential of those individuals remaining in the material flow will increase, the number of persons profiting from this development will drop.

Figure 3a: Change in the value of indicators between 1995 and 2010, the base case



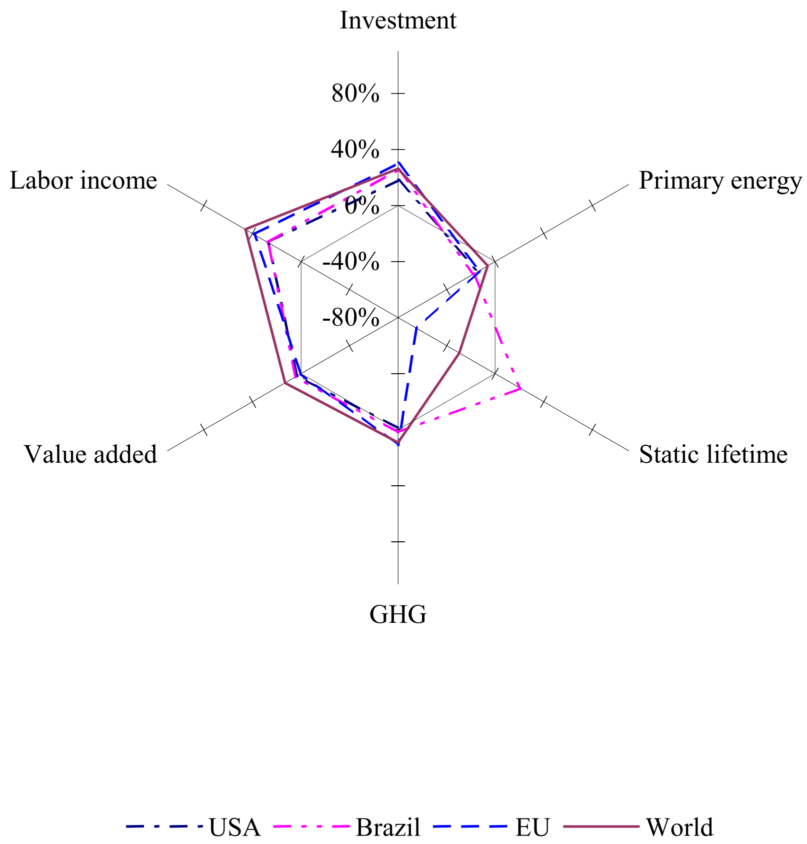
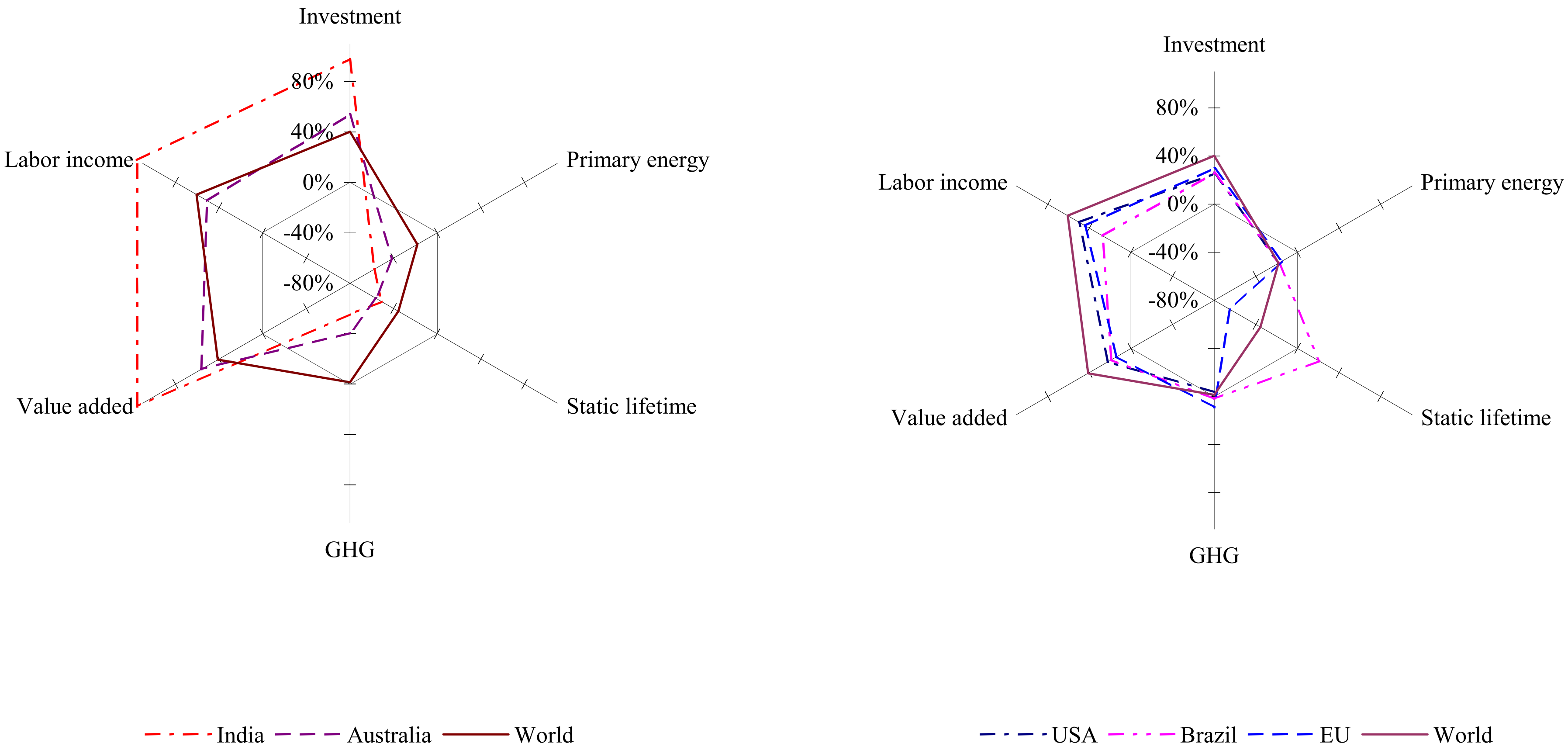


Figure 3b: Change in the value of indicators between 1995 and 2010, the high demand case



6.3.2 *India and Australia*

The above shown pattern does not hold for the selected regions. Irrespective of the chosen case, India and Australia will enhance the capacity of their part of the material flow. However, broadening the production basis above the world average is achieved at the expense of energetic and non-energetic resources, which also exceed the world average. Additionally, GHG emissions will grow considerably. However, large investments will push value added and labor income above the world average.

Though the pattern of the two countries is comparable, the driving forces are different. The development in India is mainly forced by investments in smelting, whereas Australian investments focus on mining and refining.

The remarkable capacity increase in India is protected by comparatively high tariffs to deter foreign producers from meeting the increase of domestic demand above the world average. The large investments in smelting drive the primary energy demand, which cannot be compensated by increasing the overall efficiency of supply. Though the growth of efficiency of primary energy use exceeds the world average, specific demand also surpasses the world average by 27 GJ/t PAl. This is a consequence of the wide use of coal for power generation with a low overall efficiency of supply, which in 1995 was 24%, compared to 30% worldwide. In the course of enlarging the smelting capacity the exhaustion of domestic resources increases considerably, leading to a drop in static lifetime in India to 125 years (base case) and 95 years (high demand case) from 190 years in 1995. A further consequence of investment in smelting is the significant increase of GHG emissions, which cannot be overcome by emission-relevant technical progress.

A positive effect of the capacity enlargement is the – above world average – growth of the specific value added of the material flow and labor income, though the number of persons remaining in the system will decrease, according to the calculations. Investment in new smelter technology pushes up labor productivity and thus wage rates to a level that compensates the reduced demand for labor.

In contrast to India, in Australia investments concentrate on mining and refining, a consequence of the abundance of bauxite: in 1995 about 37% of global bauxite was mined there. Since bauxite has a low value added, alumina plants are increasingly sited near mines. For primary aluminum smelting the importance of (abundant) bauxite deposits is diminished. Other factors, like cost of electricity and the proximity to demand centers, which is not the case in Australia, are becoming more crucial. Consequently, Australia's primary aluminum industry only follows the global trend.

The large investments lead to high primary energy demand. The high demand cannot be counteracted by the rising overall efficiency of supply of coal – the main energy carrier – in power generation, which, however, is low, compared to the world average. The low increase follows from the high technological level in 1995. What is striking is the fall of static lifetime. Static lifetime will presumably reach 90 years in 2010 (base case) and 65 years (high demand case), starting from about 120 years in 1995. The high increase in energy demand is accompanied by a significant increase of GHG emissions, mainly carbon dioxide.

The low increase of value added and labor income in comparison to India results from the focusing of process steps with rather low value added. However, in Australia labor demand will edge up to meet the increasing production level.

The difference between the two cases refers only to the level and not to the sign of each indicator.

6.3.3 USA

The pattern of the development of indicators assessing the material flow in the USA is comparable to that of India and Australia. Nevertheless, the levels of each indicator's value are mostly below the world average – with the exception of energy demand. This pattern is a consequence of rather low investments. The main reason for the low capacity enlargement is the existence of large free capacities in the alumina and primary aluminum industry in 1995. Furthermore, the increase of domestic demand is below world average.

Nevertheless, the capacity enlargement is achieved at the expense of energetic resources. In the base case, primary energy demand exceeds world development. In the high demand case the increase in the USA corresponds to the one worldwide. The drop in specific energy demand cannot counteract increased use, due to a rather high technological level in generating electricity in 1995. Non-energetic resources are not affected, as bauxite mining in the USA is negligible.

In the same way as in India and Australia, GHG emissions increase in both cases, although only slightly. The slight increase of GHG emissions in the USA is because of the high technological level in 1995 in smelter technology, especially relevant for PFC emissions, and the overall efficiency of supply, which is important for carbon dioxide emissions, resulting in a comparatively low drop in specific emissions.

Under the conditions of the model, an increase of value added and of labor income generated in the USA is presumably. The labor income growth is companioned by growing labor demand, a consequence of a low increase in labor productivity.

6.3.4 EU

The pattern of the EU differs from India, Australia, and USA. In the same way as in the three countries, the enlargement of capacity is achieved at the expense of energetic and non-energetic resources. In contrast to these regions, GHG emissions drop in both cases.

Capacity enlargement in the EU slightly exceeds the world average in the base case, in the high demand case it falls behind. The driving force is investments in mining, resulting in a drastic decline of the static lifetime. As a consequence, static lifetime drops from 295 years in 1995, i.e. above world average, to just 105 years in 2010, i.e. below world average.

In the base case, energy demand growth by the material flow outstrips world energy use but to a lesser degree, even compared to USA. Though specific demand declines, the cutback does not reach the level of world development, due to a rather high technological level inter alia in power generation in 1995.

Emissions in the EU will decline in both cases. Investments in new smelter technology lead to a large drop in specific PFC emissions; a consequence of the rather old stock of smelters in 1995. The below average drop in specific carbon dioxide emissions in the EU is a consequence of the wide use of coal as an energy carrier in the industry.

In the base case, the diverging trend of the indicators is intensified, as value added will presumably fall, although only slightly. This is a consequence of focusing investment on mining, an activity with low value added. Even in the high demand case, the growth is rather low. Labor income edges up in both cases.

6.3.5 Brazil

The other region which contrasts with the global pattern is Brazil. Analogously to all other regions, investment will increase, but only at the expense of energetic resources. This development is accompanied by a slight decrease of GHG emissions in both cases.

Brazil's investments, which are below world average, proceed almost completely in the alumina industry, following the trend of siting alumina plants near mines to make use of cost advantages. This results from abundant bauxite deposits and decreasing transport costs and tariffs, thus increasing Brazil's price competitiveness.

At the same time, static lifetime increases by 20%, since reserves expand by more than exploration. This will be maintained on a very high level. In 1995 static lifetime was about 275 years.

In the base case, energy demand growth by the material flow outstrips world energy use, but to a lesser degree compared to India and Australia. In the high demand case, the edging up of primary energy use corresponds to the world rate. Though specific demand declines, the cutback is low due to the use of hydropower as a main energy carrier. The overall efficiency of hydropower will not change up to 2010.

In Brazil, emissions will decline, although the decrease is rather negligible. The slight drop in PFC emissions follows from the fairly high technological level of smelters in 1995. The increase of carbon dioxide emissions above the world average results from thermal energy intensive activities (mining and refining) with high specific carbon dioxide emissions.

Value added and labor income goes up, although the growth rate will be smaller than the world average. But the number of persons remaining in the system will presumably decline, although only slightly. The small increase is a consequence of concentrating investment on process steps with low value added.

6.4 A short discussion

Summing up the results, no unique pattern for all analyzed regions can be observed. The pattern depends mainly on the investment behavior in the regions and globally also on the opportunity to make use of technological progress.

Globally, investment follows demand for primary aluminum, as it determines the output of primary aluminum, alumina, and bauxite. On the regional level, demand is of minor importance, since regional demand and supply of a good may diverge. Price competitiveness, which is greatly influenced by tariffs and by the price for electricity, and abundance of bauxite (for mining investments) are more relevant (Kuckshinrichs and Poganietz 2003. The development of price competitiveness differs from region to region, in particular due to different tariffs.

Technical progress influences the specific use of energy as well as the emissions of GHG. In the model, technical progress is implicitly dependent on the technological level in the reference year 1995, as the technical level in 2010 is exogenously given, and, regarding alumina and primary aluminum processing, explicitly by the opportunities of modernizing facilities or installing new technologies. These opportunities depend, amongst other aspects, on price competitiveness. In the case of alumina price competitiveness is influenced by the proximity to abundant bauxite deposits. Those regions could gain from technical progress which are able to promote their price competitiveness while having a rather low technological level in 1995.

7 Conclusions

Looking at the findings, neither on the global scale nor on a regional level can a unique trend in the material flow towards (or away from) sustainable development be observed. In both cases, globally as well as regionally, investment will increase. In most regions and globally, enlargement of capacities is achieved at the expense of energetic and non-energetic resources.

A slightly different picture is given by GHG emissions. In the base case, GHG emissions of the material flow drop, and in the high demand case, they increase to some extent. On the regional level, a decrease of GHG emissions could be expected only in the EU and Brazil. Looking at the gases in detail, carbon dioxide emissions will rise in all cases and in all regions. In contrast, PFC emissions will drop.

The paper shows the usefulness of combining the indicator discussion with an in-depth analysis of the interlinkages between different dimensions, taking into account the forward-looking approach of sustainable development. Nevertheless, the analysis emphasizes some additional drawbacks of the indicator discussion:

- Defining of benchmarks: The task of indicator sets is to assess the state of a system with respect to sustainable development. A precondition is the existence of reference points, i.e. benchmarks. This is true even if all indicators point in the "right" direction.

- Selection and aggregation of indicators: Though indicators aggregate information (Ott 1978), the potential number of indicators is still high, due to the complexity of the world. Therefore, a mechanism for selecting appropriate indicators is required. The aggregation problem is comparable. If indicators indicate diverging trends, as presumably happens in the primary aluminum material flow, it is necessary to develop a mechanism to stipulate whether a development is sustainable (or not). The possibility of aggregation implies the possibility of weighting indicators according to their importance for sustainable development.

  There are different approaches to selecting and aggregating indicators. They range from a rather ad hoc manner (e.g. Gilgen 2001) to more sophisticated decision systems (e.g. Kuhndt and Liedtke 1998). Though all the approaches have their merits for furthering the discussion, no approach which systematically selects and aggregates indicators is widely accepted. The aim of this paper was not to present such a procedure and therefore, a rather pragmatic approach was used, following that, for example, of Michalos (1997).

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ALUMINIUM IN OFFENEN UND GESCHLOSSENEN KREISLÄUFEN *

(ALUMINIUM IN OPEN AND CLOSED LOOPS)

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ABSTRACT

Within a material flow management in the sense of „sustainable development", besides of optimising the processes of primary metal production closing of material loops, which means preparation and treatment of secondary raw materials, wins increasing significance. Creation of inventories for life cycle assessment and life cycle analysis or determination of cumulative energy demands for metal production are still missing uniform methods of an integrated assessment of primary and secondary raw material flows. Therefore, new approaches always have to ensure methodical equality of primary and secondary material production during determination and interpretation of processes. To reach this aim, the actual separation of „the primary aluminium" and „the secondary aluminium" has to be replaced by a practice oriented view of material or alloy groups. For the inclusion of recycling loops into such an integrated assessment, firstly following distinction has to be made: On the one hand there are existing material flows which are defined as circuit material within an assessing unit, like in-house scrap, and which do not cross the assessed boundary. On the other hand there are existing material and product flows which leave one assessing unit and enter another as secondary raw material after usage. If the latter scrap is reprocessed to an equivalent use this means closed loop recycling. In this case all expenditure can be clearly ascribed to the product depending on the recycling rate and the share of recycled material for new production. If secondary raw materials and their mixtures are used for other applications after smelting one talks about open loop recycling. It can be seen, that in this case no clear assignment of expenditures is possible because every type of scrap consists of a different alloy, has gone through different production and life cycles, has a certain metal content with a certain metal yield, and achieves different recycling rates. Beside these idealised types of recycling loops there exists a wide range of transition with regard to material and location. Particularly material and qualitative changes of aluminium materials during recycling has lead to misinterpretation when using the term "downcycling". This is not accurate for aluminium with regard to material and economy.

KEYWORDS

Aluminium, recycling, open loop, closed loop

* Source: Aluminium 74 (1998), Nr. 6, pp 421-424

1. Einleitung

Innerhalb eines auf Nachhaltigkeit im Sinne des „Sustainable Development“ ausgerichteten Stoffstrommanagements gewinnt neben einer optimierten Prozeßführung der Primärerzeugung metallischer Rohstoffe die Schließung von Stoffkreisläufen und damit die Bereitstellung und Verarbeitung von Sekundärrohstoffen zunehmend an Bedeutung. Geschlossene Stoffkreisläufe ergeben sich einerseits durch die Wieder- bzw. Weiterverwendung von Produkten (Produktrecycling) und andererseits durch die Wieder- bzw. Weiterverwertung von Alt- und Abfallstoffen (Materialrecycling). Letzterer Form des Recyclings kommt derzeit und auch zukünftig die größere Bedeutung zu, da trotz eines denkbaren hochwertigen Produktrecyclings irgendwann Alt- und Abfallstoffe möglichst zu verwerten sind. Das materielle Recycling stellt somit als Grundvoraussetzung für die Schaffung geschlossener Stoffkreisläufe einen wichtigen Entwicklungsschritt zu einem ökologisch und ökonomisch sinnvollen Umgang mit vorhandenen Ressourcen dar.

Bei der Erstellung von Sachbilanzen innerhalb von Ökobilanzen und Produktlinienanalysen oder der Ermittlung des Kumulierten Energieaufwands der Metallerzeugung fehlen bisher einheitliche Methoden einer integrierten Bilanzierung von primären und sekundären Rohstoffströmen. Neue Ansätze zur Betrachtung der Stoffströme müssen deshalb immer eine gleichwertige methodische und inhaltliche Verknüpfung der primären und sekundären Metall- bzw. Rohstofferzeugung gewährleisten. Dazu soll die in den meisten bisherigen Arbeiten vorgenommene pauschale Trennung von „dem Primäraluminium“ und „dem Sekundäraluminium“ durch eine praxisorientierte stoff- bzw. legierungsgruppenabhängige Betrachtung der Metallströme ersetzt werden.

1. Qualitative Aspekte

Insbesondere die stoffliche bzw. qualitative Veränderung der Aluminiumwerkstoffe während des Recyclings hat immer wieder zu Fehlinterpretationen geführt, indem dafür der Begriff „Downcycling“ verwendet wurde. Dies ist sowohl aus werkstofftechnischer als auch aus ökonomischer Sicht nicht zutreffend. In den Anmerkungen zum Kreislaufwirtschafts- und Abfallgesetz heißt es in § 5, Grundpflichten der Kreislaufwirtschaft: „Die von § 5 Abs. 2 Satz 2 angestrebte hochwertige Verwertung soll gegen das sog. Downrecycling angehen; das ist die Verwertung von Abfällen zu einem minderwertigen Zweck“[1].

Dies ist bei Aluminium nicht gegeben. Selbst die Verwendung als Desoxidationsmittel kann nicht als minderwertig angesehen werden, da sie zum einen strenge Anforderungen an die Reinheit des Aluminiums stellt und zum anderen ebenfalls zur Erzeugung eines hochwertigen Werkstoffs dient.

Neben der werkstofftechnischen Notwendigkeit einzelner Elemente und deren festgelegten Grenzwerten zeigt ein Preisvergleich zwischen Reinaluminium, silizium- und kupferhaltigen Legierungen sowie Schrott aus Reinaluminium und Guß in Abbildung 1 die ökonomische Bedeutung der meist höher legierten Gußlegierungen. Im Unterschied zum Stahl erlauben die mit Aluminium erzielbaren Preise die Aufarbeitung nahezu jeder Schrottqualität, sofern die Metallurgie beherrschbar ist.

Aus metallurgischer Sicht können Gußlegierungen unter realistischen Bedingungen nicht zu Knetlegierungen umgeschmolzen werden, aber umgekehrt müssen in den Sekundärhütten auch Knetlegierungsschrotte zum Auflegieren bzw. Verdünnen einzelner Legierungsbestandteile eingesetzt werden, wenn auf den Einsatz von Primäraluminium verzichtet werden soll. Aus diesem sogenannten Verschneiden unterschiedlicher Arten und Mengen der Legierungs- und Verunreinigungselemente resultiert der Spielraum zur Einstellung der Ziellegierung. Denn die Tatsache, daß außer Lithium, Natrium und Magnesium fast alle Legierungs- und Verunreinigungselemente elektrochemisch edler sind als Aluminium, verdeutlicht die Schwierigkeiten einer nachträglichen Raffination. Selbst Reinaluminium aus der Schmelzflußelektrolyse enthält Eisen und Silizium in der Größenordnung von 0,1 bis 0,3%, so daß bei dessen Einsatz zum Legierungsausgleich auch nicht von Verdünnen sondern wie bei anderen Legierungen ebenfalls nur von Verschneiden gesprochen werden kann.

2. Recyclingmöglichkeiten des Aluminiums

Für die Einbeziehung von Recyclingkreisläufen in eine integrierte Betrachtung primärer und sekundärer Stoffströme muß zunächst folgende Unterscheidung vorgenommen werden:

Zum einen existieren Stoffströme, die innerhalb einer Bilanzierungseinheit als Kreislaufmaterial definiert sind und somit die Bilanzgrenze nicht überschreiten. Dies ist das prozeß- bzw. firmeninterne Recycling von Produktionsschrotten, die direkt wieder zur Herstellung der gleichen Legierung umgeschmolzen werden.

Zum anderen existieren Stoff- und Produktströme, die eine betrachtete Bilanzierungseinheit verlassen und nach ihrer Nutzung in eine weitere Bilanzierungseinheit als Sekundärrohstoff eingehen oder einer anderen stofflichen oder produktbezogenen Nutzung zugeführt werden.

Wird insbesondere bei den zuletzt genannten Stoffströmen der Schrott einem vergleichbaren Wiedereinsatz zugeführt, spricht man von geschlossenen Recyclingkreisläufen oder von closed-loop-recycling. Beispiele sind Aluminiumgetränkedosen und -fensterrahmen, deren Rückgewinnung zum äquivalenten Wiedereinsatz nur einen geringen Neumetallanteil zum Ausgleich der Verluste aus Nutzung, Sammlung, Aufbereitung sowie dem eigentlichen Umschmelzen erfordert. Für diese Form des Recyclings können diesen Produkten dann alle Aufwendungen in Abhängigkeit von der Recyclingquote bzw. des Recyclinganteils an der Neuproduktion eindeutig zugeschrieben werden. Eine Allokation kann somit durch Einbezug des gesamten Recyclingkreislaufes in die Bilanzgrenze vermieden werden.

Werden sekundäre Rohstoffe nach der Verhüttung einer anderen Nutzung (meist auch in Form anderer Legierungen) zugeführt, spricht man von offenen Recyclingkreisläufen (open-loop-recycling). Hierbei sind insbesondere die klassischen Sekundärhütten (Refiner) zu nennen, die beispielsweise aus einem Gemisch aus diversen stückigen oder paketierten Alt- und Neuschrotten Gußlegierungen für die Automobilindustrie herstellen. Man erkennt leicht, daß in diesem Fall keine eindeutige Zuordnung der Aufwendungen möglich ist, da jede Schrottsorte

- aus einer anderen Legierung besteht,
- unterschiedliche Produktions- und Lebenswege durchlaufen hat,
- einen bestimmten Metallinhalt hat und demzufolge auch verschiedene Metallausbeuten und
- unterschiedliche Recyclingquoten erfüllt.

Eine weitere Anwendungsmöglichkeit von Sekundäraluminium besteht in dem Verbrauch als Chemikalie für die Desoxidation von Stahl und die aluminothermische Reduktion. Dieses Aluminium kann nach der Nutzung nicht zurückgewonnen werden, hier liegt ein echter Metallverbrauch vor. Abbildung 2 stellt die drei diskutierten Recyclingmöglichkeiten des Aluminium gegenüber.

Neben diesen „idealisierten“ Recylingkreisläufen existiert ein fließender Übergangsbereich beider Formen in stofflicher und räumlicher Hinsicht. Stofflich deshalb, da auch Knetlegierungen zu Gußlegierungen verarbeitet werden und damit eine werkstofftechnische Veränderung erfahren. Räumlich deshalb, da Produktionsschrotte nicht nur firmenintern, sondern auch extern aufgearbeitet werden und somit nicht in einem geschlossenen Kreislauf verbleiben. Sortenreine Knetlegierungsschrotte werden dabei gezielt von den Umschmelzhütten (Remelter) aufgearbeitet, die sowohl in geschlossene als auch in offene Recyclingkreisläufe gelangen. Mischschrotte und verunreinigte Schrotte werden wie erwähnt durch die Refiner aufgearbeitet und gelangen meist in offene Recyclingkreisläufe.

Als Konsequenz dieser Betrachtung stellt sich im Hinblick auf die Bilanzierung der Recyclingkreisläufe die Frage, wie eine sinnvolle Allokation unter Einbezug der qualitativen und vielleicht auch wirtschaftlichen Aspekte durchzuführen ist. Hierbei sind nicht nur die bereits erwähnten Recyclingquoten und -anteile von Bedeutung, sondern ebenso die Art und Menge der vorhandenen und benötigten Legierungselemente, der Hilfs- und Betriebsstoffe sowie Menge und Potential entstehender Belastungen.

3. Integrierte Betrachtung der primären und sekundären Metallerzeugung

Zur Beantwortung dieses Fragenkomplexes geht das Teilprojekt „Verhüttung von primären und sekundären Aluminiumrohstoffen“ in dem seit Januar 1997 von der DFG eingerichteten Sonderforschungsbereich „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“ von folgendem Ansatz aus. Die Prozeßkette der primären und sekundären Aluminiumerzeugung mit allen relevanten Vorketten zur Erzeugung der Hilfs- und Betriebsstoffe wird in einem modularen Aufbau abgebildet, Abbildung 3. Dabei sind die einzelnen Prozeßmodule, die einer Bilanzierungseinheit und somit einem Kästchen entsprechen, so ausgewählt, daß

- sie innerhalb der Prozeßkette durch Alternativtechniken austauschbar sind,
- sie möglichst realen Betriebseinheiten entsprechen,
- sie bereits mit den erforderlichen Nebenaggregaten bzw. Vorketten teilaggregiert wurden,
- sie zunächst möglichst allokationsfrei bilanziert werden können,
- ihre Produkte immer in der daruntergelegenen Ebene eingesetzt werden,
- beim ersten Durchlauf bereits alle Sekundärrohstoffe berücksichtigt werden,
- interne Kreislaufstoffe nicht dargestellt werden müssen

- und sie auch praktisch bilanzierbar sind.

Dunkel hervorgehoben ist die Hauptprozeßkette des Aluminiumstoffstroms. Hell hervorgehoben ist die Nebenprozeßkette ersten Grades mit direktem Input in die Hauptkette und weiß sind die Nebenprozeßketten höheren Grades.

Das Modul „Schmelzen und Schmelzebehandlung“ nimmt eine Sonderstellung ein. Hier wurde eine Trennung von dem Modul „Überführung in Formate und Transportformen“ vorgenommen, um einer Masseneinheit „flüssige Aluminiumlegierung“ an der Schnittstelle zwischen Metallerzeugung und -verarbeitung die jeweiligen Aufwendungen zuordnen zu können.

Nach dem neuen Ansatz soll die erwähnte Trennung von Primär- und Sekundäraluminium durch eine stoff- bzw. legierungsgruppenabhängige Aufteilung der Metallströme ersetzt werden. Jede Gruppe hat dabei einen üblichen Erzeugungsweg, der sich aus den verschiedenen primären und/oder sekundären Prozeßstufen ergibt. Das Modul „Schmelzen und Schmelzebehandlung“ übernimmt dabei eine Mischfunktion aller Metallinputs einschließlich der Legierungselemente, so daß die Aufwendungen prozentual zugeordnet werden können. Die Bilanzierungsgrenze liegt dann primär beim Bauxitbergbau und sekundär bei der Schrottsammlung.

Dies setzt voraus, daß in dem verwendeten Bilanzierungsmodell ein gleichzeitiger Zugriff auf alle vorhandenen Modulvarianten gewährleistet ist. Darüber hinaus sollte es zur Einschränkung der Modulanzahl in der Lage sein, neben den stoffspezifischen Parametern auch modulinterne Variablen, wie etwa die Abhängigkeit des Brennstoffverbrauchs vom Sauerstoffeinsatz in einem Schmelzaggregat, zu verarbeiten, die eine schnelle Anpassung der Prozeßkette und somit eine Teiloptimierung ermöglichen.

4. Systemgrenzen und Allokation

Neben den beinahe „klassischen“ Problemstellungen der Allokation, d.h., der Verteilung von energetischen und stofflichen Aufwendungen bzw. Rückständen auf zwei oder mehrere Haupt-, Neben- oder Kuppelprodukte eines Prozesses mit dem Paradebeispiel der Chlor-Alkali-Elektrolyse existieren auch bisher weniger beachtete aluminiuminterne Zuordnungsprobleme, wie sie beispielsweise bei den gezeigten Recyclingmöglichkeiten auftreten.

Die existierenden Ansätze liefern bisher nur für einige Idealfälle brauchbare Allokationsregeln die sich aber in der Praxis oft nicht anwenden lassen. So muß bisher für jeden abweichenden Einzelfall eine Begründung für die Nichteinhaltung dieser Regeln gegeben werden oder eine Allokation durch Systemerweiterung bzw. -aufteilung vermieden werden [3-9].

Bevor die eigentliche Entscheidung getroffen werden muß, welche Aufwendungen wie auf verschiedene Stoffflüsse verteilt werden, kommt der Definition der Systemgrenzen eine entscheidende Rolle zu. Hierbei spielen insbesondere die Abschneidekriterien für die Betrachtung der der Hauptprozeßkette vorgelagerten Bereitstellungsprozesse eine Rolle. Wird mindestens ein Abschneidekriterium (Masse, Volumen, Preis, Arbeitsaufwand, Energieinhalt, Toxizität, etc.) nicht erfüllt, muß die entsprechende Vorkette ebenfalls bilanziert werden. Fließt aus dieser Vorkette beispielsweise nur einer von mehreren Stoffen in die Hauptprozeßkette, muß eine Allokation der Aufwendungen nach den gleichen Kriterien geschehen. So können etwa nicht nach einer durch ein Preiskriterium berücksichtigten Vorkette deren Aufwendungen nach den Gewichtsverhältnissen verteilt werden.

Dies führt zu der Feststellung, daß auch aus dem Blickwinkel unterschiedlich angelegter Szenarien schon die Auswahl der Abschneide- und Allokationskriterien für den jeweiligen Fall das Ergebnis der Berechnungen entscheidend beeinflußt. Somit muß sich diese Auswahl nach der gesamten Zielsetzung der Bilanzierung richten.

Im Sinne der Gesamtbetrachtung des SFB 525 sollen in diesem Zusammenhang die Möglichkeiten zur stofflichen und energetischen Allokation nach einem definierten Nutzen untersucht werden, das heißt, nach dem um ökologische und ressourcenökonomische Kriterien erweiterten Wert der zu betrachtenden Produkte und Prozesse. Angestrebt wird eine möglichst einheitliche und im Idealfall übertragbare Abschneide- und Allokationsregel. Es bleibt dann durch iterative Prüfung zu zeigen, ob sich Einzelfehler in den Berechnungen statistisch verstärken oder eliminieren und wie stark sich die Ergebnisse bei Anwendung dieser Regel von einer zuvor durchgeführten allokationsfreien Berechnung unterscheiden.

Schließlich bleibt die Frage zu klären, ob und wie der dem Metallinhalt der Schrotte zugehörige Anteil seiner ursprünglichen Primärerzeugung anzurechnen ist. Hierzu wird vorgeschlagen, eine Verteilung der Aufwendungen und Belastungen für Bergbau, Aufschluß und Elektrolyse auf die gesamte wiederholte Nutzung unter Einbeziehung des Recyclings vorzunehmen. Der Aluminiuminhalt der Sekundärrohstoffe wurde ja selbst einmal aus Primärrohstoffen erzeugt und bringt einen bestimmten Anteil dieser Aufwendungen in die Bilanz ein [10, 11].

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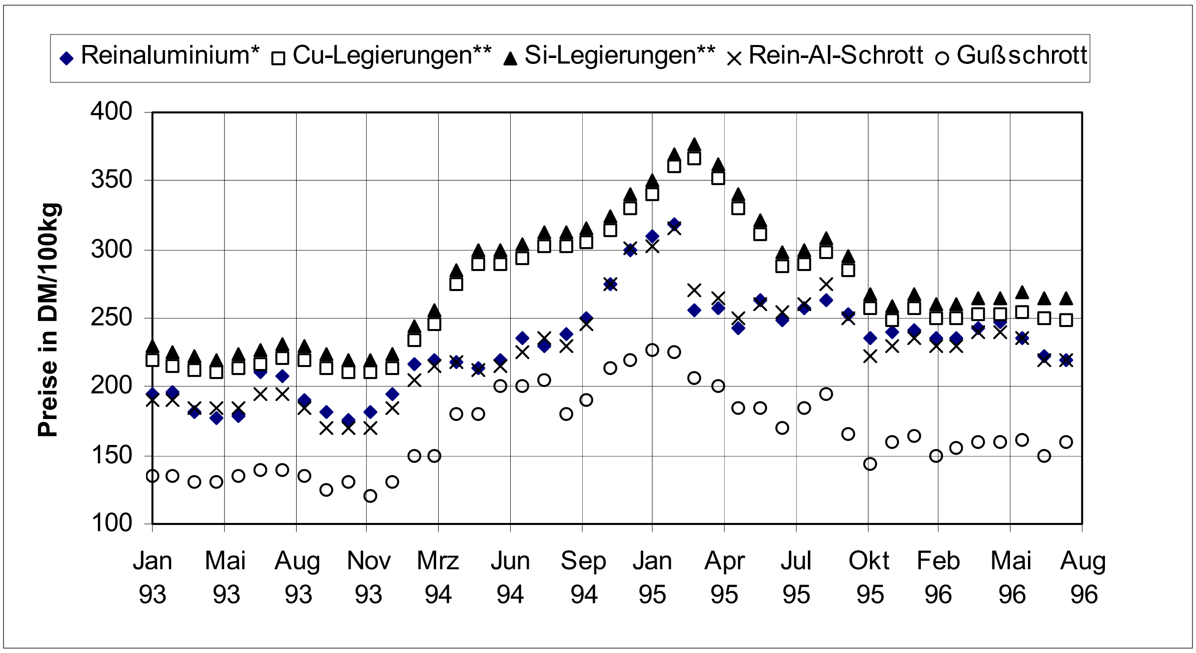

(*LME-Kassanotierung für unverzollte Ware
**Kleinmengen bis 3 t, für größere Mengen sind Abschläge bis 25 DM/100 kg möglich)

Abbildung 1: Preisvergleich zwischen Reinaluminium, Si- und Cu-haltigen Legierungen sowie Schrott aus Reinaluminium und Guß [2]

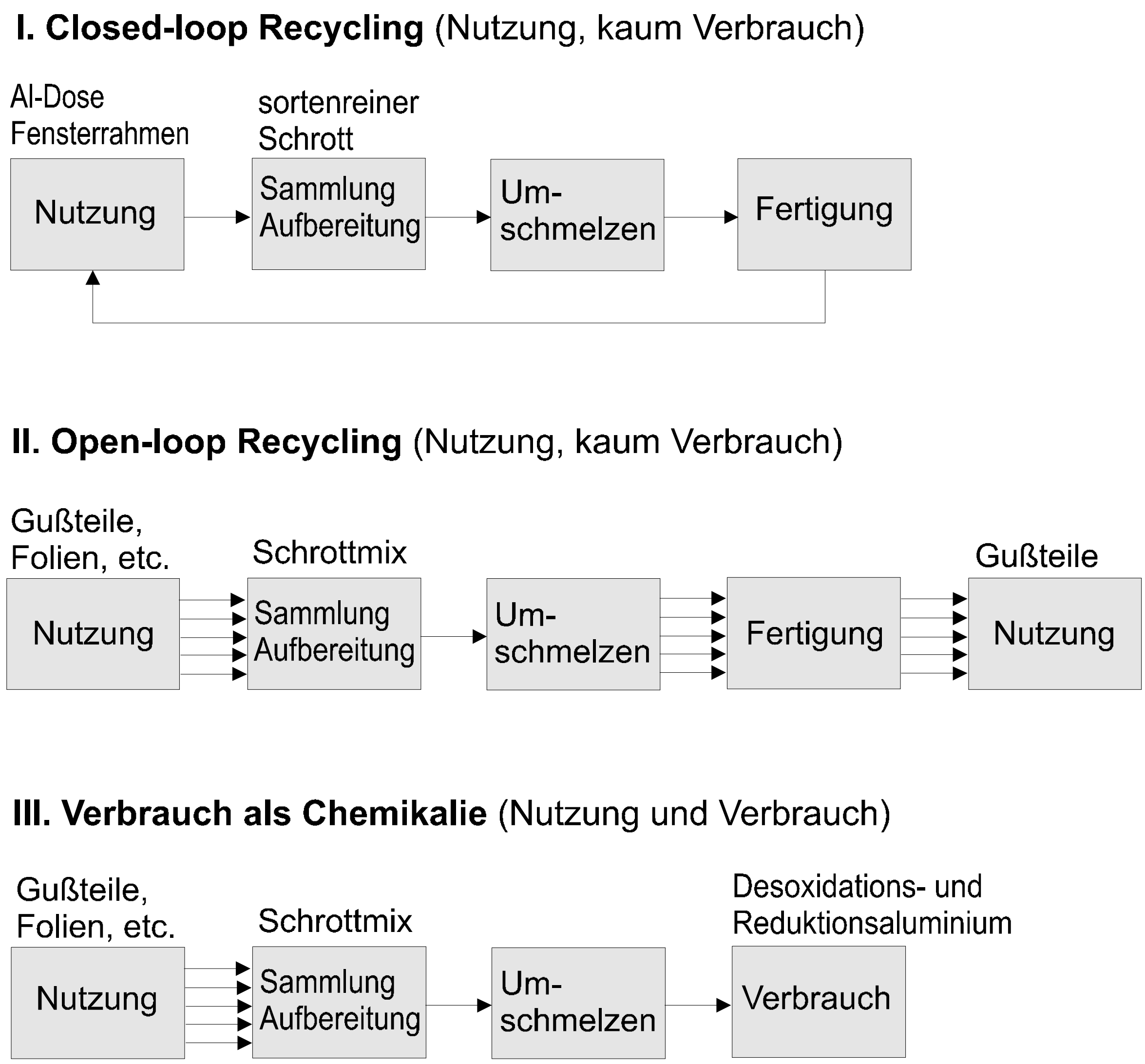

Abbildung 2: Recyclingmöglichkeiten des Aluminiums

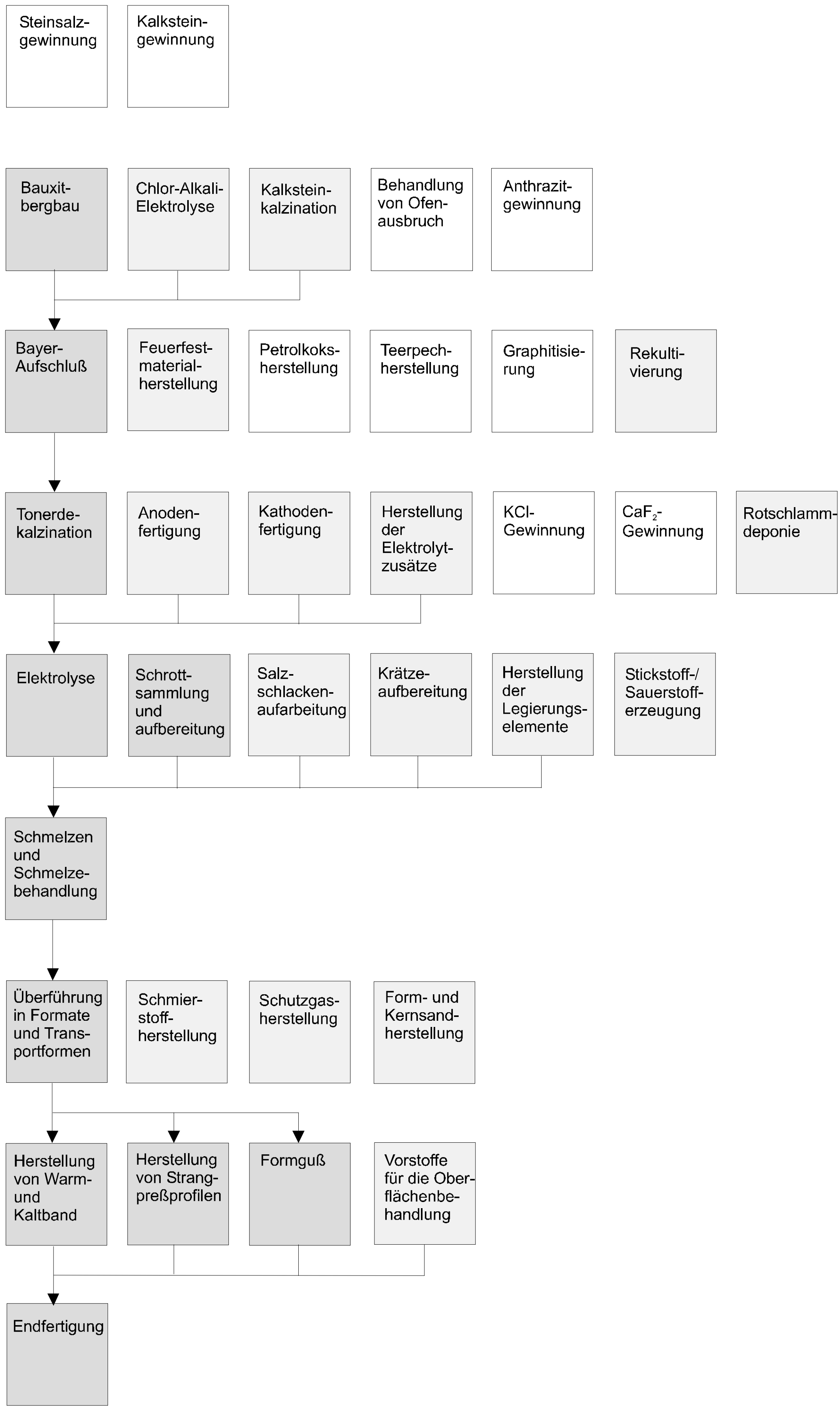

Abbildung 3: Modulare Prozeßkette der primären und sekundären Aluminiumerzeugung

ELEMENTS OF A RESOURCE-ORIENTATED ANALYSIS OF THE MATERIAL FLOW OF ALUMINIUM: A SYSTEMS ANALYSIS APPROACH*

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ABSTRACT

The production, processing and use of aluminium initiates direct and indirect material and energy flows. Resulting environmental damages justify efforts to reduce the flows. The Collaborative Research Centre (SFB) 525 „A Resource-Orientated Analysis of Metallic Raw Material Flows" aims to analyze existing options and to develop operative recommendations for a resource-sensitive utilization of metallic raw materials. The analysis is carried out using computer-based models. The models reduce the complexity of the material flows to its main elements, taking into account its technical, economical and ecological aspects on a different level. They are applied to set up balances of present material and energy flows. Using scenario techniques, trends and plausible developments are demonstrated. Its effects on material and energy flows, choice of production location, and resource productivity are to be analyzed. The paper concentrates first on methodological aspects of modelling the material flows of aluminium. It focuses on a process chain model and a model of the global aluminium industry. Moreover, model-based calculations of energy use and greenhouse gas emissions of present and future aluminium flows are presented.

KEYWORDS

Material flow, energy flow, process chain model, model of global aluminium industry, scenario

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1. INTRODUCTION

Worldwide, scientists and politicians are discussing the concept of sustainable development. At the moment, the discussion is shifting to resource and environmentally sensitive products and industries. Besides energy and its conversion, now nonferrous metals and the metals industry are not excluded (Stern, 1995; Shinya, 1998; Sánchez, 1998; Schwarz, 1999b). Experts agree, that for any development path to be sustainable economic, ecological and social aspects must be kept in mind, as well as aspects of intergenerative and intragenerative justice (fig. 1).

It is agreed, too, that for more practical purposes there is a need to differentiate strategic rules, which are already formulated on a highly aggregated level, with respect to special aspects of products and production sectors, in order to formulate operative recommendations.

The long-term goal of the Collaborative Research Centre (SFB) 525 „Resource-orientated analysis of metallic raw material flows“ is the identification of options for resource and environmental-sensitive supplying and processing of metallic raw materials considering technical developments and economic and ecological aims. The reproduction of interdisciplinary interactions is regarded as an important aspect of a resource-orientated analysis.

The scope of the analysis of SFB 525 ranges from deposit evaluation to extraction through the processing and smelting of mineral resources up to manufacturing and utilization. The recycling processes for supplying secondary resources after the use phase are also analysed and assessed as an integral part of the raw materials supply. Transportation, supply of final energy and utilization or disposal of the most important waste flows along the process chain are included in the investigation. This procedure makes it possible to analyse both environmental and economical aspects of the technical process chain, as well as selected social aspects.

As part of SFB 525, STE is developing and using computer-based tools within the framework of systems analysis. The combination and use of these tools is illustrated in fig. 2. The STE tools comprise an information system, a model to analyse material and energy flows in process chains, and a model to analyse the global metal industry. Additionally, experts from Aachen Technical University are developing tools for modelling single processes.

Starting from the inventory of the status quo and the analysis of the corresponding resource utilization, scenarios will be designed to reflect a range of plausible developments. This includes basic trends of technical and organizational progress to be compared with goal-orientated scenarios considering interventions, e.g. by political decision makers. The potential effects on the material flows, the energy consumption, the choice of location for mining and processing plants and resource productivity will be examined for all scenarios.

Fig. 1: Methodological aspects of sustainable development concepts

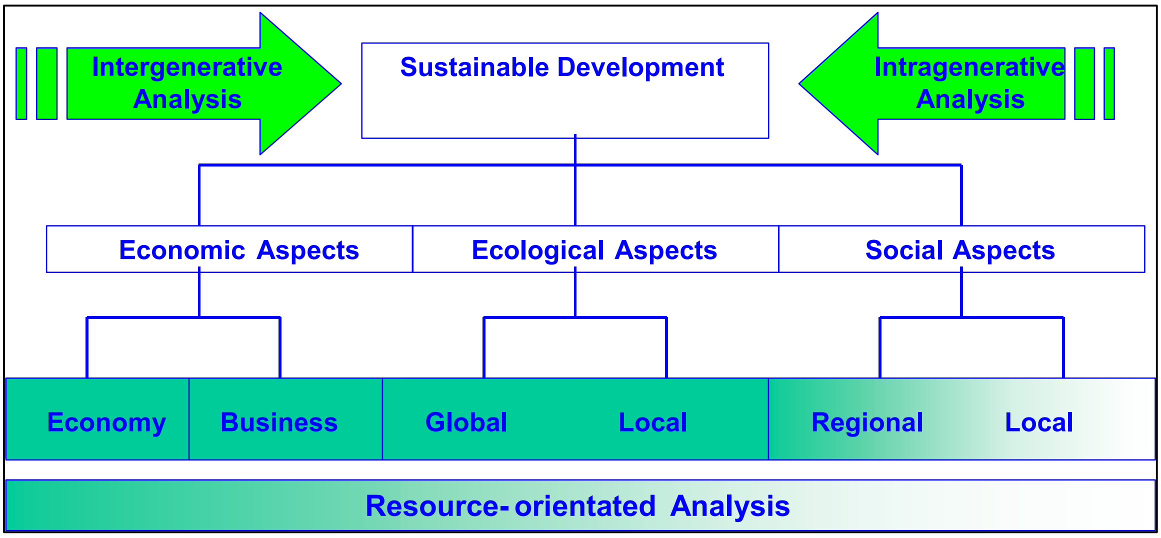
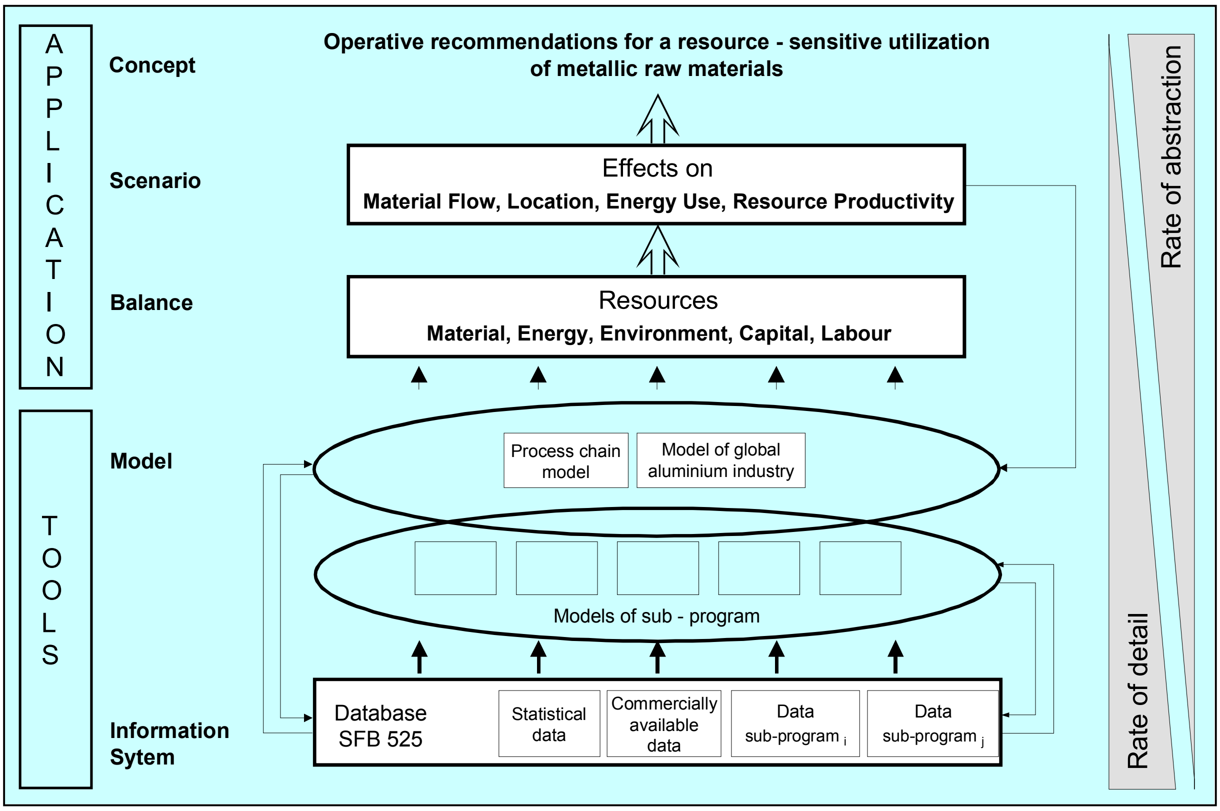


Fig 2: Tools and their application by SFB 525



This paper concentrates on methodological aspects of analysing the material flow of aluminium with the process chain model and the model of the global aluminium industry. Moreover, model-based calculations of energy demand and greenhouse gas emissions of present and future aluminium flows are presented.

2. MODELLING OF THE MATERIAL FLOW OF ALUMINIUM

2.1 *Global material flow*

The production of aluminium is divided into bauxite mining, production of alumina, and production of primary and secondary aluminium. Mining of bauxite is tied to regions with natural deposits, whereas the production of primary aluminium is related to regions with sufficient and cheap electricity. The geographical distribution of production at each value-adding stage is the result of weighing up the competitive advantages and disadvantages of competing locations. Further basic aspects comprise geopolitical stability (especial for mining activities), environmental policy, infrastructure, and level of training of employees.

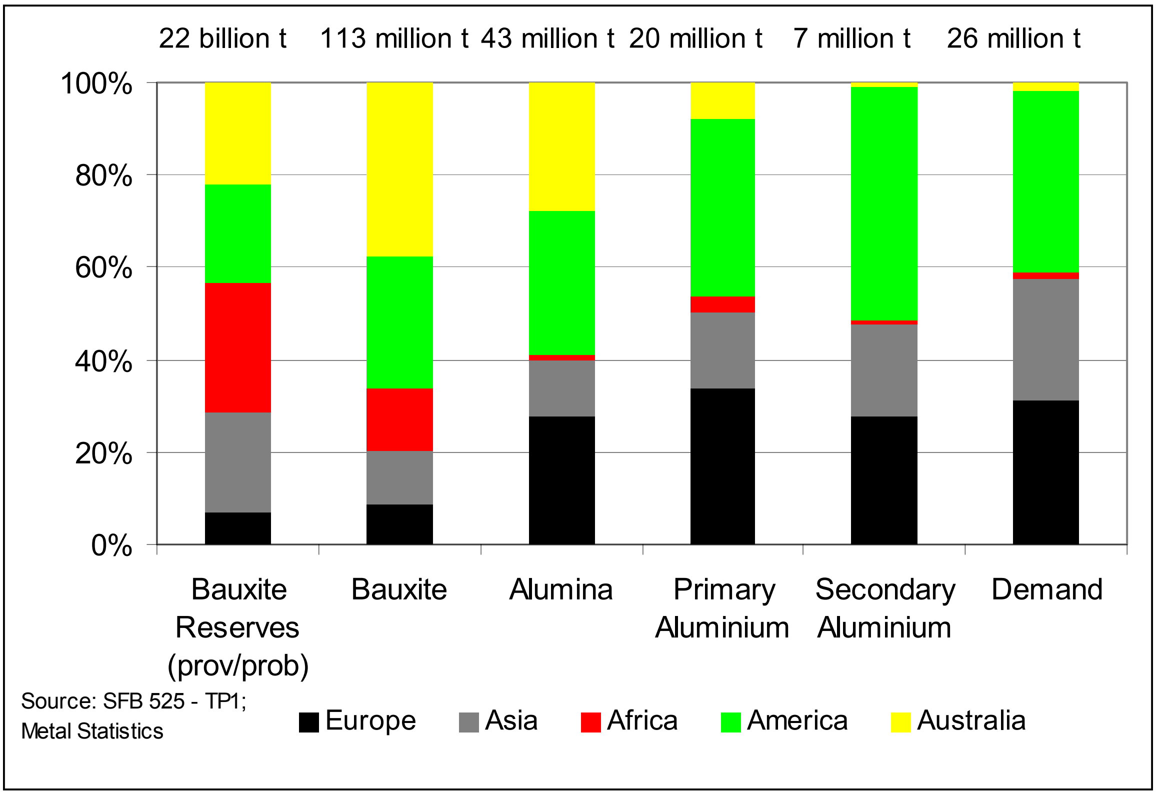
Production and demand figures are statistically fairly well covered. Fig. 3 gives an overview for 1995 and shows regional shares of bauxite reserves, production at different value-adding stages, and demand. Moreover, fig. 3 points to the aspects of global integration and international division of production of the aluminium industry. Different regional shares for production and consumption support this argument.

The production and processing of aluminium and use of aluminium-based products initiates direct and indirect material and energy flows, which in contrast to production figures are basically only available on a company level. These flows comprise red mud, industrial effluents, primary energy carriers, and greenhouse gases, e.g. CO_2 and perfluorinated hydrocarbons.

To quantify material and energy flows of the aluminium industry on a national or regional level model-based approaches may be used. It has to be taken into consideration that material and energy flows are determined technically, but motivated economically. Whereas the refining of bauxite to alumina reflects a technical production process, the decision to produce at a special location is taken considering economic aspects.

To analyse the material and energy flows of aluminium two computer-based models have been developed. The models are independent, but complement one another, as they look at material and energy flows from different viewpoints and focus on either technical or economic aspects.

Fig. 3: Bauxite reserves, production, and consumption of aluminium and its regional shares



2.2 *The process chain model*

Aims of process chain analysis

The process chain model serves for the presentation and evaluation of material and energy flows arising from the use of nonferrous metals and their environmental impact. Due to a very detailed presentation of technologies it offers the opportunity to investigate the effects of technology variations in the first place. In contrast to many other studies in the field of process chain analysis of raw materials (Shen, 1981; Tellus, 1992; Habersatter, 1995; EAA, 1996; BGR, 1997) the work of SFB 525 puts the main emphasis on the high disintegration for the presentation of sequences within the processes, rather than differences within geographical regions. The aggregation level of the various process modules is lower than in other studies. Possible questions may be:

- Which processes have the biggest share in the consumption of resources?
- With which process alternatives can the material and energy flow be reduced, while maintaining the same level of production?
- How must closed-loop material recycling be designed to reduce raw material input?
- What effects does an increase of the recycling quotas have on material and energy use?
- How does technical progress affect material and energy use and emissions?

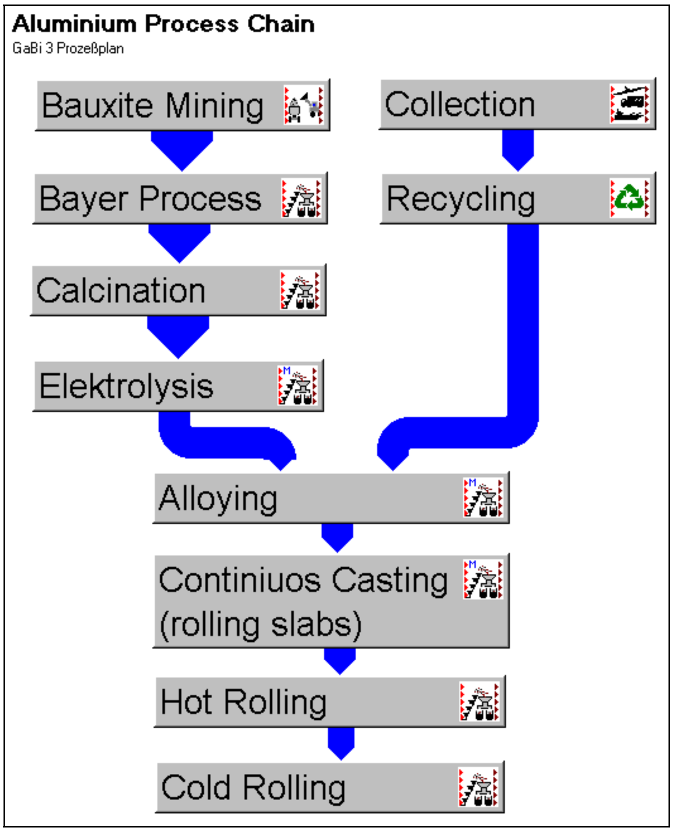
Other questions can be answered, which refer to special regional features. Therefore, the location-independent modules have to be assigned to the different regions. The results show the influence of varied import and export structures.

Structure of a process chain for the German packaging sector

Within the work of SFB 525 further methodological aspects of the process chain analysis have been developed for the use of aluminium in the German packaging sector. The packaging sector is well documented and various aspects of process chain analysis, such as consideration of different alloying qualities, mixing of primary and secondary aluminium, or recycling concepts, can be modelled. At the same time the variety of products in this sector is smaller than for example in the transport sector. A mixing of the different methodological approaches is decreased by the limited product complexity.

Inputs and outputs of the entire process chain are collected for the base year in the inventory analysis. The chosen process chain starts with the mining of the raw material bauxite according to the German imports, considers the production of alumina in the Bayer process with subsequent calcination, the production of aluminium from alumina in the electrolysis, the mixing of primary and secondary aluminium in the process step of alloying, up to the semifinished product foils, through the production of transportable formats, and finally hot and cold rolling. In the field of secondary production, the used packages are collected and mechanically or thermally recycled. The metal-containing prematerials are used to produce alloys. Figure 4 shows a simplified structure of the process chain.

Fig. 4: Simplified structure of the aluminium process chain in the packaging sector



In between the various production processes transport processes take place, which are also included in the analyses. Also taken into consideration are side chains for electricity production to obtain the necessary final energy for the processes. The production of intermediate materials for the Bayer process includes soda (NaOH) and lime (CaO) production. At the electrolysis level, anode, cathode, aluminium fluoride (AlF_3) and petroleum coke production is included in the balance. At the moment processes for waste treatment concentrate on red mud treatment, which is the biggest output along the process chain.

The second stage of manufacture and also the use phase are important elements in the process chain, but have not yet been included. First aspects in the analysis have already been made (Bauer et al., 2000).

To obtain a process chain, a process library has been set up, which includes all processes of the aluminium flow. Technology-specific and location-independent modules were determined. The technical status of the processes is considered in the classification of different technology levels. The processes are divided into old technologies (old), present technologies (PT), and the latest available technologies (NT). Furthermore, technical options for future use (FT) are presented. To keep the number of possible process modules small, those processes which differ just insignificantly are combined. The calculation of average modules of the site-independent processes is in a production-weighted manner.

At the moment about 170 processes directly connected with the production and recycling of aluminium, about 30 processes concerning intermediate inputs or outputs and about 120 modules describing transport and energy supplying processes are included in the process library. Additionally, mineralogical information on 170 deposits is included.

Contrast to other studies

The process chain, developed within the framework of SFB 525, differs greatly from other projects (Tellus, 1992; Hydro Aluminium a.s., 1994; EAA, 1996; BGR, 1997; Gielen, 1997; Reuter, 1998). Most of the studies do not directly include the mineralogical qualities of the deposits. It is therefore impossible to obtain detailed information. In the mining field many studies model regions. Different geological qualities in one region cannot be adequately considered. Local mining is mainly influenced by the geological structure rather than the region in which it is located.

If no mineralogical deposit information is known, the modelling of the Bayer process can only be done with average parameters, irrespective of the real geological structure. Also it is normally not considered whether the bauxite used is of gibbsitic quality or has a higher share of boehmite, which is important for the selection of the technology needed.

Quite a lot of studies about aluminium are comparisons of products which simulate specific locations in the process chain. Within the framework of SFB 525 production-weighted worldwide averages have been modelled by using site-independent processes, which can easily be modified for country-specific analysis.

An analysis of the primary process chain is performed by most of the studies. Often the scope ends here. The secondary production chain is not always integrated. One goal of SFB 525 is to give a complete overview of the production and recycling processes. In the module group ‘alloying’ a mixing of primary and secondary aluminium takes place. From this point on the process chain is not only modelled according to its condition but also according to its alloying contents. This approach is new. Now it is possible to deal with all aspects of the variety of aluminium alloys. Similarly, the production of semi-finished products is modelled showing the respective qualities.

Recycling of aluminium is not taken into consideration in many studies or only modelled in a highly aggregated way. For this production chain model different modules of recycling processes for the various sources of secondary raw material coming from the use phase are developed. Moreover, the recycling of new scrap is also taken into consideration.

2.3 *Model of the global aluminium industry*

The model of the global aluminium industry permits an integrated analysis of the technical, geographical, ecological and economic dimension of the material flow of primary aluminium (Schwarz, 1999a; Schwarz et al., 2000). Questions which can be answered by the model are:

- How will the production geography of the worldwide flow of primary aluminium change in the future?
- What about the trade flows?
- Which technologies will be successful in competition and will old plants, upgraded and expanded old plants, or new plants be used for future production?
- How will the absolute and specific final and primary energy consumption and emissions of greenhouse gas develop worldwide and in the regions?

Additionally, the effects of instruments of material flow management can be assessed, for example:

- What are the effects of national or global energy or carbon dioxide taxes on production geography and greenhouse gas emissions?
- What happens when import duties on bauxite, alumina or primary aluminium are perceptibly reduced or raised?

The model of the global aluminium industry answers these questions through simulation of a competitive market for primary aluminium and intermediate products. The flow of primary aluminium is seen as economically determined. Human needs and market processes are responsible for the extent, the technical conditions, and the ecological effects of the material flow. The demand for primary aluminium induces the material flow. Different technologies and regions are in competition to satisfy the demand for primary aluminium and intermediate products. The market process decides which technologies and regions will win the competition and therefore what quantity of emissions will be generated.

Model classification

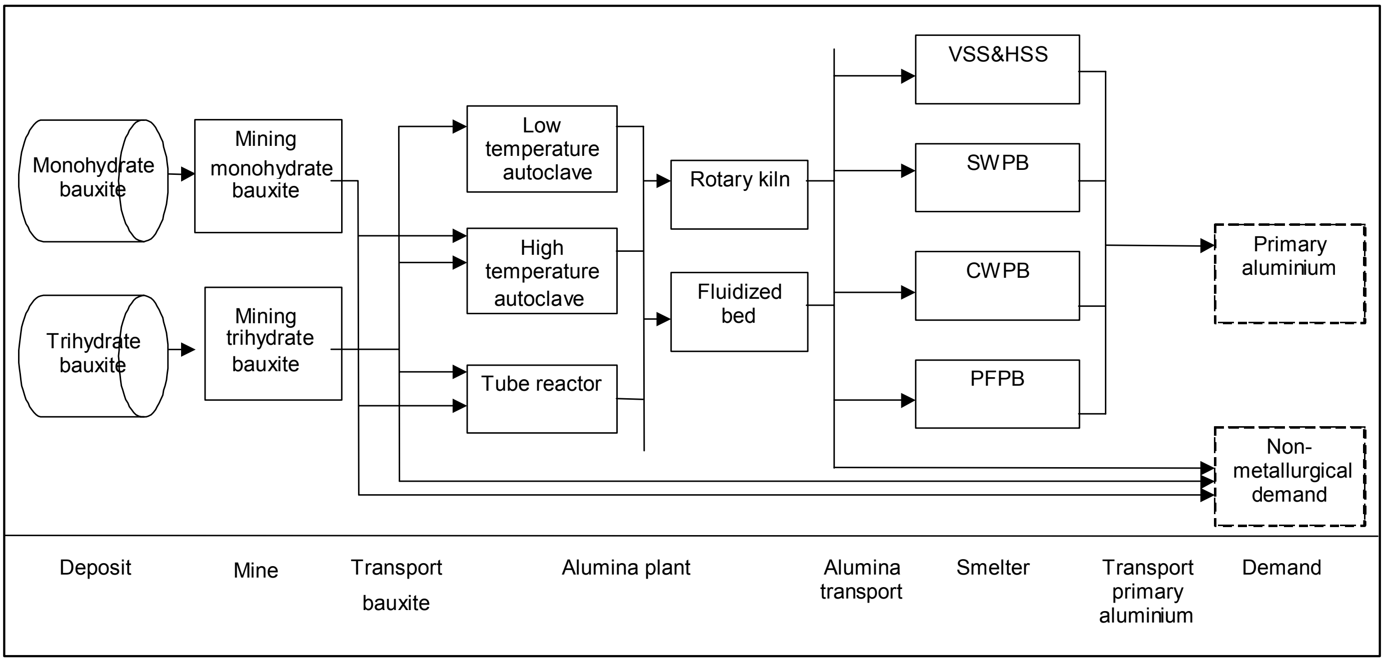
The model of the global aluminium industry is a further development of existing approaches (Brown et al., 1983; Nichols et al., 1992; Manne et al., 1994). It is computer-based and uses a linear programming technique. The demand for primary aluminium is assumed to be given and its extent is independent of price from the model's perspective. The model is static. All the model parameters and all the variables (production and transport quantities, investment) refer to the year 2010. The reference year 1995 influences the model results only indirectly. The assessment of model parameters for the year 2010 is based on figures for 1995 or a period including 1995. The implemented mathematical algorithm calculates a long-term market equilibrium with perfect competition (Takayama et al., 1971; Landwehr, 1997). It is therefore assumed that the producers of bauxite, alumina and primary aluminium maximize their profits decentrally. They accept the market price as given and adjust their production quantities according to their marginal costs.

Material flow modelling

The model of the global aluminium industry considers the global flow of primary aluminium. The manufacture of primary aluminium in the remaining process chain, reusage through recycling and, if necessary, waste disposal is additionally part of the total flow of aluminium.

Technical transformations within the material flow are reflected in three process steps: mining, refining and smelting (Fig. 5). The chemical and mineralogical heterogeneity of bauxite is reflected in 18 bauxite types. The different technical options for the three process steps are integrated into a few technologies. Six technologies are distinguished for refining and four technologies for smelting. The model separates four kinds of investment strategies: old plants, upgrading, brownfield expansion and greenfield expansion. Upgrading of old plants means that the technical parameters of the plants are improved by changing components. Outmoded technologies are usually replaced by modern technology. Within the model, upgrading is not connected with capacity expansion. It is the brownfield expansion which leads to the capacity expansion of existing plants. Greenfield expansion means that new plants are built. The reason for considering the different investment strategies is, on the one hand, that old plants and new plants do not have the same technical parameters even if they use the same technology. Usually the new plant will be superior. On the other hand, new plants as well as brownfield expansion and upgrading cause investment costs, whereas the

Fig. 5.: Simplified structure of the model of the global aluminium industry



(former) investment costs of old plants are not relevant from the model's perspective ('sunk costs').

The model considers three transportation steps: mine to refinery, refinery to smelter and smelter to final demand. Means of transport are truck, rail, conveyor belt, inland and overseas ship. The model considers 15 world regions: USA, Canada, Brazil, Rest of Latin America, Germany, Rest of European Union, Rest of Western Europe, Former Soviet Union, Rest of Eastern Europe, Africa, Near and Middle East, India, China, Rest of Asia and Australia.

2.4 *Comparison of model characteristics*

The models considered in this paper are both process-based, complementing one another, but with different viewpoints concerning material and energy flows. Therefore, their contribution to the resource-orientated analysis differs in scale and direction.

Whereas the process chain model concentrates on the detailed reproduction of technical processes, the model of the global aluminium industry follows an economic approach. Both tools show material and energy flows along the production chain of aluminium, using the concept of process description via inputs and outputs. At the moment, the model of the global aluminium industry follows the production chain of aluminium from bauxite mining to production of primary aluminium on a global scale. As important side chains, the supply of final energy carriers, of anodes and of soda are included. Moreover, the process chain model follows the production chain up to the supply of secondary resources. Additionally, it includes further important side chains such as handling of red mud and supply of aluminium fluoride (AlF_3). The process chain model follows the concept of a site-independent tool, which can easily be modified for country-specific or regional-specific studies based on a higher disintegration of technical processes.

Table 1 shows a comparison of important model characteristics. It focuses on the model's concept, the system's boundary, the exogenous parameters, and the model results.

- Whereas the process chain model simulates technical processes based on specific input-output data, the model of the global aluminium industry simulates a competitive aluminium market, using full aluminium trade balances.
- Whereas the process chain model exclusively uses technical parameters as exogenous parameters, demand for primary aluminium and cost parameters including duties and taxes constitute further important exogenous parameters of the model of the global aluminium industry.
- Whereas the process chain model assesses the specific demand for preproducts of the aluminium chain as well as the specific demand of a range of side chains and important emissions, the model of the global aluminium industry restricts itself to determining absolute balances of the production chain up to primary aluminium, and fewer, but important side chains. Moreover, as an economic model, it determines regional production and investment allocation.

Table 1: Characteristics of the model approaches

	Model of the global aluminium industry	Process chain model
Concept	Market simulation, cost minimization	Simulation of integrated technical processes
	Absolute aluminium trade balance	Specific input-output data
	Aggregated technologies	Disaggregated technologies
Systems boundary	Global	Regional / country-specific / site-independent
	Bauxite mining to primary aluminium	Bauxite mining up to processing and casting including recycling of secondary resources
Exogenous parameters	Demand	
	Technical parameters	Technical parameters
	Cost parameters Duties	
Model results	Regional and value-added stages: Production, investment	
	Demand for main input	Demand for main input
	Other inputs: e.g. energy, caustic soda, anodes	Other inputs: e.g. energy, caustic soda, petrol coke, pitch, lime, anodes, cathodes, AlF_3
	Emissions: CO_2, CF_4, C_2F_6	Emissions: e.g. CO_2, CF_4, C_2F_6, HF, red mud, industrial effluents

3. RESOURCE-ORIENTATED ANALYSIS FROM A MODEL PERSPECTIVE

Offering the opportunity to analyze a system from a technical or an economic viewpoint, and to balance both energy use and emissions, the models are used first for inventory analysis. In the following, model-based scenario calculations for material and energy flows are presented.

3.1 *Inventory Analysis*

With respect to different questions for the models, to different model characteristics, and the resulting different system boundaries, the models are used to quantify different complementary balances. The process chain model focuses on the production of aluminium for packaging purposes in Germany whereas the model of the global aluminium industry concentrates on the worldwide production of primary aluminium. For the global model, 1995 serves as the base year, but 1997 for the process chain model.

To give a better understanding of energy use and CO_2 emissions calculated for the base year 1995, some reflections are useful. The specific final energy consumption within the material flow just depends on the energy efficiency of the technologies used for mining, refining and smelting. The primary energy consumption is also influenced by the efficiency of the primary energy conversion, especially the efficiency of the electricity supply for electrolysis. Furthermore, a differentiation between the contract mix and the regional mix for electricity supply results in different calculations.

The figures of overall efficiencies for regional electricity production and the associated CO_2-emission factors were assessed by project partners (Briem et al., 1999). Contract mix and regional mix are differentiated for smelting. The contract mix considers the energy carriers for electricity production used in accordance with existing contracts for smelting or for self-generated electricity. The regional mix on the other hand reflects the average shares of the energy carrier for the regional production of electricity. The contract mix is characterized by a high share of hydro-based electricity production on the world average. In 1995 this share was about 60%. This is not surprising. Cheap hydro-based electricity is the important locating factor for smelters. The share of hydro-based electricity for the regional mix was much lower, about 30%. Fossil-fuelled power plants had, in contrast, a much higher share with more than 56%. For the contract mix, the share was less than 37%.

Process chain model

In a weak point analysis those processes can be identified, which exert a major influence on the use of resources. One of the resources considered is the energy demand (see Fig 2). Geographical and time boundaries are given to calculate the starting condition. In the field of collecting and recycling secondary raw Material, data about the distribution of the technologies used cannot be gathered from the base year, but from 1997. Therefore this year is chosen as the starting period. A first analysis show the German situation, i.e. the mixing of primary and secondary aluminium, the production of the semifinished products and the scrap recycling only considers the German sites. The process chain sequence of primary aluminium production includes the imports and exports of bauxite, alumina and primary aluminium.

At the moment, the calculations are based on the assumption of regional mix for electricity supply. Electrolysis has the highest primary energy demand along the entire process chain during the production of aluminium foils as well as for another product. Per tonne of aluminium foil 175 GJ primary energy is needed, which corresponds to 143 GJ/t primary aluminium (see Fig. 6). Besides that the influence of the other processes will be analysed as well. In a first step, an order of the processes relative to the primary energy demand was collected. The process variations on one level (e.g. CWPB, PFPB) were combined. Side chains were analysed separately. The second most important process after electrolysis is the Bayer process, which with about 25 GJ/t aluminium foils needs far less primary energy. The subsequent calcination has the third highest primary energy demand with about 15 GJ/t foil. Hot and cold rolling, anode production and the alloying process need 6.5 – 4 GJ/t foil. In the recycling sector the demand for the reuse of total packaging is identified (1 GJ/t foil) and not only the demand for that part which can be reused to produce foils. Mining, continuous casting, cathode production and red mud deposition need the lowest amount of primary energy and may be neglected.

Decisive for these results is the distribution structure of the exporting countries with the associated technologies and the chosen power mixes used to convert the final energy demand into primary energy. Beside the analysis of primary energy demand other questions such as the value of emissions occurring or the fluctuation rate of single inputs or outputs in one level of the process chain can be answered. To answer other questions a new process chain using the process library must be first built up.

Model of the global aluminium industry

The results are based on the assumption of contract mix for electricity supply. Hydro-based electricity has the highest overall efficiency and is free of carbon dioxide emissions. Therefore the global primary energy consumption and carbon dioxide emissions are lower for the contract mix. In 1995 the flow of primary aluminium consumed 2.4% of total world electricity production. Smelting itself was responsible for about 95% of the consumption of electricity in the material flow. In 1995 the world average specific primary energy consumption was about 160 GJ and the world average carbon dioxide emissions was 10.7 tonnes per tonne of primary aluminium for the contract mix (the figures for the regional mix were assessed to be 200 GJ and 13.2 tonnes). As the worldwide consumption of primary energy in 1995 was assessed at about 343,000 PJ, the share of the flow of primary aluminium was about 1%. Respectively, flow of primary aluminium initiates about 1% of energy-based global carbon dioxide emissions.

3.2 *Scenario*

As in the inventory analysis for the initial situation, the two approaches are used against the background of the different model characteristics in different ways for future projections of the aluminium supply and the resulting material and energy flows. The aim of work with the process chain model is the preparation and analysis of a scenario analysing the impacts of technical progress on material and energy flows. This is implemented by altering the process chain of a base year by replacing individual technologies. This procedure enables, for example, old or currently used technologies to be replaced by the latest available technologies. A scenario assuming a range of primary aluminium demand is calculated using the model of the global aluminium industry. It is thus possible to analyze the impacts of different levels of demand on the production geography, the technology mix and the resulting material and energy flows.

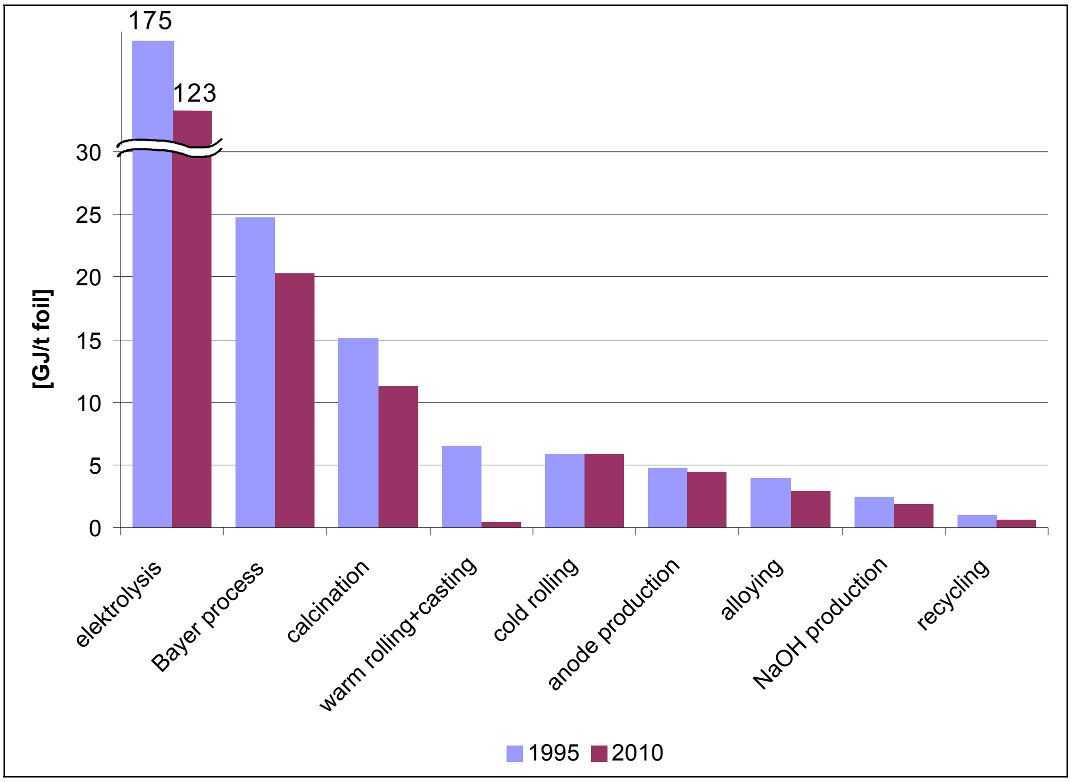
The target year for both scenarios is 2010.

Process chain model

Using the process chain model and considering the process structure it is appropriate to answer questions concerning technical problems first. Therefore, in a first scenario only technical variations are investigated. Until 2010 neither a totally new structure of today's technical concepts nor the introduction of totally new technologies is likely. Instead, an assimilation of existing technologies is assumed. For the calculation the demand for packaging and the import structure according to 1997 has not (yet) been changed. Furthermore, some assumptions concerning technical change are presented.

The chosen time horizon of 15 years is a very short period for mining activities. Mining in one deposit normally takes much longer than that (30-40 years).

Figure 6: Primary energy demand per tonne aluminium foil



Hence, for Germany no import change is assumed, the deposits will be the same for both years. Technical progress in mining processes is expressed in such a way, that mining activities approach those of the best deposits.

The mineralogical qualities will still determine the choice of Bayer technology. Changes in alumina production only result from the replacement of old rotary kilns by new fluidized bed furnaces.

The developments of the last few years have shown that most of the old Soederberg electrolysis plants have been replaced by modern prebaked technology (Pawlek, 1998). This trend will continue for the scenario calculations for 2010. It is assumed that all Soederberg plants will be replaced by PFPB plants (Quinkertz, 1999).

The next level is the alloying step. Right now, new furnaces types are being developed in this area. Nevertheless, it is assumed that existing concepts will be optimized by 2010 and their energy demand will decrease due to the use of synergetic effects.

Processes for semifinished products have been optimized over a long period. An improvement up to the year 2010 can be reached by replacing the technologies used today with alternative technologies, such as continuous casting processes.

In the process chain sequence, recycling of secondary raw materials is shifted towards modern technologies. Composite material recycling and pyrolysis are currently the latest technologies in use.

For the area of energy supply two effects have to be considered for the scenario calculations for 2010. One is the shift in the mix of the primary energy carriers, the other is the change in the energy demand. The construction of new power plants means building plants with the latest technical standard (NT) (Briem, 1999).

A first look has been taken to the change of the energy demand following out of the suggested technical variations. To make the different final energy carriers comparable along the entire process chain they have been transformed into primary energy. Figure 6 shows the decrease of the primary energy demand for the most important processes per tonne aluminium foils produced.

The decrease of the primary energy demand is influenced by a combination of four single effects: improvement of existing technologies, replacement of technologies, technical related changes of material flows and an improvement in the energy supply. The influence of either of this four effects can differ between the various process steps. For example, the energy demand of the electrolysis decreases by 30 %. The mayor influence for this is the reduction of the material flow due to the exchange of the warm rolling process by an continous rolling process. The material demand of primary aluminium is lower. The second highest effect is combined with the improvement of the energy supplying technologies. The replacement of electrolysis technology has only a minor effect in this example.

Therefore every result has to be analysed carefully to yield to a better understanding of the complex system. Beside the energy demand other effects can be investigated such as emissions or material changes. In reality influences can occure which prevent the total scoop of the technical potential estimated in this example. Most of the time this are economic reasons, which are not considered in the process chain model. Economic models are used to investigate this effects.

Model of global aluminium industry

As a critical model parameter, assumptions on future demand of primary aluminium have great influence on model results because the implemented material balance equations lead to an equalization of supply and demand. Moreover, projections of the future global demand for primary aluminium are difficult. The reason is that the growth rates of the demand for primary aluminium are dependent on the future development of the world economy. Competition with other raw materials and the recycling quota additionally influence demand. Therefore, future demand for primary aluminium is varied to reflect a range of possible developments.

Three cases are distinguished. Firstly, the base case assumes a moderate growth rate of primary aluminium of 1.9% per year from 1995 to 2010. This is the growth rate which was valid for the period from 1980 to 1995. The low-demand case assumes a growth rate of 1.4% per year and the high-demand case a growth rate of 2.4%. The assumptions for future technological developments are similar to the assumptions for process chain modelling.

Though we use the model to analyse future energy use and greenhouse gas emissions of global primary aluminium industry, the scenario calculations allow to deduce several fundamental trends:

- Only gradual change in production geography: The reason for this is the good competitive situation of the old capacity. By means of upgrading, old capacity achieves almost the same technical parameters as new plants. At the same time upgrading is much cheaper. Therefore upgrading of old plants is often an economic alternative to building new plants even if the price situation of one region is disadvantageous, e. g. because of high energy prices or wages. The reason for changes in production geography is not so much the old capacity being superseded by new but rather additional demand which cannot be satisfied by existing capacity.
- Shifting of production of alumina to regions with significant bauxite production: The cost of bauxite is crucial for alumina production. On a worldwide average the bauxite costs in 1995 were about one third of total operating costs. The transport costs are essential for the regional differences in the costs of bauxite. The longer the transport distances and the lower the alumina content of the bauxite, the higher the specific transport costs are. This explains the trend for locating refineries close to mines and why only bauxite with a high alumina content is traded between regions. Because of the remarkably high capital costs of refining the shifting of production is relatively low.
- Shifting of production of primary aluminium to regions with cheap electricity for smelting: Alumina costs are dominant for smelting with a share of one third of total operating costs. Nevertheless, electricity costs which were responsible for one quarter of the costs are more important for the location of smelters. The reason for this is that the variation in prices of electricity is much higher than that of alumina. This is not surprising. Hydropower has a natural competitive advantage and electricity is only to a limited extent tradable. The existence of old plants in disadvantageous regions is usually not endangered. The total costs of new plants in privileged regions are mostly higher than the operating costs of existing plants in disadvantageous regions. But the building of new plants and capacity expansions of existing plants are usually realized in regions with low electricity costs so that the production shares of these regions are gradually increasing.
- Declining interregional trade of bauxite and growing trade of alumina and primary aluminium: The changes in production geography have a strong influence on interregional trade. The share of total regional net exports in world production is decreasing for bauxite whereas it is stable or slightly increasing for alumina and primary aluminium. Instead of bauxite, the manufactured goods - alumina and primary aluminium - are traded.
- Changes in technology mix of primary aluminium and alumina production: In 1995 Soederberg plants produced more than 30% of world primary aluminium. Soederberg plants have high energy requirements. This leads to high operating costs. Therefore Soederberg plants will be upgraded with PFPB or shut down. CWPB and SWPB plants will also lose importance in comparison to PFPB plants. Autoclave technology will further dominate the digestion of bauxite. Tube reactors with a share of 2% of world alumina production in 1995 will enlarge their share only to a very limited extent. In 1995 the rotary kiln was used for calcination of 26% of world alumina. Because of higher energy requirements and therefore cost disadvantages the rotary kiln will be superseded by the fluidized bed in the near future.

The expansion of demand for primary aluminium will have great influence on the absolute figures of primary energy consumption and greenhouse gases as well. In the base case, assuming demand increase of 1.9% per year, absolute use of primary energy and CO_2 emissions increase only moderately. Perfluorinated hydrocarbons decrease considerably. In the low case, assuming demand increase of 1.4% per year, absolute primary energy use and CO_2 emissions decrease moderately, whereas perfluorinated hydrocarbons decrease by 44%. In the high case, assuming demand increase of 2.4% per year, absolute primary energy use and CO_2 emissions increase perceptibly. But even in the case of high demand, perfluorinated hydrocarbons decrease considerably.
In all cases, specific figures show a uniform decreasing trend. The specific consumption of electricity for smelting will decrease because of Soederberg technology being superseded by modern PFPB technology. There will also be a decline in specific consumption for other energy carriers.

The world average specific primary energy consumption in the material flow will decrease considerably (fig. 7). Reduced consumption for smelting accounts for more than 70% of this reduction. There are three reasons for this. In the first place, the higher efficiency of electricity generated from fossil fuels leads to a reduced consumption of primary energy. Secondly, modern PFPB plants use less electricity than the Soederberg plants they replace. And thirdly, the production of primary aluminium is being shifted to regions where the production of electricity is mainly based on hydropower. The shift itself is economically determined. There is a strongly marked (inverse) correlation between the share of hydropower for electricity production in one region and the regional tariffs for electricity for electrolysis.

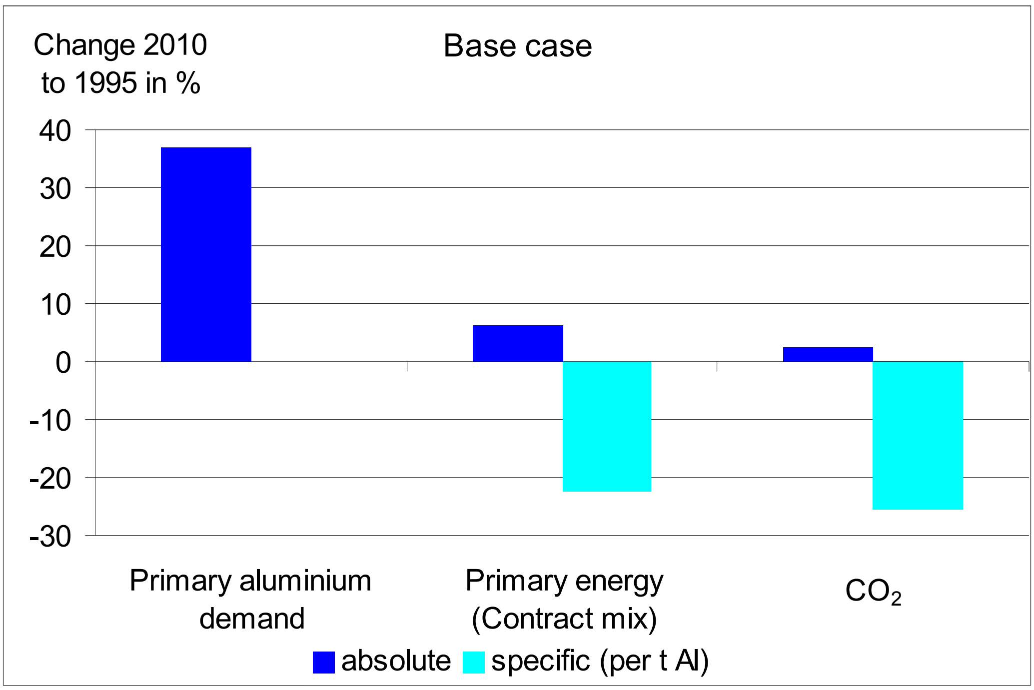
The specific CO_2 emissions will decline significantly for the same reasons than the primary energy consumption. A decline in specific perfluorinated hydrocarbon emissions is very likely. The modern PFPB plants have much fewer anode effects. Therefore fewer perfluorinated hydrocarbons are generated.

4. CONCLUSIONS

The paper describes important elements in a resource-orientated overall consideration of the aluminium material flow, which is the object of Collaborative Research Centre 525. These elements comprise computer-based models for analysing the material and energy flows in process chains and for analysing the global aluminium industry, as well as their application in scenarios.

Methodological aspects of modelling the aluminium material flow are discussed in detail. The model approaches are characterized in a comparative manner and their potential elucidated with respect to application for an inventory analysis of a base year and for scenario calculations. It thus becomes apparent that the models complement each other in a re-

Fig. 7: Results of the base case



source-orientated overall consideration.

The basic results obtained by the inventory analyses performed with the two approaches for the base year 1995 are discussed.

Basic assumptions for the projection of future developments of the aluminium material flow are discussed. With respect to the scenario results and interpretations, major emphasis is placed in this paper on the model of the global aluminium industry.

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INVENTORIES FOR METALLIC RAW MATERIAL FLOW ANALYSIS TECHNICAL STATUS AND RECYCLING DEFINITIONS*

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ABSTRACT

Metallic raw material flows interfere with a large number of sustainability issues. To identify challenges for the redesign of existing supply chains, a scientific instrument has been developed at the University of Technology, Aachen in cooperation with the Forschungszentrum Jülich to provide information on complex metal flow systems. This integrated resource management system consists of a set of tools which are designed to determine existing potentials and to estimate resulting ecological, economical and social effects of various actions.

Technical innovation represents one key challenge to reduce emissions and to increase resource efficiency. Therefore, a technology-orientated process chain model has been developed along the material flow of aluminium from mining, smelting, to recycling and disposal. Within this inventory each production level is represented by a variation of technology-specific and location independent modules. The technical status is classified into different technological categories. These are old technologies (OT), present technologies (PT), the newest available technologies (NT) already being in use, and technical options for future use (FT).

Beside the description of the present situation, scenarios are used to show possible future developments as well as their effects on material and energy flows, plant locations and resource productivity by choosing different technological developments.

Another key topic regarding metals and life cycle principles is the influence of recycling mechanisms on the material flow considered. Even if metals are fully recyclable according to their atomic structure, different alloy compositions and impurities can restrict the re-usability. Therefore, a product specific distinction between various alloy qualities is used to model the differences of their supply systems. In the sense of life cycle analyses this enhancement of the inventory enables the identification of specific potentials and the simulation of optimised recycling systems.

Parallel to the development and interpretation of scenarios for aluminium the above mentioned tools are extended and enhanced for the copper material flow.

KEYWORDS

LCIA, process chain, recycling, alloys

* Source: Proceedings of Life Cycle Assessment of Metals - Issues and Research Directions, SETAC USA, Pensacola

1 Introduction

Metallic raw material flows interfere with a large number of sustainability issues. To identify challenges for the redesign of existing supply chains, a scientific instrument has been developed at the University of Technology, Aachen in cooperation with the Forschungszentrum Juelich in Germany to provide information on complex metal flow systems. This integrated resource management system consists of a set of tools, which are designed to determine existing potentials for a resource-sensitive supply and use of metallic raw materials. So far, case studies are based on aluminium and extension and enhancement of the tools have been started for copper.

This paper concentrates on the integration of the technical status and the definition of recycling within the process chain model of this management system.

2 An integrated resource management system

The University of Technology, Aachen and the Forschungszentrum Juelich are joint in a collaborative research center (CRC 525) aiming at a resource-sensitive supply and use of metallic raw materials [1]. Throughout the last 6 years, they have developed instruments for material flow management including an life cycle inventory (LCI) data base. Engineers, natural scientist and economists have implemented the integrated resource management system shown in figure 1 consisting of a set of tools which are designed to determine existing development potentials and to estimate resulting ecological, economical and social effects of various actions.

This integrated approach is based on various data and field specific models for mining, smelting, use, recycling and disposal of metals as well as transport or energy supply. A technology-orientated process chain model following the LCI approach links the information of the entire material flow. Further ecological investigations include the different environmental characteristics of the world wide distribution of sites. Based on the collection and management of a number of environmental global data such as topography, climate or land cover a geographic information system (GIS) is used to structure the information for an site-dependent environmental impact assessment (see also Bauer/Zapp; "Towards generic characterisation factors for land use and water consumption" in this volume). However, to broaden the approach of LCA, additional modelling concepts are used to identify existing technical and economic potentials. Beside technical analyses, additional studies of market mechanisms are include into the material flow analysis, investigated in a separate economical model. Here, especially changes in demand or legal frameworks are taken into consideration.

In addition to the description of the present situation, scenarios are used to show possible future developments as well as their effects on material and energy flows, plant locations and resource productivity by choosing different technological developments. Key results of the application of this resource management system will lead to the identification of options for decision-making towards a resource-sensitive supply and use of metallic raw materials.

Technically-orientated analyses can illustrate the overall medium or long-term effects of technical progress and specific potentials or answer questions such as the limits of recycling activities. In order to depict these effects, technical status and recycling definitions have to be integrated in the process chain model.

3 Technical status

To describe the entire complex material flow within a process chain model, a suitable level of detail for the describing modules has to be applied. In LCI different technologies are considered normally. In addition to this approach the CRC 525 also considers the technical status of these technologies. Thus, it is reasonable to consider changes according to time and development status necessary for the application of scenarios, in order to represent technical innovation for example. The CRC 525 distinguishes between 4 status categories:

- Old technology (OT)
- Present technology (PT)
- Newest available technology (NT)
- Future technology (FT)

Each technology can be represented by various technical status. This differentiation allows to model not only the replacement of a technology but also the upgrading of a technology at a specific site. Another advantage is the ability to illustrate differing technological status at different sites even though same technologies are applied (e.g. developed and undeveloped).
Figure 2 shows the example of specific SO_2-emissions and the share in total for 1997 as reference year, depending on the used electrolysis technologies without gas treatment and their technical status. The specific SO_2-emissions decrease from horizontal and vertical stud Soderberg anode cells (HSS/VSS) to modern computer-controlled cells (PFPB). Nevertheless, old point-feeder electrolysis cells (PFPB OT) have higher specific emissions than new side-worked cells (SWPB NT) or present center-worked cells (CWPB PT) [2]. The categorisation depicts the variation of SO_2-emissions of up to 10% within one technology depending on the technical status. This information would be lost differentiating technologies only.

4 Recycling definitions

Recycling is another key topic regarding metallic raw material flows. Metals are entirely recyclable according to the atomic structure. However in reality, particularly for aluminium, the re-use in other systems is restricted. This has to be considered when modelling recycling mechanisms. The CRC 525 distinguishes between 6 alloy categories for aluminium: wrought unalloyed, low, medium and high alloyed; cast refined and primary. Using this categories, the general re-usability of aluminium can be modelled, but also the restricted re-usability in other systems. Figure 3 illustrates three aluminium systems and their exchange of scrap. While material descending from the unalloyed packaging system can be used in all other systems, the re-usability of scrap from the low alloyed system decreases. Cast alloys can only be refined to cast alloys again.
In connection with discussions about sustainability and recycling, often closed loop recycling or a high recycled metal content of a product is demanded. At least referring to the aluminium system these two parameters do not coincide with the intended aim. The unalloyed aluminium packaging foil has a recycled metal content of zero, but the scrap has a high re-usability in all other systems (see also Buxmann; “LCA of aluminium products – key features” in this volume). A more sustainable system can be achieved by increasing the recycling quota of the aluminium flows.
Within the metal community different perceptions of recycling quotas exist. The CRC 525 defines the recycling quota to be the combination of the collection quota and the technical recycling quota. This distinction explains the different levels of recycling shown in figure 4. The understanding of these different levels represents the basis for a resource-oriented view of recycling that incorporates the following terms:

- The collection quota (CQ): determining the quantity of available after use scrap which is registered in a collecting system and relating it to the quantity of metal used in the product.
- The technical recycling quota (RQ,t): representing the quantity of collected material, that is actually available for re-utilization after recycling, i.e. the yield of the technical processing and melting processes.

The technical recycling quota consists again of two parts: the processing quota (PQ), which indicates how much metallic aluminium from collection is provided for melting; and the smelting yield (SY), which indicates how much aluminium is obtained as liquid metal. The return flows from salt slag (SR) and dross treatment (DR) are taken into consideration also.

The combination of collection quota and technical recycling quota result in the resource-oriented recycling quota (RQ,r) [3].
The largest material losses for a national or regional recycling system often-times occur during collection. About 60% of the German deregistered vehicles for example, are exported, mostly for further use, and are therefore lost for the German recycling system. Although the material is not lost for the overall aluminium system worldwide, the management of a recycling flow crossing country borders becomes more complicated, due to different legislation and other influencing factors. Figure 5 depicts the resource-orientated and the technical recycling quota for some German aluminium products [4]. It reveals that, for the construction system the technical and the resource-oriented quota are the same because nearly all material is collected. The highest losses occur referring to the urban waste system.

5 Discussion

To model a complex metal flow system it is necessary to determine an adequate level of detail for the LCI data base. Within this study, technical status and recycling definitions have been chosen to enhance common LCI practice of module development.
In order to reduce the amount of information necessary for the description of all sites of a material flow, this approach considers modules describing different technologies and their technical status. The plethora of technological levels worldwide can be expressed by classifying the technologies in old, present, newest available and future technologies, varying in the relation of inputs and outputs not however in the technical description.
The recycling quota is chosen as the suitable parameter to evaluate the contribution of a metal system to sustainable development by recycling. Technical and resource-orientated recycling quotas can be differentiated. Referring to the aluminium system, it is inevitable to separate between various alloy groups to consider the limited re-usability in other systems. This differentiation is necessary with respect to the aluminium system, while, for other metals, such as copper, the alloying elements can be separated during refining. Copper produced from recycled material has the same quality as from primary resources. Although all metals are recyclable, they have to be modelled differently due to their metal specific properties.

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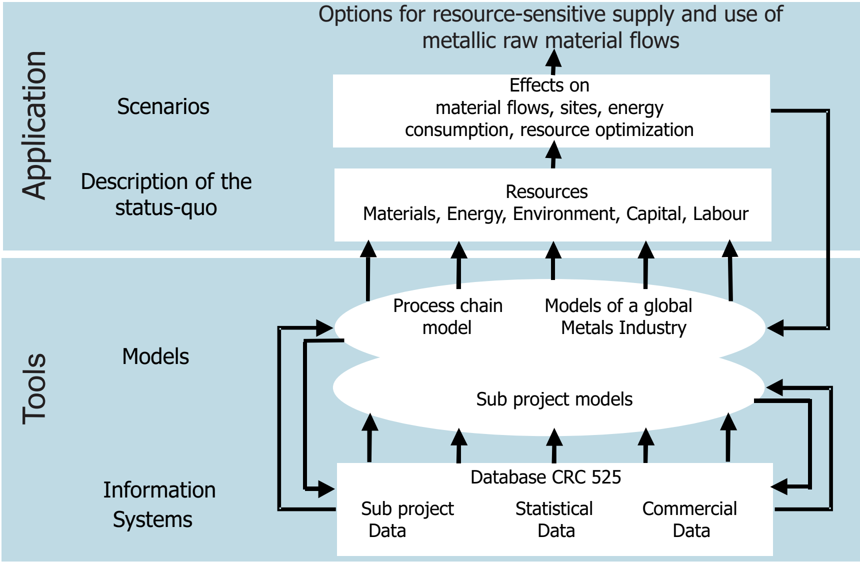

Figure 1: Integrated resource management system

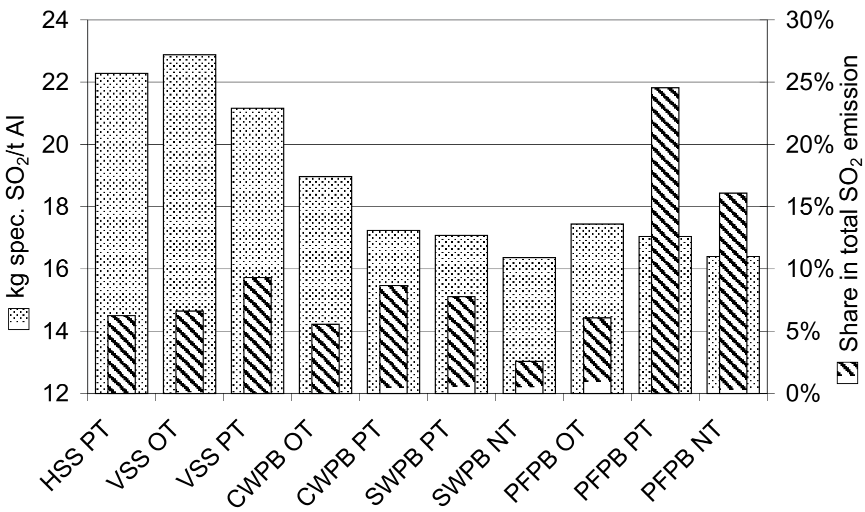

Figure 2: Specific SO_2-emissions and share in total SO_2-emissions in 1997 of the electrolysis process without gas treatment

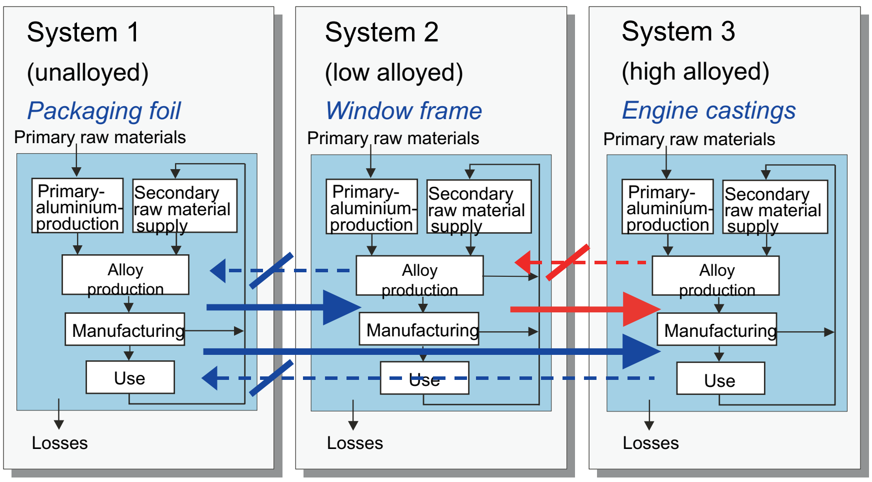

Figure 3: Interaction between product systems

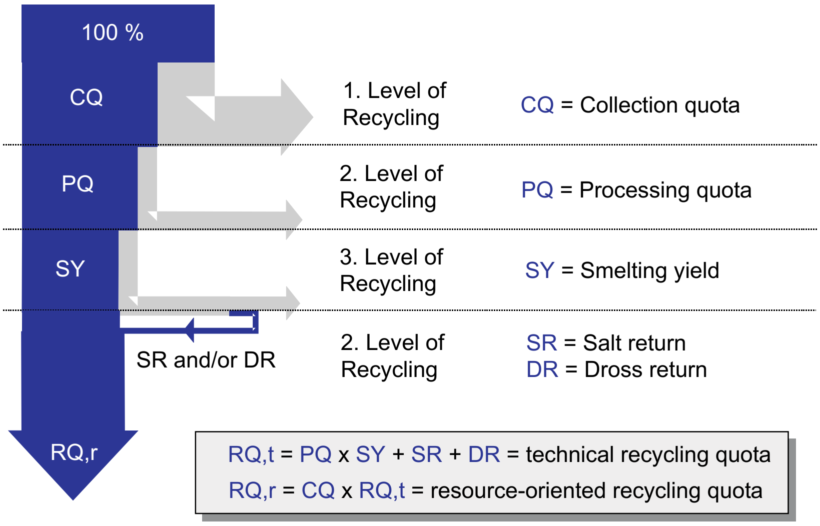

Figure 4: Definition of recycling quotas for collection, processing and smelting

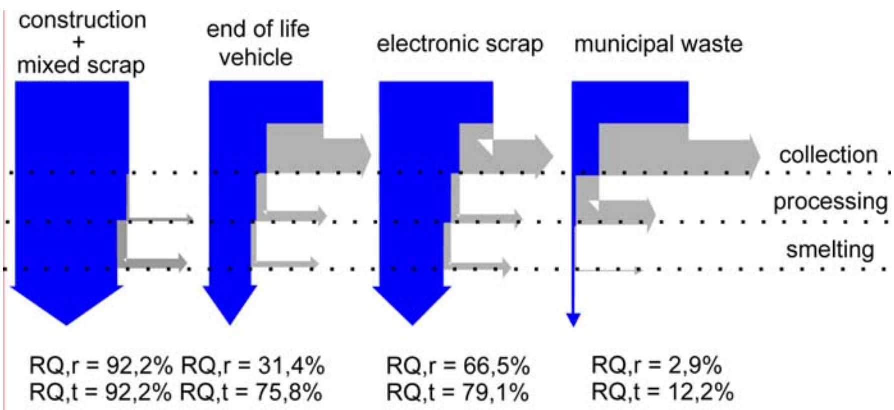

Figure 5: Technical and resource-oriented recycling quotas for German aluminum products

TECHNICAL PROGRESS IN THE ALUMINIUM INDUSTRY –A SCENARIO APPROACH–*

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ABSTRACT

Analysis and modelling of material flows in complex production systems are appropriate instruments to show existing potentials for an efficient use of resources following the idea of sustainable development. Using scenario techniques significant future developments of aluminium production, manufacturing and recycling can be evaluated. This article focuses on technical progress along the material flow of aluminium from mining, smelting, to recycling and disposal. For this a technology-orientated process chain model has been developed. As an example the German packaging industry and its special recycling concept, including material and energy supply and transport has been chosen. The 1997 basis scenario is compared with a calculation considering newest technologies known today and a further one with regard to their possible application in the year 2010. The results help to identify technical potentials in different process steps of packaging life cycle and to analyse their impacts on the environment.

KEYWORDS

Material flow, technical progress, scenario, process chain, packaging material, recycling

* Source: Proceedings TMS 2001

Introduction

Worldwide, the concept of sustainable development is being discussed. At the moment, the discussion is shifting to a group of resource and environmental sensitive industries. Aluminium production is regarded as one of the group [1]. Agreeing that sustainability requires to balance economic, ecological and social aspects, experts formulated strategic rules for the use of renewable and non renewable natural resources, the assimilative capacity of the environment, and the adequate consideration of time [2]. For more practical purposes there is a need to develop differentiated rules keeping in mind special aspects of products, production processes and industrial sectors.
Technical progress is regarded as a means of creating sustainable production systems by dematerialization or efficiency revolution besides other means as e.g. sustainable demand behaviour. Although technical progress can not be easily quantified, its impacts on resource use and emissions can be evaluated on condition that information is available on the level of different processes and locations. Furthermore, the concept of technical progress needs to integrate market processes. Therefore, reliable projections of technical progress differentiate between the technical potential of full capacity replacement by newest technology and the smaller potential of reduced replacement in 2010 which can be realistic implemented under consideration of financial and market aspects.
To reduce the complexity this study selects exemplary the use of aluminium in the German packaging system. It introduces the concept of technical progress for the production and recycling of aluminium packaging, giving detailed description of expected technical progress on the process level within the next decade. The approach follows the modelling concept of a process chain analysis [3]. Using a scenario approach and differentiating between the maximum and predicted technical potential the impacts of the implementation of modern technical concepts on resource use and emissions are quantified.

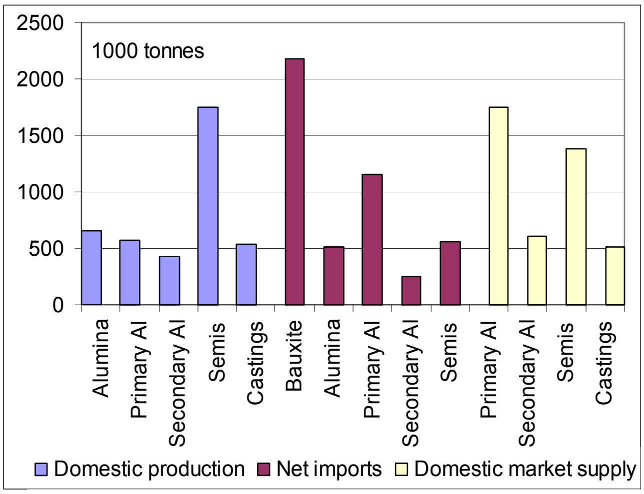
Production of aluminium and its use as basic material for packaging in Germany

Applications of aluminium as a packaging material are still increasing. The variety ranges from combined coffee-packaging with a low metal content to full aluminium containers. The following data and figures introduce the German packaging system.

Production and use of aluminium packaging material in Germany

World aluminium demand in 1997 was 30 million tonnes. Germany's share was 8.5% of total, but 30.7% of European metal demand which characterises Germany as one of the big aluminium markets.
German aluminium supply is highly dependent on imports (fig. 1). Whereas the proportion of imported bauxite is 100%, the proportion for alumina and aluminium is less but considerably high.

Roughly two thirds of primary aluminium supply is imported material. On the other hand the supply of secondary aluminium was mainly covered domestically. The overall use of primary and secondary aluminium was 2.5 million tonnes, 1.8 million tonnes were semi-finished wrought products and 0.6 million tonnes were castings.
The total German production of packaging material for domestic use and export was 540,000 tonnes which makes it the biggest in Europe with a share of 32% of total rolled products. In Germany itself, with 110,000 tonnes, the packaging sector is the third important end-use sector of semi-finished products behind building and transport.



Sources: Metal Statistics/Statistisches Bundesamt/GDA

Fig. 1: Aluminium balance for Germany, 1997

Another argument to investigate aluminium packaging is the actual discussion of the German system of recycling of light packaging materials [4].
The production of packaging material starts with primary aluminium production from bauxite (fig 2). In the cast houses of the smelters unalloyed aluminium is cast directly into rolling slabs for foils. Alloyed aluminium for strip, especially can body and can lid stock, is cast after addition of scrap and/or alloying elements to the molten metal. Latter is also done at remelting facilities of rolling mills which mainly use in-house fabrication and foreign scraps and primary ingots. The following strip production is done by conventional hot and cold rolling. There the foil reaches a size reduction down to 7 microns for unalloyed material and down to 100 microns for AlMgMn-Alloys. For the various aluminium bins, tubes and cans the investigation ends up with the production of alloyed strip for deep-drawing operation.

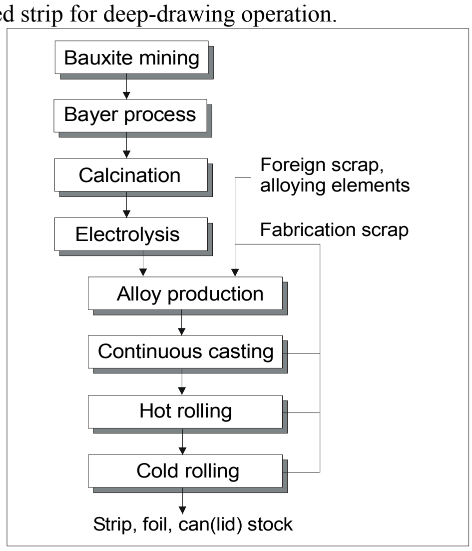


Fig. 2: Production scheme for aluminium packaging material

Recycling of aluminium packaging

In Germany, aluminium packaging is recycled together with other light packaging material (LPM) by the Duales System Deutschland AG (DSD). 1997 nearly 2 Million tonnes of LPM-material were collected separately from household waste and afterwards recycled. 56,470 tonnes of that were aluminium packaging with a metal content of 28,580 tonnes [5]. Beside that, 21,650 tonnes of bottle closures and 7,000 tonnes of menu plates were collected. It is to note that in Germany no separate collecting system for used beverage cans exist, because the share of aluminium cans is only about 15 %.
Figure 3 shows the process steps which form the system of LPM recycling in Germany. The system for the recycling of aluminium is divided into three levels. First, the collection of the secondary raw material takes place. Second, the material has to be processed in order to achieve an aluminium product which can be remelted. Therefore, the aluminium fraction is separated from other packaging material in sorting plants. As the aluminium fraction has an aluminium content of only about 40%, further processing is necessary prior to remelting. This processing takes place in three different types of plants and can be characterised as mechanical processing, processing of combined material with subsequent pyrolysis, and straight pyrolysis.

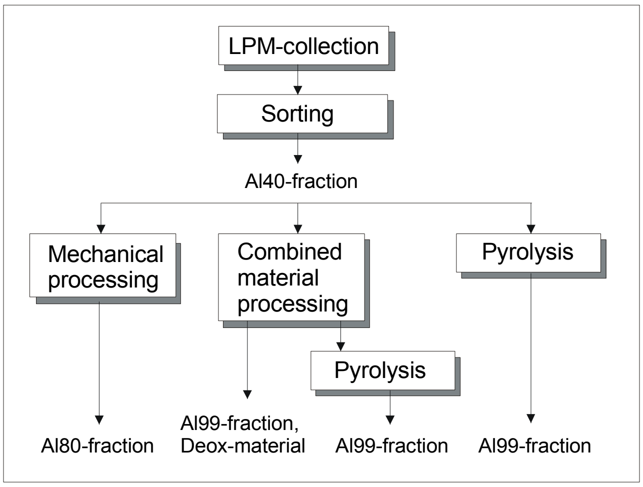


Fig. 3: German recycling system for LPM (level 1 and 2)

Finally, the remelting of the aluminium fractions on the third level of recycling takes place. Here, a certain amount of metal is lost due to oxidation in dross or salt cake.
The efficiency of the recycling system for aluminium packaging in Germany can be described for collection, processing and remelting. Each level of recycling causes losses of metal so that the overall recycling quota (collection, processing, remelting) is 60 % and the technical recycling quota (processing, remelting) is 67%.

Process chain model

To analyse the material and energy flows of aluminium a process chain model has been developed [3]. Its main aspect is a technical link of production processes, showing the material and energy flow of the aluminium production using the concept of process description by input and output parameters. The process chain model describes the aluminium flow from bauxite mining to the production of aluminium including primary and secondary aluminium and the recycling of the used material.

Beside the production levels shown in figures 2 and 3 transportation and energy supplying processes are also taken into consideration as well as the production processes of intermediate products and waste treatment. Each production level represents a variation of technology-specific and location independent modules. The technical status of the processes is classified into different technology categories. They are old technologies (OT), present technologies (PT), and the newest available technologies (NT) which are already introduced. Furthermore, technical options for future use (FT) are existing.
The end product manufacturing process and also the use phase are important elements in the process chain, which will be included in near future [6].

The scenario "technical progress"

Technical progress is one subject in the discussion of sustainable development which can be evaluated using scenario technique [7]. For the chosen example the changes in material and energy flows due to technical progress and innovation and its impacts on the environment was investigated in a first analysis. To separate different effects the scenario approach is carried out in three steps:

1. The reference case shows the domestic market supply for Germany for **1997** (including import and export of primary aluminium, its pre-products and secondary aluminium).
2. As a second case the maximum technical potential is calculated considering the exclusive application of newest technology (**NT**) for each process of the 1997 structure.
3. In a third case financial and market aspects are taken into account. Looking at **2010** as the target year only a part of existing plants will be replaced by NT. Some plants will be upgraded and others will not be changed at all. This differentiation is not a model result but exogenously determined based on expert information.

The results of all three cases were compared resulting in possible and probable effects of technological progress and its impact on the environment in a medium term time frame.

Set of assumptions

The calculations are based on constant amounts of production and recycling. Also the import structure and the share of secondary raw materials for alloy production were not varied. To ensure comparability the different calculations need assumptions to close data gaps and differences between statistic and plant information.

1997 reference: For the production of semi-finished products for the packaging sector bauxite, alumina and primary aluminium were imported from several countries. Table I shows the share of these countries in 1997 distinguishing between direct sources and indirect sources. Latter are those countries which export pre-products to direct suppliers.
For the bauxite mining the calculation bases on long-term supplying contracts, because of the lack of actual supplier structure information for the year 1997. Because no complete production numbers of single locations are available for the alumina production process data of different digestion techniques are capacity weighted and related to the missing plants in the various countries. With the supplying structure also unknown country related mixes are modelled. The same has been done for the primary smelters but with the distinction of pure and alloyed aluminium.

Table I: Direct and indirect sources of bauxite, alumina and primary aluminium for the German packaging system 1997

	Bauxite %	Alumina %	Aluminium %
Australia	14.8	8.5	
Brazil	9.1	7.5	7.5
Canada		2.4	9.0
France		0.4	0.9
Germany		19.9	46.9
Ghana	2.0		
Greece	0.1	0.1	
Guinea	19.0	0.1	
Guyana	8.6		
Iceland			4.4
Ireland		7.0	
Italy		2.9	
Jamaica	30.1	29.4	
Norway			12.0
Russia	11.8	11.8	12.8
Spain		1.4	
Suriname	4.0	3.6	
UK		1.9	6.4
USA		2.1	
Venezuela	1.2	1.2	
direct sources			
Total amount	2,459,000 t	1,158,000 t	573,000 t

For the alloy production (incl. remelting and refining) a mass flow scheme for pure and alloyed aluminium has been created from several statistics, which was extended to single alloy groups. It is assumed that pure metal is made 100 % from primary materials and alloyed metal has a share of 43 % of secondary materials (which represents the 1997 average value, excluding in-house scrap from rolling). The same is assumed for the UK and France, imported alloys from the other countries are made of primary metal plus alloying elements.

For the LPM-recycling the existing mixture of mechanical processing, pyrolysis and processing of combined material with subsequent pyrolysis is used for the calculation as well as the mix of remelting furnaces.

The energy supply is based on the energy carrier mix in 1997. The power supply for electrolysis reflects a contract mix, which differs from the national grids due to ownership and base load supply [8].

NT (Full replacement): Under the viewpoint of technical progress, the selection of newest technologies in the different process steps followed the criteria in table II. It shows, that for nearly all process levels the technical potential is expressed through the saving of energy and reduction of emissions. Additionally, for alloy production, semis production and material processing the material yield becomes another major factor.

The modelled levels from bauxite mining to electrolysis consider only one technique. The bauxite quality remains the same. For the alumina production only the tube-digestion and fluid bed calcining takes place. The Russian alumina production from nepheline was not replaced. A fully automated pre-baked cell technology with point feeding is used for modelling the electrolysis [9]. The alloy production (incl. remelting and refining) changes completely to modern technology of the various furnace types by implementing oxygen burners or heat recovery systems.

Table II: Selection criteria for "newest technology"

Process step	Selection criteria for NT
Bauxite mining	Energy, emissions
Alumina production	Energy, yield
Red mud disposal	Land use, emissions
Primary smelting	Energy
Anode production	Emissions
Alloy production, remelting, and refining	Energy, metal yield
Semis production	Metal yield
Material processing	Energy, metal yield, material quality
Transport	Energy, emissions
Energy supply	Efficiency, emissions

For continuous casting slab weights of 30 t are assumed. So the amount of fabrication scrap during the strip and foil production can be minimised. Due to the high throughput of rolling mills for strip and foil stock production, the conventional route via hot rolling has not been replaced by continuous strip casting.

LPM-recycling is only done by fully automated separation, pyrolysis and twin chamber furnace to reach best metal recovery.

For the transport system all modules have been replaced by newest technology.

For electric power supply also newest conversion technology is used, but the mix of energy carriers remains equal to 1997.

2010 (Reduced replacement): Technological improvements are limited realised considering beside possible physical improvements also financial and markets aspects. Some plants will be expanded or upgraded and others will not change at all.

For bauxite mining the closure of some mines until 2010 has to be considered. Again the bauxite quality do not change.

For the alumina production a reduction of energy consumption of 10 % can be expected by lowering the liquor volume. Also an improvement of the metal yield of 1 % seems achievable. The land filling of red mud will only take place in orderly deposits.

For the aluminium smelters a modernisation by computer control of the cells and the feeding system and a capacity expansion only by modern point-feeder technology can be assumed.

For the alloy production (incl. remelting and refining) the share of furnaces with modern technology like oxygen burners or heat recovery systems increases.

Continuous casting will change to bigger slab weights causing decreasing amounts of fabrication scrap during the whole strip and foil production. Beside decreasing metal demand hot and cold rolling itself changes to lower energy and material demand.

For packaging recycling the fully automated separation for LPM reaches a share of 10 % and the mechanical processing will be replaced by pyrolysis and combined material processing.

In addition to the technical improvement a variation in the German energy carrier mix is expected until 2010, which has a big influence to the electricity depending results.

Results

As mentioned before the energy demand is one major parameter to represent technical progress. Therefore, focus is laid on the investigation of the amount, share and influence of the reduction for the different process steps, in the evaluation of the scenario results. First of all table III gives an overview on the absolute final energy demand for the three scenario calculations and the achieved improvements. The data are given for the production of one tonne primary aluminium for the German packaging system for the main consuming process steps. For the electrolysis, which demands 92 % of the electric energy, there seems a maximum improvement of 10 % possible and a predicted one for 2010 of 4 % for the aluminium suppliers of the German market (table I).

Table III: Scenario results for the final energy demand of the production of one tonne primary aluminium

inal energy	unit	1997	NT		2010	
per tonne prim. Al				Δ		Δ
l. power	kWh	16,405	14,927	-9.0%	15,858	-3.3%
electrolysis	kWh	15,191	13,617	-10.4%	14,503	-4.5%
alumina production	kWh	1,006	956	-5.0%	1,010	0.4%
avy oil	MJ	17,380	4,331	-75.1%	15,926	-8.4%
steam production	MJ	12,866	0	-100.0%	11,402	-11.4%
lime-sinter/nephelin	MJ	2,940	2,940	0.0%	2,940	0.0%
transport	MJ	1,009	774	-23.3%	991	-1.8%
el oil	MJ	5,518	4,430	-19.7%	5,555	0.7%
calzination	MJ	4,776	3,874	-18.9%	4,782	0.1%
tural gas	MJ	7,052	13,590	92.7%	6,975	-1.1%
alumina production	MJ	4,196	10,898	159.7%	4,103	-2.2%
electrode production	MJ	2,050	1,959	-4.4%	2,066	0.8%

Especially for the NT case a shift of the energy carrier can be recognised, due to the change of technology for bauxite digestion. Here steam heated autoclaves are replaced by gas fired tube reactors. Only the part of oil fired alumina production from lime-sinter and nepheline process in Russia remains the same.
In Table IV the input and outcome of important materials is presented, showing the changes in amount depending on the scenario. The selected materials give a small insight in the complex aluminium flow system. Bauxite and foreign scrap are inputs to the overall system. The values of primary aluminium and fabrication scrap represent mass flows within the system which induce further changes in preceding or following processes. On the output side a small portion of unalloyed fabrication scrap leaves the packaging system and feeds other systems. The aluminium content in the processed scrap represents the achievement in the recycling system. Red mud and carbon dioxide, CF_4 and C_2F_6 are selected emissions caused by production and recycling of aluminium which can strongly be reduced by improved technology.

Table IV: Scenario results for the material flow due to the production of one tonne packaging material

	1997	NT		2010	
Input per tonne packaging material [kg]			Δ		Δ
Bauxite	4,554	3,957	-13.1%	4,322	-5.1%
Primary aluminium	1,062	985	-7.3%	1,023	-3.7%
Foreign scrap	239	237	-0.8%	238	-0.4%
Fabrication scrap (circuit)	325	211	-35.1%	268	-17.5%
Output per tonne packaging material [kg]					
Fabrication scrap	297	225	-24.5%	261	-12.2%
Al-content of recycled LPM	38	48	26.6%	40	4.7%
CO2	4,668	3,423	-26.7%	4,315	-7.6%
CF4	0.531	0.049	-90.7%	0.358	-32.6%
C2F6	0.053	0.005	-90.7%	0.036	-32.6%
red mud	2,368	1,871	-21.0%	2,165	-8.6%

To compare the energy consumption of the various process steps, each using different forms of energy, the final energy consumption was converted into a primary energy demand. Figure 4 shows a ranking of the absolute values of primary energy demand of the different scenario calculations.

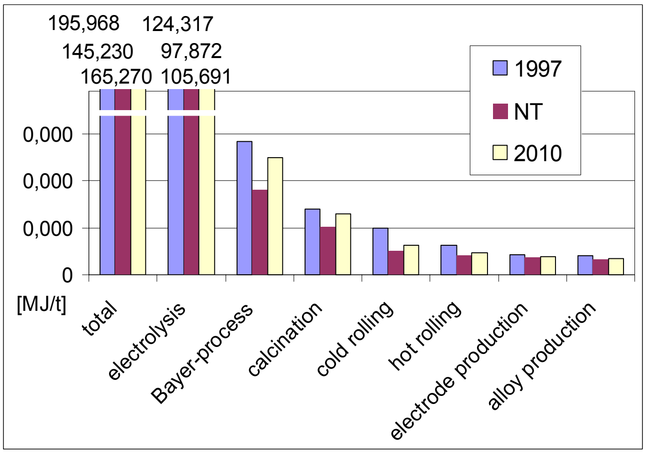


Fig. 4: Primary energy consumption of the scenario calculations per tonne of packaging material

Here the big total and electrolysis values are cut and given by numbers. The energy demand per tonne of packaging material was 196,0 GJ in 1997 and is 145,2 and 165,3 GJ for newest and 2010 realised technique respectively. Beside the dominating primary smelting the Bayer-digestion and the alumina calcination show remarkable energy demands followed by the cold and hot rolling operation, the electrode production (including coke and pitch production for pre-baked and Söderberg cells) and the alloy production from primary and secondary raw materials.
On the further places not shown in the diagram follow caustic soda production, transport, lime production, bauxite mining, aluminium fluoride production, continuous casting and red mud treatment.
The NT and 2010 scenario calculations of primary energy consumption are influenced mainly by three different effects, the technical improvement of the different processes itself, the increase of material efficiency per tonne of produced packaging material and the improvement of the energy supply. The particular share of these three effects varies for each process level. Figure 5 shows the share of the overall primary energy savings. It can be seen, that the entire improvement in the case of newest technology (NT) is 26% and that in the year 2010 16% can be realised.

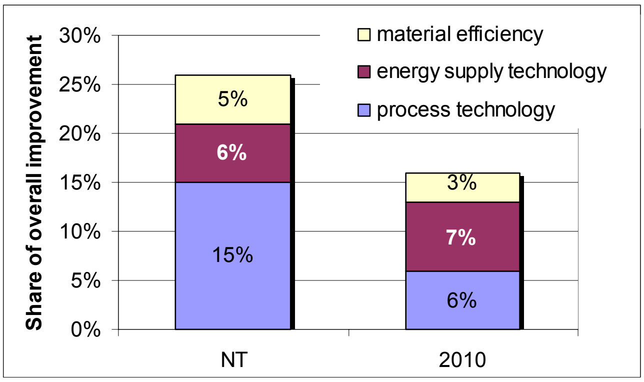


Fig 5: Share of overall primary energy saving for full (NT) and reduced capacity replacement (2010)

Beside the dominating part of technical improvement for the exclusive use of newest technology it is shown that in 2010 the part of energy supply improvement increases significantly. In addition to technical improvements of the energy conversion the expected changes of the energy carrier mix for electrical power supply in Germany generate a big influence of the energy system. The average conversion efficiency of the national grid increases from 31,5 to 43,1 %. Again it is to note that all results are based on the production of one tonne of packaging material (foil, strip, can stock and can lid stock).

Analysing the primary energy savings at the process level further questions for both, newest technology and 2010 realised technology arise: How big is the share of technique, material and energy influenced changes, what are the improvements of each single process step, and what impact do they have on the overall improvements of the entire process chain?

To identify each part of the energy saving fig. 6 compares the pure technique specific potential of selected NT process steps with the product specific potential (per tonne packaging material) excluding improved energy supply. So the effect of decreasing mass flows and respective increasing metal and material yield can be isolated. A third calculation gives the values for the product specific potential including the energy supply to isolate the effect of more efficient fuel and electricity production as well as changes in the energy carrier mix.

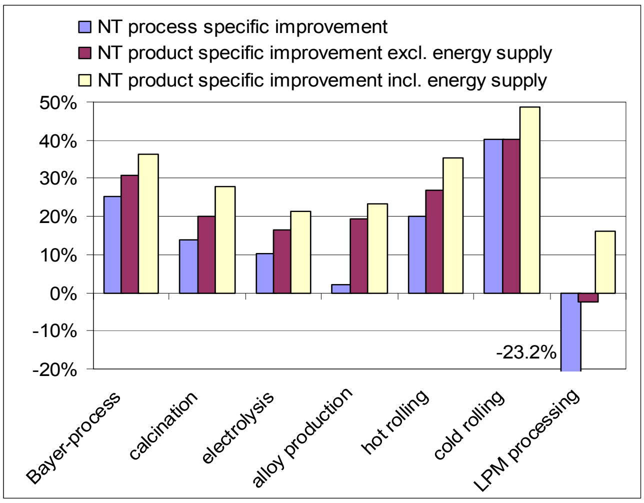


Fig. 6: Comparison of selected process and product specific improvements for the use of newest technology

As it can be expected from fig. 5 the three parts of the process improvements are generally in the same order of magnitude. For cold rolling there is no mass depending part, because it is the last step of the process chain. So the process specific improvement is equal to the product specific one. The alloy production, which also includes all remelting activities for secondary raw materials shows the largest influence of mass reduction per tonne of packaging material due to the decreasing amount of fabrication scraps. On the other hand there is only a small energy related improvement for these mainly fuel fired operations. Another exception of the values shows the LPM-processing where technology development causes a higher energy demand. But concerning the better metal recovery the decline decreases and even turns to an improvement also concerning better energy conversion.

In spite of the higher energy demand it has to be considered, that the NT and 2010 recycling concepts for LPM recover 3880 respective 740 tonnes of aluminium more than 1997. The overall recycling quota increases to 72 % for NT and 62 % for 2010 and the technical recycling quota reaches 81 and 70 % respectively. That results in an energy saving of 860 respective 180 MJ/t aluminium packaging taking the corresponding primary metal substitution into account. That aspect wins importance due to the small part of closed loop recycling for packaging material of only 2% and that the other part feeds other recycling systems.

Fig. 7 shows the corresponding results for the 2010 case. There is no change in technology expected for the calcination and alloy production facilities related to the German packaging system. The 2010 realised improvement is about 13 percent points below that one for newest technology. The share of energy related improvement, especially for the electric powered processes like electrolysis, rolling and LPM-processing, again has increased against NT due to the assumed change in electric energy supply until 2010.

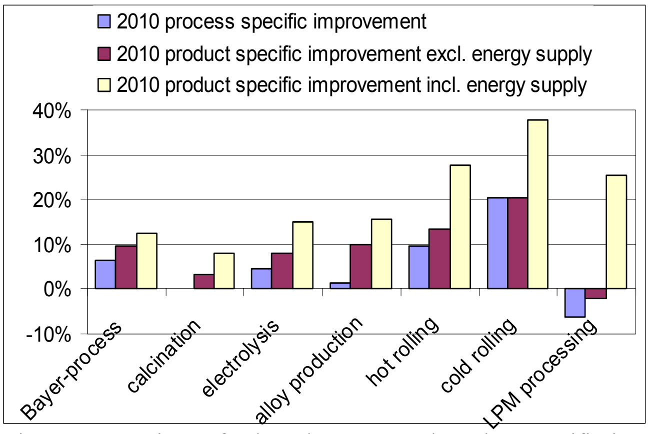


Fig. 7: Comparison of selected process and product specific improvements for the 2010 realised technology

Evaluating the calculated reduction potentials of primary energy demands for the different process steps there is a big variation of total and realised potentials. The specific improvement of each process level related to one tonne packaging material shows fig. 8.

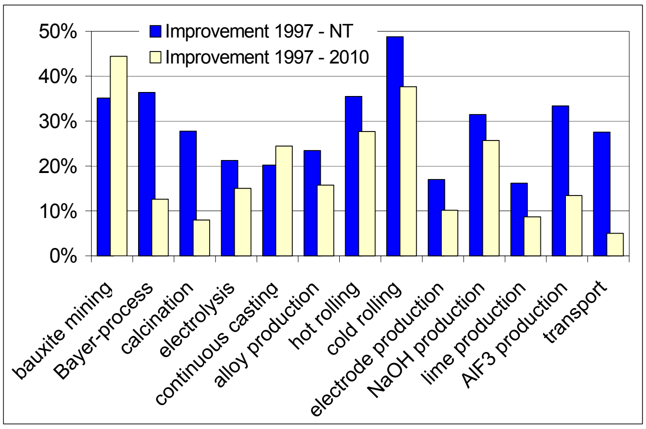


Fig. 8: Product specific improvements of the various process steps per tonne produced packaging

It can be seen that the difference for the NT and 2010 scenario is process specific. As expected the realised 2010 improvements are smaller than the possible technical ones except mining and casting. For mining there are bigger technical improvements expected in 2010 due to the short lifetime and fast development of mining equipment. For continuous casting the effect of electrical power supply overlay the technical improvements.

Changing the entire process chain towards newest technology it is also of interest which processes have the biggest share of the overall improvement. In direct comparison to the maximum product specific values discussed before the results for the NT calculation in fig. 9 confirm the dominance of the electrolysis with 52% of entire technical potential.

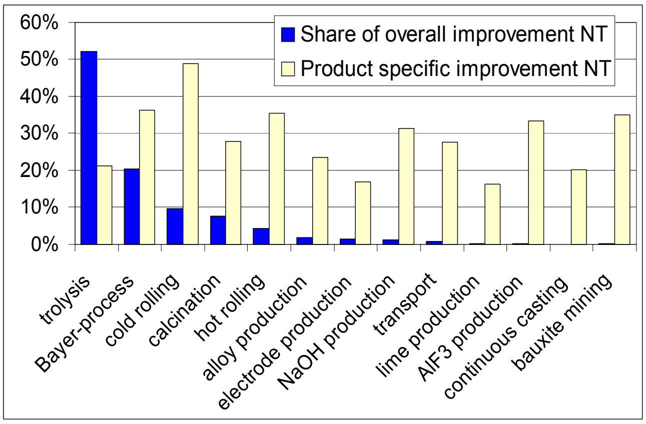


Fig. 9: Comparison of overall and product specific improvement for the NT case study

In spite of strongly increasing specific values it is followed by 20% for the Bayer-digestion, 10% for cold rolling, 8% for calcination and 4% for hot rolling. The corresponding diagram for the 2010 case study in fig. 10 shows slightly different values.

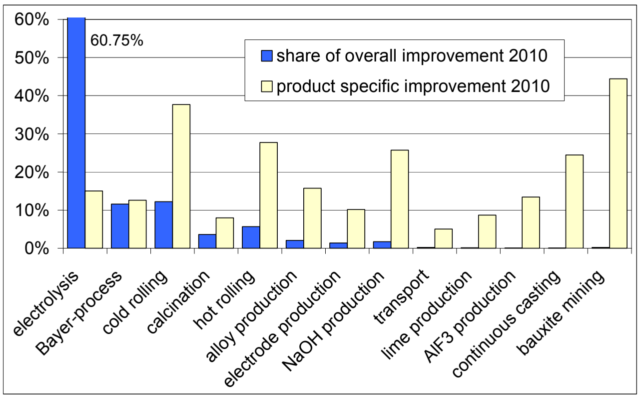


Fig 10: Comparison of overall and product specific improvement for the 2010 case study

Fig. 11 compares the share of the entire process chain improvement of NT and 2010. It can be seen that the Bayer-process steps digestion and calcination, the two mainly fuel fired processes, will achieve significant bigger parts of the overall improvement for newest technology. For 2010 the improvement of the big electric energy consumers dominates the picture due to different mix of energy carriers together with more efficient power conversion.

Beside the energy consumption the influence of technical progress on resource use and emissions are also of interest. As mentioned before a change in material efficiency has an impact on the energy demand and on the same time on the use of resources itself. Analysing the emissions along the entire process chain the share of the various process levels can be investigated.

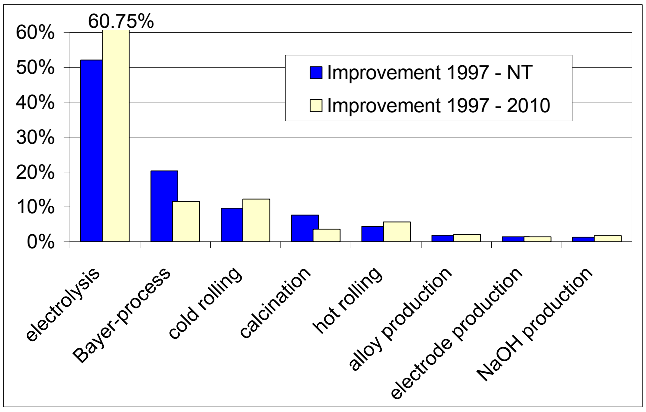


Fig 11: Share of process steps of the overall improvement

In fig. 12 various greenhouse gases are represented, showing impact of the different process levels of primary aluminium production on the global warming potential (GWP). It is to note, that the biggest share of CO_2 emissions is related to the supply of electricity for electrolysis (energy el.) and alumina production (energy a.p.). The CH_4 emissions are only related to energy supply. The CF_4 and C_2F_6 emissions are only process related to electrolysis and show the biggest reduction potential. The overall reduction potential is 43 % for the NT case and 14 % for 2010.

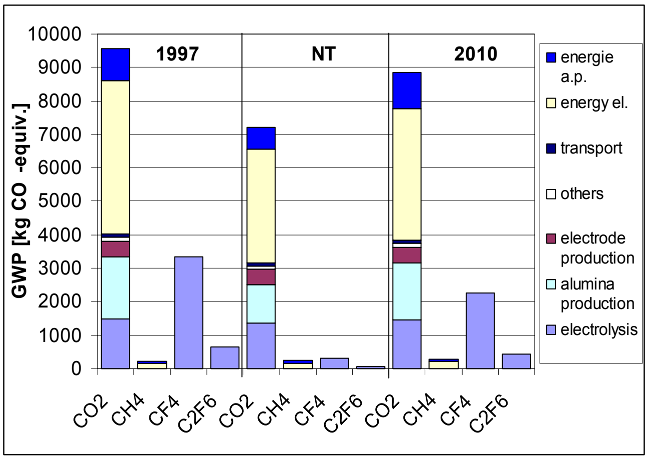


Fig 12: Share of process steps on the GWP in CO_2-equivalences

These results are representative for a variety of possible calculations in the field of environmental impact assessment which can be determined from the existing data base.

Conclusion

To model technical progress in the aluminium industry a scenario has been developed for the German packaging industry. Here the 1997 reference case is compared with a full capacity replacement by newest technology and a realistic case of reduced replacement due to economic and market considerations. Reduced replacement means partial replacement as well as upgrading and capacity expansion. The most important assumptions were that no structural changes of the packaging system itself take place until 2010 except the energy carrier mix of the power plants. It is to note that the results are strongly depending on the assumptions to forecast realistic conditions. The results show a big difference between the maximum technical potential and its predicted application in 2010. The entire primary energy savings in the case of newest technology (NT) is 26% (50 GJ/t packaging material) and in 10 years 16% (30 GJ/t) can be realised. For the isolated technology aspects improvements of 15 respective 6% can be expected. The material related effect will be 5 and 3% and the energy related one 6 and 7%, taking the dominating effect of a changed energy carrier mix in 2010 into account. Under realistic market conditions the technology related improvement potential in 2010 is relatively low due to the long lifetime and high investment costs of metallurgical plants. Compared with world-wide average values the German aluminium system has already undertaken big efforts to reach a high technical and environmental standard. Nevertheless further process optimisation like automation and circuit material reduction are promising possibilities for domestic as well as foreign producers.

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TECHNOLOGICAL DEVELOPMENT IN ALUMINIUM PRODUCTION - CONTRIBUTIONS TO ENVIRONMENTAL CHANGES -*

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ABSTRACT

Following the discussion of sustainable development the need to develop differentiated rules considering special requirements of products, production processes and industrial sectors becomes obvious. Technical progress is one major aspect in this discussion.

To show the existing potentials for an efficient use of resources in complex production systems analysis and modelling of material flows are appropriate instruments. For this a technology-orientated process chain model has been developed along the material flow of aluminium from mining, smelting, to recycling and disposal.

Differentiating between the maximum and predicted technical potential the impacts of the implementation of modern technical concepts on resource use and emissions are quantified. Based on a scenario approach the 1997 basis is compared with a calculation considering full replacement by newest technologies available today and a further one with regard to reduced replacement in the year 2010, taking financial and market aspects into account. As an example the German packaging industry and its special recycling concept, including material and energy supply and transport has been chosen.

With the technical improvement of the different processes itself, the increase of material efficiency per tonne of produced packaging material and the improvement of the energy supply, three different effects are responsible for the overall results. The quantifications decompose the overall results according to the three effects. Focus is laid on selected emissions.

KEYWORDS

Packaging material, technical progress, process chain, technical potential, resource use, emissions, scenario, material efficiency

* Source: Proceedings of EMC 2001

Introduction

Metallic raw material flows interfere with a large number of sustainability issues. Stakeholders including industry, politics or NGO's are integrated in the discussion to promote the "highest" potential. For more practical purposes there is a need to develop differentiated rules keeping in mind special aspects of products, production processes and industrial sectors. To support this mediation process a scientific instrument has been developed to supply information on complex metal flow systems. This integrated resource management system is a set of tools which are designed to point out existing potentials and to estimate resulting ecological, economical and social effects of various actions.

Technical progress is regarded as a means of creating sustainable production systems by dematerialization or efficiency revolution besides other means as e.g. sustainable demand behaviour. Although technical progress can not be easily quantified, its impacts on resource use and emissions can be evaluated using process chain analysis on condition that information is available on the level of different processes and locations. Furthermore, the concept of technical progress needs to integrate market processes. Therefore, it was differentiated in this paper between the technical potential of full capacity replacement by newest technology (maximum technical potential) and the smaller potential of reduced replacement in 2010 which can be realistically implemented under consideration of financial and market aspects (predicted technical potential) to get reliable projections of the impacts of technical progress.

Using a scenario approach and differentiating between the maximum and predicted technical potential the impacts of the implementation of modern technical concepts on emissions and resource use are quantified. Standing in place of other effects the impact on greenhouse gases is discussed in more detail. A supplementing description concentrating on the impacts on the energy demand can be found in [1].

To reduce the complexity this study exemplarily selects the use of aluminium in the German packaging system. It introduces the concept of technical progress for the production and recycling of aluminium packaging, giving detailed description of expected technical progress on the process levels within the next decade. The approach follows the modelling concept of a process chain analysis [2].

Production and use of aluminium packaging material in Germany

World aluminium demand in 1997 was 30 million tonnes. Germany's share was 8.5% of total, but 30.7% of European metal demand which characterises Germany as one of the big aluminium markets. The overall use of primary and secondary aluminium for production was 2.4 million tonnes, 1.8 million tonnes were semi-finished wrought products and 0.6 million tonnes were casting alloys. Figure 1 shows the share of applications of wrought products in Germany in 1997.

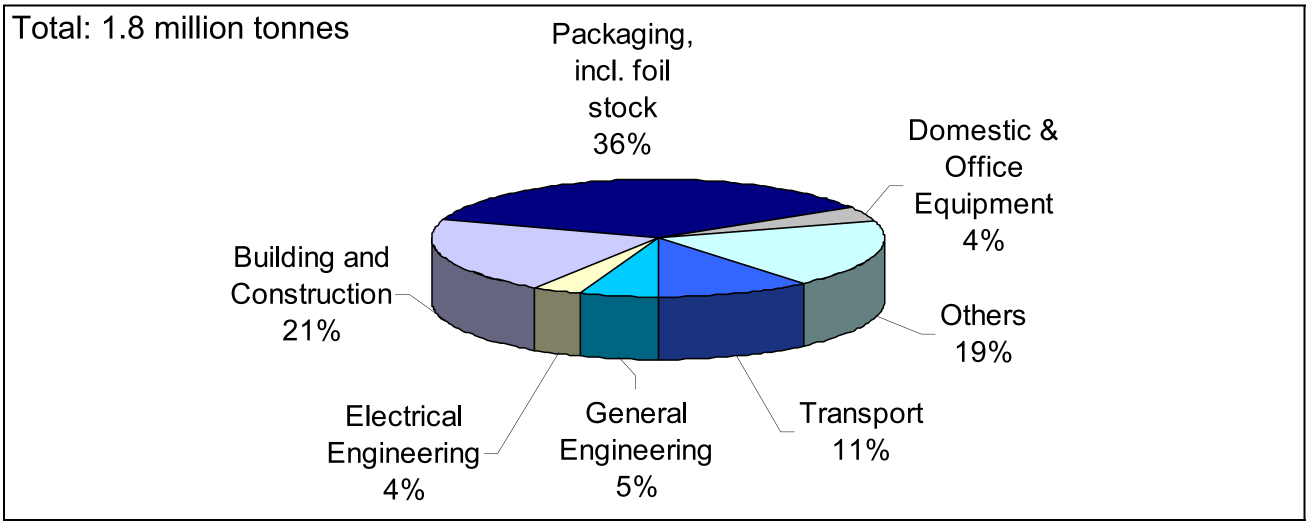

Figure 1: German semi-finished wrought material production for different areas of application

Applications of aluminium as a packaging material are still increasing. The variety ranges from combined coffee-packaging with a low metal content to full aluminium containers. The total German production of packaging material for domestic use and export was 600,000 tonnes which makes it the biggest in Europe with a share of 20% of total rolled products. In Germany itself, with 110,000 tonnes, the packaging sector is the third important end-use sector of semi-finished products behind building and transport.

German aluminium supply is highly dependent on imports. Whereas the proportion of imported bauxite is 100%, the proportion for alumina and aluminium is less but considerably high. Roughly two thirds of primary aluminium supply is imported material. On the other hand the supply of recycled aluminium was mainly covered domestically.

The biggest share of about 56,470 tonnes of aluminium packaging in 1997 was collected together with other light packaging material (LPM) by the Duales System Deutschland AG (DSD). The nearly 2 million tonnes of LPM had an aluminium amount of 28,580 tonnes [3]. Beside that, 21,650 tonnes of bottle closures and 7,000 tonnes of menu plates were recycled separately.

Process chain model

To analyse the existing system of production and recycling of packaging material a process chain model has been developed. Using this model the effects of technical progress on emissions and resource can be quantified by building up a scenario differentiating between maximum and predicted technical potential.

Within the process chain model production, use and recycling of aluminium products is divided into single processes which are represented by technology-specific and location independent modules.

They can be seen as entities of a production system, each of which has specific inputs and outputs of materials, energies, emissions and products taking distinct natural and technical properties into account. The technical status of the various processes is classified into different technology categories. They are old technologies (OT), present technologies (PT), and the newest available technologies (NT) which are already introduced. Furthermore, technical options for future use (FT) are existing.

The production of packaging material starts with primary aluminium production from bauxite (fig. 2). In the cast houses of the smelters unalloyed aluminium is cast directly into rolling slabs for foils. Alloyed aluminium for strip, especially can body and can lid stock, is cast after addition of scrap and/or alloying elements to the molten metal. Latter is also done at remelting facilities of rolling mills which mainly use in-house fabrication and foreign scraps and primary ingots. The following strip production is done by conventional hot and cold rolling. There the foil is reduced down to a thickness of 7 microns for unalloyed material and about 100 microns for AlMgMn-Alloys. For the various aluminium bins, tubes and cans the investigation ends up with the production of alloyed strip for deep-drawing operation.

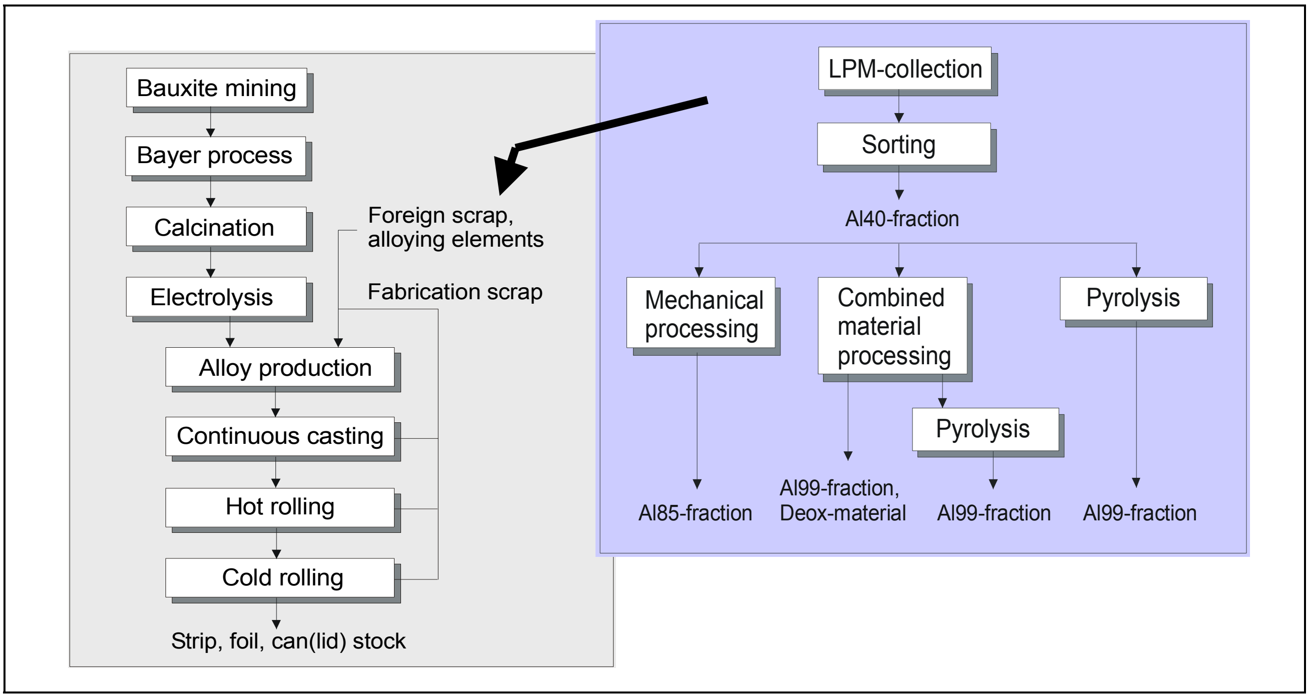

Figure 2: Production and recycling of packaging material

The recycling of LPM can be divided into three levels: collection, processing and remelting. After the collection, the aluminium fraction is separated from the packaging materials in a sorting plant. The received aluminium content of 40% is not high enough and needs further processing for a sufficient metal yield during remelting. Three processing technologies were implemented in 1997 for this. The smallest fraction (10%) was processed in a mechanical plant, 35% were the processing of combined material with a subsequent pyrolysis and the rest (55%) by straight pyrolysis. The obtained scrap has an aluminium amount of 85% and 99%, respectively. From the remelting processes (third level of recycling, included in alloy production) only those are included in the investigated system, which's material is reused for packaging production (fig. 2).

The efficiency of the recycling system for aluminium packaging in Germany can be described for collection, processing and remelting. Each level of recycling causes losses of metal so that the overall recycling quota (collection, processing, remelting) is 60% and the technical recycling quota (processing, remelting) is 67%.

Beside the production levels shown in figure 2 transportation and energy supplying processes are also taken into consideration as well as the production processes of intermediate products and waste treatment. The end product manufacturing process and also the use phase are important elements in the process chain, which will be included in near future [4].

The scenario "technical progress"

Technical progress is one subject in the discussion of sustainable development which can be evaluated using scenario technique [5]. For the chosen example the changes in material and energy flows due to technical progress and innovation and its impacts on the environment was investigated in a first analysis. To separate different effects the scenario approach is carried out in three steps:

1. The reference case shows the domestic market supply for Germany for **1997** (including import and export of primary aluminium, its pre-products and secondary aluminium).
2. As a second case the maximum technical potential is calculated considering the exclusive application of newest technology (**NT**) for each process of the 1997 structure.
3. In a third case financial and market aspects are taken into account. Looking at **2010** as the target year only a part of existing plants will be replaced by NT. Some plants will be upgraded and others will not be changed at all. This differentiation is not a model result but exogenously determined based on expert information.

The results of all three cases were compared resulting in maximum and predicted potential of technical progress and its impact on the environment in a medium term time frame.

Set of assumptions

To explore a reliable scenario a comprehensible set of the assumptions becomes very important. Following, the main assumptions concerning all calculation steps and the variations within the three cases will be described.

The calculations are based on constant amounts of production and recycling. Therefore, there is no effect of capacity increase. German aluminium supply is highly dependent on imports. The import structure is shown in table 1 distinguishing between direct sources and indirect sources. Latter are those countries which export pre-products to direct suppliers. This import structure is left unchanged for all three cases.

Table 1: Direct and indirect sources of bauxite, alumina and primary aluminium for the German production of packaging material 1997

	Bauxite %	**Alumina** %	**Aluminium** %
Australia	14.8	8.5	
Brazil	9.1	7.5	7.5
Canada		2.4	9.0
France		0.4	0.9
Germany		19.9	46.9
Ghana	2.0		
Greece	0.1	0.1	
Guinea	19.0	0.1	
Guyana	8.6		
Iceland			4.4
Ireland		7.0	
Italy		2.9	
Jamaica	30.1	29.4	
Norway			12.0
Russia	11.8	11.8	12.8
Spain		1.4	
Suriname	4.0	3.6	
UK		1.9	6.4
USA		2.1	
Venezuela	1.2	1.2	
direct sources			
Total amount	2,902,000 t	1,230,000 t	637,000 t

The share of secondary raw materials for alloy production was not varied. A mass flow scheme for pure and alloyed aluminium has been created from several statistics, which was extended to single alloy groups. It was found that pure metal is made 100% from primary materials and alloyed metal has a share of 43% of secondary materials (which represents the 1997 average value, excluding in-house scrap from rolling). The same is assumed for the UK and France, imported alloys from the other countries are made of primary metal plus alloying elements.

The energy supply for the various processes is based on the energy carrier mix of the investigated year. Only for electrolysis a special so-called ‘contract mix’ is used. Here, the ‘contracted’ electrical energy supplier of the smelter and its base load mix has to be considered [6].

Beside the case independent assumptions each case has a set of specific assumptions to describe the investigated system. For the NT (full replacement) case, the selection of newest technologies in the different process steps is expressed through the saving of energy and accordingly a reduction of emissions. The modelled levels from bauxite mining to electrolysis consider only one technique.

Additionally, for alloy production, semis production and material processing the material yield becomes another major factor.

The assumptions can be categorised in three main groups. The first group reflects the change of technology itself. Beside that, those assumptions which effect the increase in material efficiency and another considering the energy supply situation can be made out.

Until 2010 (reduced replacement) the technological improvements will be limited realised considering beside possible physical improvements also financial and markets aspects and investment behaviour. Table 2 summaries the main assumption for the three cases.

Table 2: Set of main case-specific assumptions

<table>
<tr><th></th><th>1997</th><th>NT</th><th>2010</th></tr>
<tr><td>Mining</td><td>Base year supplying mines</td><td>Constant bauxite quality</td><td>Closure of some mines</td></tr>
<tr><td>Alumina production</td><td rowspan="3">Base year technology mix of supplying countries</td><td>Only tube-digestion and fluid bed calcining</td><td>10% energy savings, 1% higher yield</td></tr>
<tr><td>Electrolysis</td><td>Only newest PFPB cell technology</td><td>Modernisation, expansion only by NT</td></tr>
<tr><td>Alloy production</td><td>Only modern furnaces with oxygen burners or heat recovery</td><td rowspan="3">Increasing share of newest technology</td></tr>
<tr><td>Continuous casting</td><td rowspan="3">Base year technology mix</td><td>Max slab weights = min fabrication scrap</td></tr>
<tr><td>Hot/Cold rolling</td><td>Lower energy and material demand</td></tr>
<tr><td>LPM recycling</td><td>Only fully automated separation and pyrolysis</td><td>10% of fully automated separation, replacement of mechanical processing</td></tr>
<tr><td>Energy supply</td><td>1997 energy carrier mix</td><td>1997 energy carrier mix, newest conversion technology</td><td>Technical improvement and 2010 energy carrier mix</td></tr>
</table>

For the bauxite mining the calculation bases on long-term supplying contracts. Nevertheless, until 2010 the closure of some mines has to be considered. The bauxite quality remains the same for all cases.

Because no complete production numbers of single locations are available for the alumina production process data of different digestion techniques are capacity weighted and related to the missing plants in the various countries. With the supplying structure also unknown country related mixes are modelled. For the NT case only the tube-digestion and fluid bed calcining takes place. Until 2010 a reduction of energy consumption of 10% can be expected by lowering the liquor volume. Also an improvement of the metal yield of 1% seems achievable. The land filling of red mud will only take place in orderly dump sites for both, NT and 2010, cases. The Russian alumina production from nepheline was not replaced in any calculation.

The relation of capacity weighted techniques to country mixes was chosen also for the primary smelters but with the distinction of pure and alloyed aluminium. A fully automated pre-baked cell technology with point feeding, reducing anode effects and consequently emissions, is used for modelling the electrolysis in the NT case [7]. In the 2010 case modernisation by computer control of the cells and the feeding system and by modern point-feeder technology can be assumed.

The alloy production includes remelting and refining and is represented by the 1997 technology mix. It changes completely to modern technology of the various furnace types by implementing oxygen burners or heat recovery systems for the NT case. The share of furnaces with modern technology increases until 2010.

Continuous casting will change to bigger slab weights causing decreasing amounts of fabrication scrap during the whole strip and foil production. In the NT case slab weights of 30 tonnes are assumed for continuous casting. So the amount of fabrication scrap can be minimised. Due to the high throughput of rolling mills for strip and foil stock production, the conventional route via hot rolling has not been replaced by continuous strip casting. Until 2010, beside decreasing metal demand hot and cold rolling itself changes to lower energy and material demand.

The earlier described system for the LPM-recycling will be replaced by fully automated separation and pyrolysis to reach best metal recovery for the NT case. Until 2010 this technique will reach a share of 10% and replaces the mechanical processing entirely.

For the supply of electric power the mix of energy carriers remains equal in the 1997 and NT cases. The implementation of newest conversion technology is assumed. Until 2010 a change in the energy carrier mix for the production of electrical power in Germany is expected. This will have a major impact on the resulting emissions according to the energy supply.

Results

Using the process chain model the changes along the three calculation steps can be quantified. The results allow an analysis in various directions considered in the sustainability discussion. In table 3 some of the major topics can be identified. It shows the most important inputs and outputs per tonne of packaging material. As could be expected, the improvements in the NT case are always bigger than for the 2010 case. Nevertheless the values are different for the various inputs and outputs.

The amount of bauxite necessary for the production will be discussed under the topic "use of mineral resources". 13.1% less bauxite is demanded due to higher digestion efficiency and less primary aluminium input for the NT case and 5.1% for 2010. This has also a big effect on the red mud output, the highest solid waste amount of the system. Another discussion concentrates on the recycled content of a product and therefore the relation of primary and recycled aluminium which was considered constant in this scenario. Other topics of interest are the metal yield of the recycled products expressed through the increasing Al-content of recycled LPM.

The major parameter to represent technical progress in the aluminium production however is the energy demand and the connected emissions to air. To reduce the complexity of the subjects in a first analysis focus was laid on the effects on the energy demand, which can be found in [1]. With CO_2 and other greenhouse gases (GHG) being directly connected to the energy discussion this paper concentrates on these emissions. As can be seen in table 3 the reduction potentials for both, the NT and the 2010 case, are relatively high. The various impacts leading to their reduction are discussed now.

Table 3: Calculation results for the material and energy flow due to the production of one tonne packaging material

Input per tonne packaging material	Unit	**1997**	**NT**	Δ	**2010**	Δ
Bauxite	kg	4,554	3,957	-13.1%	4,322	-5.1%
Primary aluminium	kg	1,062	985	-7.3%	1,023	-3.7%
Foreign scrap	kg	239	237	-0.8%	238	-0.4%
Primary energy	MJ	195,968	145,230	-25.9%	165,270	-15.7%
Output per tonne packaging material						
Fabrication scrap	kg	297	225	-24.5%	261	-12.2%
Al-content of recycled LPM	kg	38	48	26.6%	40	4.7%
CO_2	kg	11,491	7,969	-30.7%	9,467	-17.6%
Red mud	kg	2,368	1,871	-21.0%	2,165	-8.6%

The background for a GHG discussion is that various countries committed to limit these emissions. The Kyoto Protocol for example claims a reduction of the four gases CO_2, CH_4, N_2O, and SF_6 and two groups of fluorinated gases (HFC and PFC) of at least 5% below 1990 levels in the commitment period 2008-2012. In Annex B of the protocol the European Union claims the reduction of 8% [8]. This overall target has been distributed on a differentiated basis to individual member states under an “EU burden sharing” agreed upon by the Council of Ministers in June 1998. The target for Germany is therefore 21%. Although this does not refer to any specific industry, it gives an order of magnitude if supposed the reduction would be shared by every industry in the same way.

In addition to these country agreements, industrial sectors in various countries voluntarily committed to reduce GHG. The German aluminium industry participates in two ways. As a member of the German non-ferrous metals industry it committed to reduce specific energy consumption by 22%

until 2005 (base year 1990). In a second voluntary agreement the German aluminium industry in 1997 has announced to reduce perfluorocarbons (PFC) by 50% until 2005 starting from the 1990 figures [9].

In the following the paper does not claim to be a monitoring report. Neither the scope packaging material, the spatial system boundaries nor the base and target years of the scenario cover the system considered in the commitments. Nevertheless it's important to calculate emissions reduction potentials for a defined example.

The total CO_2 emissions per tonne packaging material was nearly 11,500 kg in 1997 and is about 8,000 kg and 9,500 kg for the newest and 2010 realised technique, respectively (fig. 3). The highest CO_2 production is in all three cases due to the carbon consumption during smelting. To a much lesser extent the Bayer-digestion and the alumina calcination are responsible for the amount followed by the cold rolling, electrode production (including coke and pitch production for pre-baked and Söderberg cells), hot rolling and the alloy production from primary and secondary material. The effects of the other processes, such as transport, soda or lime production, bauxite mining or red mud treatment can be neglected.

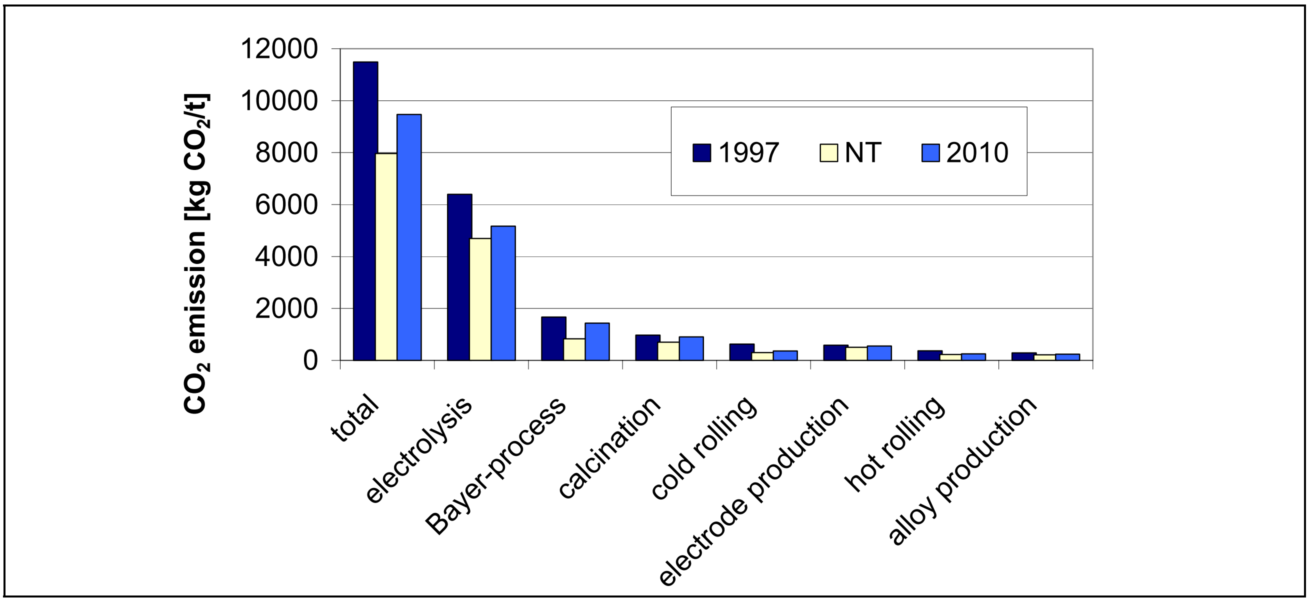

Figure 3: CO_2 emissions of the scenario calculations per tonne of packaging material

It is common in the CO_2 discussion to differentiate between process and energy induced emissions [10]. Typical process induced CO_2 emissions of the aluminium industry are those generated during electrolysis. More interesting for the discussion about technical progress is the differentiation between those CO_2 emissions which can be determined by the aluminium industry itself (Al-industry), by selection of technology or handling of the processes, and those emissions related to the supply of energy (energy supply), shown in figure 4. Latter cannot directly be determined by the aluminium industry.

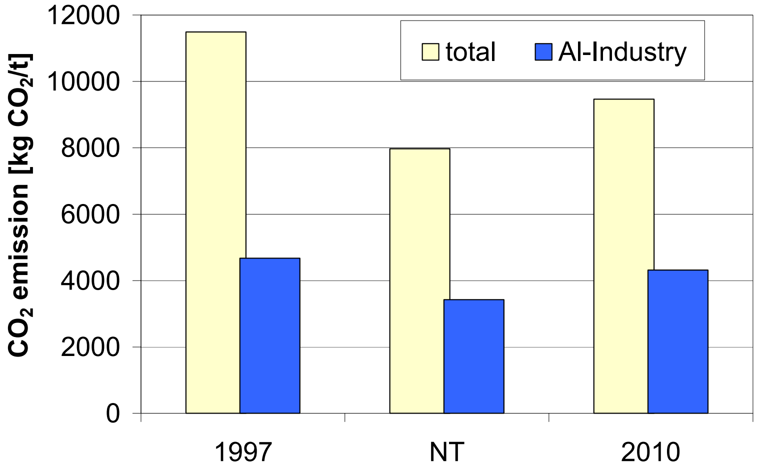

Figure 4: Comparison of total and Al-industry determined CO_2 emissions per tonne of packaging material

As mentioned above the commitments are often country related and can differ between them. Therefore it is interesting where the emissions occur. Figure 5 shows the reduction potential of CO_2 emissions. Beside the total reduction potential (entire system incl. energy supply) the potential of the aluminium industry in Germany and the potential of the metal supplying countries are considered. It can be seen that the technical reduction potential of the export countries (32%) is higher than the German one (17%). Compared with the average imports the German aluminium system has already undertaken big efforts to reach a high technical and environmental standard. Nevertheless, less than half of the possible potential in Germany is likely to be reached until 2010, whereas only a third will be reached by the other countries included in the investigated system. The reduction in Germany and supplying countries will reach about 7% until 2010 with regard to CO_2 emissions.

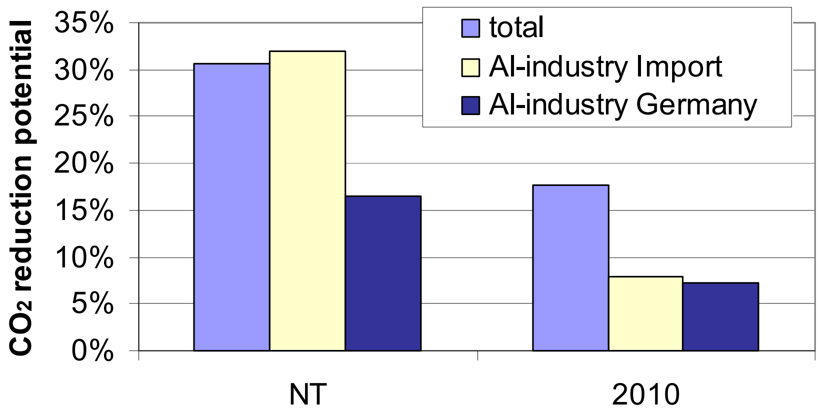

Figure 5: Reduction potential of CO_2 emissions per tonne of packaging material determined by the Al-industry, differentiating between the locations of occurrence

Other GHG than CO_2 important for the aluminium industry are the perfluorocarbons (PFC) and methane (CH_4). All GHG are commonly expressed by their global warming potential (GWP) in

CO_2-equivalences. In this paper the GWP (100) is used. Although CF_4 and C_2F_6 have a small amount their GWP (100) is rather high, with 6,300 CO_2-equivalences for CF_4 and 12,500 CO_2-equivalences for C_2F_6 [11].

In figure 6 the reduction potential of the German packaging production sector separated for the GHG expressed in CO_2-equivalences is shown. The possible reduction due to a total capacity replacement is more than 45%. The predicted reduction is estimated to just more than 20%. As before, also in this diagram it is differed between those emissions which can be determined by the aluminium industry and those emerging during the supply of energy. The reduction potential of the CO_2 gases is mainly determined by the energy supplying industry. Also the CH_4 emissions occur mainly in the energy supply processes (here mainly natural gas supply), whereas the PFC emissions occur exclusively in the electrolysis process. Latter have a high reduction potential.

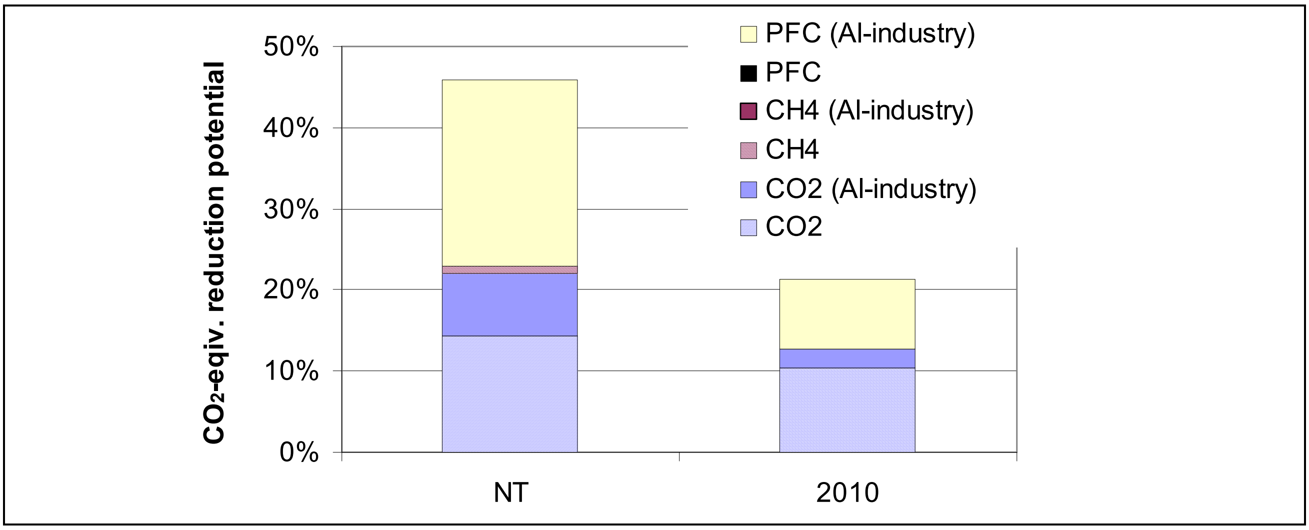

Figure 6: Reduction potential of greenhouse gases separated to Al-industry determined and total amounts

Nearly half of the reduction in both cases, NT and 2010, is reached by the decrease of perfluorocarbons. As they occur only in one process it is obvious, that the electrolysis process has the biggest share of the overall reduction potential. With about 74% of the overall reduction potential (fig. 7) it plays a dominating role. In the NT case the Bayer-process has the second highest share of the overall improvement whereas until 2010 the changes in the cold rolling processes will have a bigger influence on the reduction. Similar it is for the calcination and hot rolling processes. Where the first has a share of about 4% for the NT calculations, latter will have a higher influence in the 2010 case. Again, the other processes are not shown. With respect to the GHG emissions the electrolysis becomes the process where even a moderate effort in process improvement will have a major influence on the entire system.

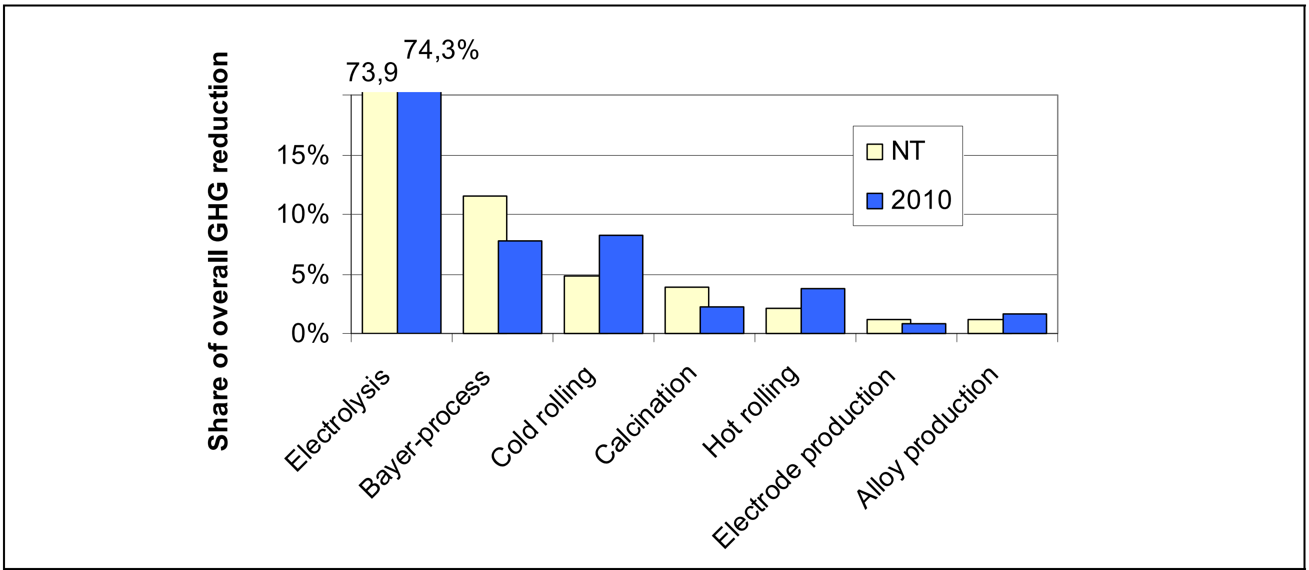

Figure 7: Share of overall GHG reduction according to the different processes per tonne of packaging material

The improvement of every process step are achieved by three main effects, the technical variations of the aluminium production processes, increasing material efficiency per tonne produced packaging material and improvement of the energy supply. In figure 8 these three effects and their influence on the primary energy demand is shown [1]. It can be seen, that the entire improvement in primary energy demand in the case of newest technology (NT) is 26% and that in the year 2010 16% can be realised. Beside the dominating part of technical improvement for the exclusive use of newest technology it is shown that in 2010 the part of energy supply improvement increases significantly. In addition to technical improvements of the energy conversion the expected changes of the energy carrier mix for electrical power supply in Germany generate a major influence of the energy system. The average conversion efficiency of the national grid increases from 31,5 to 43,1 %.

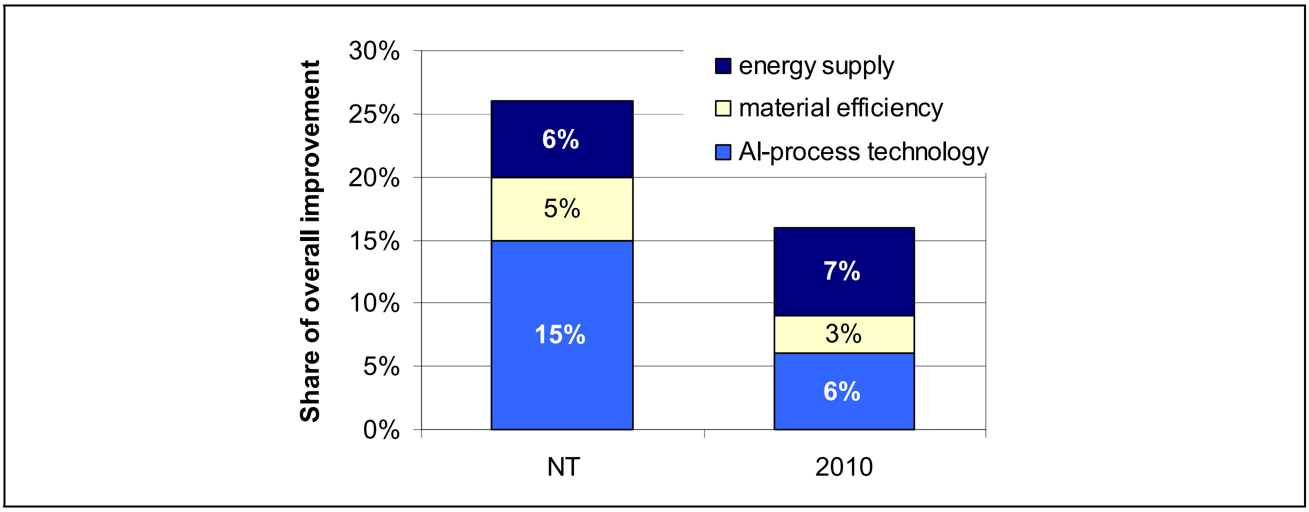

Figure 8: Share of overall primary energy saving for full replacement (NT) and reduced capacity replacement (2010) [1]

With CO_2 and CH_4 emissions mainly connected to the energy supply and the PFC emissions only connected to the electrolysis process the share of the three effects will differ from those of the primary energy savings. As stated before, the reduction potential of GHG emissions for full replacement (NT) is more than 45%. The changes of processes which could be done by the aluminium industry itself would cause a reduction of 34%, plus 4% due to an increasing material efficiency following out of that. The improvement of the energy supplying industry would add another 7%. Less than half of the maximum technical reduction potential is likely to be achieved until 2010 (fig. 9).

The GHG emission reduction which can be determined by the aluminium industry will reach 17% points from 38% possible. In contrast to the increasing significance of the energy supplying sector in the primary energy reduction, the share of GHG emission reductions will decrease from 7% to 5%.

The expected change in the energy carrier mix for Germany, which results in an higher efficiency of the national grid, results in an increase of GHG emissions. This is mainly due to the higher percentage of gas fired power plants. Its high efficiency is overcompensated by the increasing CH_4 emissions during the supply of the gas.

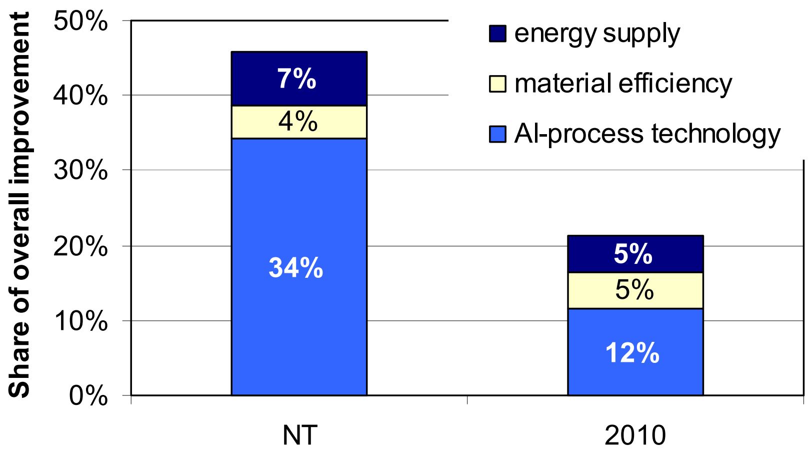

Figure 9: Share of GHG reduction for full replacement (NT) and reduced capacity replacement (2010)

These results are representative for a variety of possible calculations in the field of environmental impact assessment which can be determined from the existing data base. They also show the various facets of the sustainability discussion. An improvement in the energy reduction does not automatically leads to a reduction in emissions as well. To support the discussion the process chain model can be used, to analyse the complex material flow.

Conclusions

Technical progress has an influence on a variety of topics which are related to the sustainability discussion. In this analysis focus was laid on the reduction of greenhouse gases. It was differentiated between the maximum technical potential already achievable with today's known technology and the predicted potential implemented within the next decade. To reduce the complexity of the entire system the German packaging sector was chosen as a first example.

The greenhouse gases occurring in this system are CO_2, CH_4, CF_4, C_2F_6. The maximum reduction potential of newest technology (NT) is 45%, whereas 21% are likely to be realised until 2010. Looking at the improvement in more detail, it is of interest to differ between the actors who can determine the changes necessary for reduction in the system. To differentiate between the 'responsible' sectors is important to prevent double counting in the monitoring of reduction targets. It was differentiated between those determined by the aluminium industry itself and those related to the supply of energy. From the 45% maximum potential 38% points can be determined by the aluminium industry, the rest is due to the supply of energy. In the 2010 case 17% are depending on the changes in the aluminium industry.

Reduction commitments are often country related. Therefore, it must be analysed where the emissions occur. It was shown, that the predicted CO_2 reduction in Germany (2010) is nearly as high as that of the exporting countries of the system (7%) although latter have a much higher maximum technical potential (27%). The main reason can be seen in the already high technical and environmental standard in Germany. Nevertheless only half of the maximum potential will be reached until 2010.

The various process steps have different impacts on the overall reduction potential. The electrolysis process has a dominating part in this. Even a moderate success in the process improvement will change the entire system significantly.

The comparison of primary energy and greenhouse gas emission reduction potentials shows, that within the same system changes can have different effects. A more energy efficient technology might have higher GHG emissions if efficiency increases are accompanied by different energy mixes. For a widespread discussion about sustainable development other aspects such as other emissions, the use of mineral resources, or recycling concepts have to be investigated closely and integrated, too.

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ZUKUNFTSSZENARIO ALUMINIUM UND AUTOMOBIL*

(A SCENARIO OF FUTURE AUTOMOTIVE ALUMINIUM)

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ABSTRACT
This paper presents different possible developments for aluminium in automotive applications describing the resulting impact on aluminium production and recycling. Based on detailed process chain modelling, the use of aluminium in the German car industry is analysed along the entire life cycle chain. To identify major innovations in the automotive industry several life periods of cars have to be covered, which was achieved by choosing 2040 as the target year. A variety of parameters influence the demand for metal (primary and/or recycled) and the availability of aluminium scrap. Investigated are market developments of automobiles in general, and design strategies for car components differentiating between conventional and aluminium-intensive constructions. For the analysis the automotive aluminium is classified into casting or wrought alloys, which have to be distinguished with regard to recycling aspects.

KEYWORDS

Automotive applications, recycling, process chain model, demand for metal, availability of scrap, aluminium-intensity, alloys

* Source: Preprint for ALUMINIUM, 78, Heft 6

Einleitung

Im Jahr 2000 war die deutsche Automobilproduktion weltweit die drittgrößte, nur übertroffen von den USA und Japan. Zugleich hat sich eine entsprechend große Zulieferindustrie entwickelt, die wiederum der größte Abnehmer für Aluminiumwerkstoffe ist. Die Wachstumsraten des Aluminiumbedarfs sind stark von der Automobilproduktion abhängig, dies mit steigender Tendenz. In Europa war der Transportsektor im Jahr 2000 der größte Anwendungsbereich von Aluminium mit 29 % des Gesamtbedarfs. In diesem Sektor spielt das Automobil mit 95 % Produktionsanteil die Hauptrolle. Obwohl die Wachstumsraten der Automobilproduktion selbst, mit durchschnittlich 1 % gering sind, wird ein zunehmender Aluminiumbedarf durch den schnell ansteigenden Aluminiumanteil in den einzelnen Fahrzeugen verursacht.

Nahezu die gesamte Bandbreite der deutschen Aluminiumproduktion wird von der Automobilproduktion beeinflusst, da neben den bewährten Gusslegierungen auch zunehmend Bleche, Strangpressprofile, und Schmiedeteile aus Knetlegierungen im Fahrzeugbau eingesetzt werden. Entsprechend den unterschiedlichen Bereitstellungspfaden dieser Legierungen richtet sich das Hauptaugenmerk auf die Verfügbarkeit der jeweiligen primären und sekundären Vorstoffe. Dabei ist der Automobilsektor sowohl der größte „Produzent“ als auch der größte Abnehmer von Neu- und Altschrotten. 1997 wurden dort etwa 40 % der verfügbaren Schrottmenge (ohne Kreislaufschrotte) eingesetzt.

Zur Darstellung verschiedener möglicher Entwicklungen des Aluminiumeinsatzes im Automobil und ihres Einflusses auf die Produktion und das Recycling der benötigten Legierungen wurde die Szenariotechnik eingesetzt. Die Berechnungen basieren auf einem detaillierten Prozesskettenmodell mit der entsprechenden Mengenverteilung für das Referenzjahr 1997. So kann die Aluminiumversorgung der deutschen Automobilindustrie entlang der gesamten Bereitstellungskette analysiert werden. Schwerpunkt dieser Untersuchung war bisher weniger die Auswertung der Prozessbilanzen, sondern die Entwicklung der primären und sekundären Rohstoffströme sowohl in Deutschland als auch in den exportierenden Ländern. Entsprechend dem Szenarioansatz sind die Ergebnisse nicht als Vorhersage des zukünftigen Automobil- und Aluminiummarktes zu verstehen, sondern als Fallstudie möglicher Bedarfsentwicklungen.

Die Arbeiten entstanden im Rahmen des Sonderforschungsbereiches 525 „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“ der RWTH Aachen und des Forschungszentrums Jülich. Wir danken der Deutschen Forschungsgemeinschaft für die finanzielle Unterstützung.

Aufbau des Szenarios

Bei einer weitreichenden Betrachtung der zukünftigen Mengen an produzierten und genutzten PKW, muss die Veränderung des Werkstoffeinsatzes und der sich daraus ergebende Bedarf an Aluminium berücksichtigt werden. Darüber hinaus werden die Auswirkungen auf die Versorgungssituation einschließlich der Importe modelliert. Zur Identifizierung wichtiger Entwicklungen wurde das Zieljahr 2040 gewählt, um mehrere Lebenszyklen und die veränderte Aluminiumanwendung in die Untersuchung einzuschließen. Aus der Vielzahl von Parametern, die den Bedarf an Guss- und Knetlegierungen insgesamt und die Verfügbarkeit anfallender Schrotte beeinflussen, wurden die zukünftige Entwicklung der Produktion und des Recyclings von Aluminium im Automobilbau sowie verschiedene Fahrzeugkonzepte untersucht. Dabei wurde in zwei Fallbeispielen ein steigender Aluminiumeinsatz für Fahrzeuge mit konventioneller Stahlkarosserie mit der Umsetzung aluminiumintensiver Fahrzeugkonzepte verglichen. Das Szenario setzt sich aus drei Schritten zusammen:

- **1997:** Im Referenzfall wird der Aluminiumstoffstrom der Automobilproduktion in Deutschland abgebildet, inklusive der Importe und Exporte primärer und sekundärer Rohstoffe und des Recyclings von Altautos im Jahre 1997.
- **2040:** Im zweiten Fall wird der Anstieg des Aluminiumeinsatzes in konventionellen Fahrzeugkonzepten mit Stahlkarosserie für das Zieljahr 2040 berechnet.
- **AIV:** Die dritte Berechnung geht von einer verstärkten Umsetzung aluminiumintensiver Fahrzeugkonzepte (Aluminium Intensive Vehicle) aus, ebenfalls für das Zieljahr 2040.

Die Ergebnisse der verschiedenen Fallstudien werden hinsichtlich möglicher Effekte innerhalb des gewählten langfristigen Zeithorizonts verglichen.

Das System Aluminium und Automobil

Zur Analyse der Material- und Energieflüsse bei der Aluminiumbereitstellung wurde ein Prozesskettenmodell entwickelt [1]. In diesem Modell werden die einzelnen Prozessschritte von Produktion, Nutzung und Recycling von Aluminiumprodukten durch technologie-spezifische und standort-unabhängige Module abgebildet. Jedes dieser Module ist durch spezifische Inputs und Outputs von Materialien, Endenergien, Emissionen und Produkten gekennzeichnet, die die natürlichen und technischen Eigenschaften berücksichtigen. Das Prozesskettenmodell beschreibt so den Aluminiumstoffstrom vom Bauxitbergbau bzw. der Entfallstellen von Aluminiumschrott bis zur Produktfertigung.

Obwohl für die vorgestellte Analyse des deutschen Automobilsystems nur einige der verfügbaren Module der Prozesskette genutzt werden, muss der gesamte Stoffstrom des Aluminiums für den Inlandsbedarf und den Export berücksichtigt werden. So betrug der Aluminiumbedarf der verarbeitenden Industrie in Deutschland 1997 insgesamt 2,5 Mio. t, wovon 1,3 Mio. t auf den inländischen Markt gelangten. Abbildung 1 zeigt die Struktur der Aluminiumversorgung aus primären und sekundären Rohstoffen, die neben dem Automobilsektor auch alle anderen Anwendungen repräsentiert. Somit haben Veränderungen eines Anwendungsgebietes Auswirkungen auf die Versorgungssituation des Gesamtsystem.

Im Folgenden werden die Annahmen für den Referenzfall vorgestellt:

Importsituation

Aufgrund des hohen Metallbedarfs der deutschen aluminiumverarbeitenden Industrie sind die Importanteile entsprechend hoch. 1997 wurde für Recycling-Gusslegierungen ein Importanteil von 38 % ermittelt, für legiertes Primäraluminium 47 % und für unlegiertes Primäraluminium 55 %. Die wichtigsten Lieferländer für legierte Knetwerkstoffe im untersuchten System waren Norwegen mit 43 %, Großbritannien mit 26 % und Island mit 10 % sowie Frankreich, Russland, Kanada und Brasilien. Dabei wurde für Großbritannien und Frankreich ein Recyclinganteil von 43 % angenommen. Dieser entspricht dem deutschen Wert. Die anderen Länder stellen Knetlegierungen überwiegend aus Primäraluminium her [2].

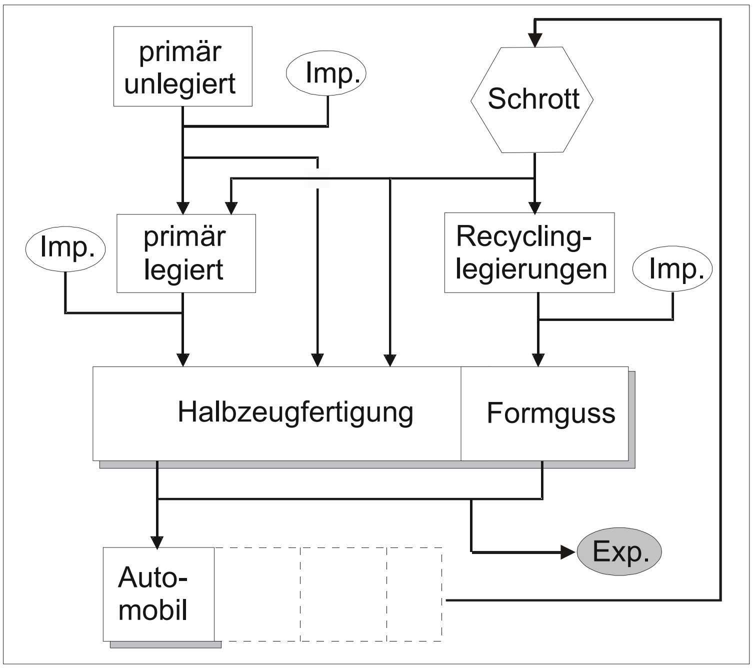

Abbildung 1: Schematische Darstellung des System der deutschen Aluminiumversorgung

Produktion von Gussstücken und Halbzeugen für Automobilkomponenten

Der Hauptanteil von 78 % der Aluminiumwerkstoffe im Automobil bestand 1997 aus Gusslegierungen. Etwa 80 % davon wurden in den Recyclinghütten aus sekundären Rohstoffen erzeugt. Der Recyclinganteil kann dabei zu 100 % angenommen werden. Die restlichen 20 % der Gusslegierungen sind sogenannte Primär-Gusslegierungen, die in den Hüttengießereien meist nur aus Elektrolysemetall und Legierungselementen erschmolzen werden. Für die Verarbeitung der Gusslegierungen werden im Modell Druckguss und Schwerkraft-Kokillenguss unterschieden (Abbildung 2).

Häufigster Recycling-Gusswerkstoff für nahezu alle Einsatzbereiche im Fahrzeug ist die Legierung AlSi9Cu3 mit einem Anteil von ca. 50 %. Daneben werden die eutektische AlSi12-Legierung sowie AlSi10Mg sehr häufig eingesetzt, mit Anteilen von 16 bzw. 12 %. Letztere hat ihren Anteil in den letzten 4 Jahren nahezu verdoppelt. Bei den Primär-Gusslegierungen wird zunehmend die Legierung AlSi7Mg im Bereich von Sicherheitsbauteilen wie Felgen oder Bremsbauteile eingesetzt. Tabelle 1 zeigt eine Zusammenstellung typischer Automobillegierungen und ihren Anteil an der Verwendung [3-5].

Tabelle 1: Häufige Aluminiumlegierungen im Automobilbau und deren Anteile

Legierungstyp	AA Nr.	Bezeichnung	Anteil
Gusslegierungen (78%)	359	AlSi9Cu3	48%
	356	AlSi7Mg	20%
	361	AlSi10Mg	12%
	-	AlSi12Cu	9%
	413	AlSi12	7%
	332	AlSi12CuNiMg	4%
Knetlegierungen (22%)			
davon - Pressprofile	6060	AlMgSi0.5	35%
- Schmiedeteile	6082	AlMgSi1	11%
- Walzprodukte	3003	AlMn1	10%
	5182	AlMg4.5Mn0.4	9%
	5754	AlMg3	14%
	6016	AlSi1.2Mn0.4	15%
	7020	AlZn5.4Mg1	6%

Für die im Automobil eingesetzten Knetlegierungen sieht das Bild komplexer aus, da der Schrotteinsatz für niedrig, mittel und hoch legierte Werkstoffe unterschieden wird. Demnach hatten niedrig legierte Press- und Schmiedelegierungen einen Recyclinganteil von 47 %. Für Walzlegierungen wurden 35 % (niedrig legiert), 80 % (mittel legiert) und 65 % (hoch legiert) ermittelt. Unlegiertes Material hat abgesehen von werksinternen Kreislaufschrotten keinen Recyclinganteil. Die Herstellung der Knetlegierungen erfolgt in den Hüttengießereien oder in Umschmelzbetrieben durch Verschneiden von flüssigem Elektrolysemetall oder Masseln mit sortenreinen Schrotten und Legierungselementen. Daraus werden Walzbarren und Pressbolzen stranggegossen und über Warm- und Kaltwalzen bzw. Strangpressen weiterverarbeitet. Schmiedestücke werden als Strangpressprofile bilanziert.

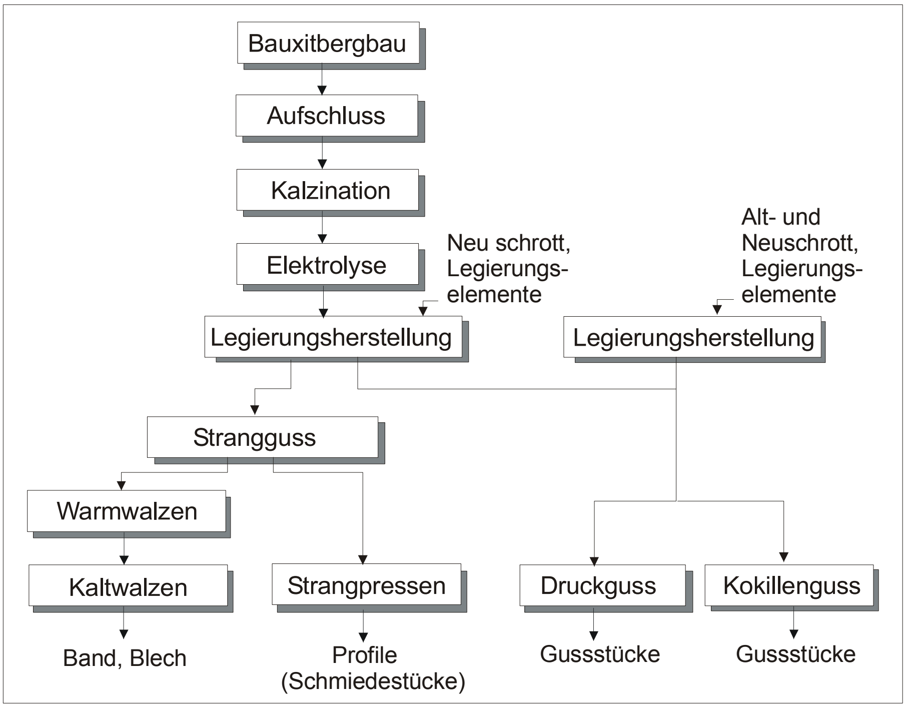

Abbildung 2: Produktionsweg der Halbzeuge und Gussstücke für den Automobilsektor

Wichtige Anwendungsbeispiele für Knetlegierungen sind Wärmetauscher (AlMn1), Schmiedefelgen (AlMgSi1), Stossfänger (AlZn5,5Mg1) sowie innere (AlMg4,5Mn, AlMg3) und äußere Strukturteile (AlSi1,2Mn) [4-8]. Im Modell werden diese Werkstoffe in niedrig legierte Strangpresslegierungen (46 %) sowie niedrig und legierte Walzlegierungen (25 bzw. 29 %) aufgeteilt.

Altautorecycling

1997 wurden in Deutschland 3,4 Millionen Altfahrzeuge stillgelegt, von denen etwa 40 % hierzulande in das Recyclingsystem gelangten (Abbildung 3). Der Rest wurde zum weiteren Gebrauch exportiert, überwiegend nach Ost- und Südosteuropa sowie Nordafrika.

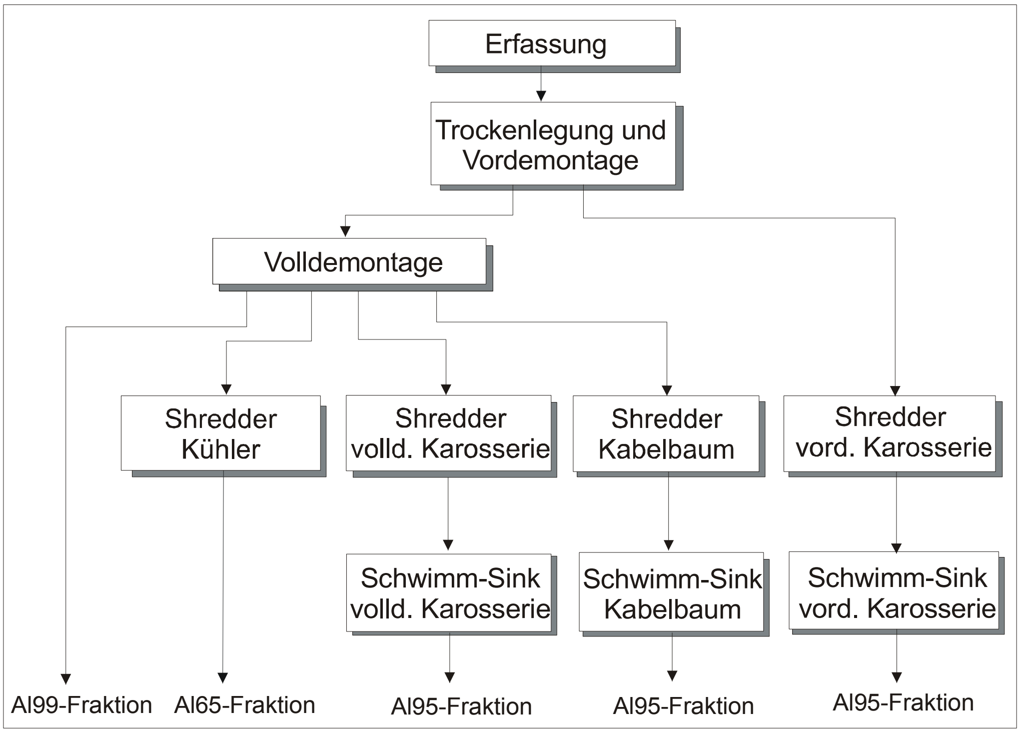

Abbildung 3: Recyclingsystem von Altautos in Deutschland

Nach der Trockenlegung wird ein Teil der Fahrzeuge demontiert. Felgen und Reifen, Batterien, Lichtmaschinen und Katalysatoren werden entfernt und dem Schrotthandel zugeführt. 60 % der teilzerlegten Fahrzeuge werden vollständig demontiert. Die leeren Karosserien, der Antriebsstrang und die Kühler sowie die verbleibenden 40 % werden anschließend geshreddert. Außer der Kühlerfraktion, die direkt in den Recyclinghütten eingesetzt wird, gelangen alle Shredderfraktionen in eine Schwertrübetrennung zur Aluminiumabscheidung [9]. Bisher wird in der Praxis keine Unterscheidung zwischen Guss- und Knetwerkstoffen getroffen. Alle Fraktionen werden anschließend in offenen oder geschlossenen Kreisläufen recycelt.

Zukünftige Entwicklungen

Die wichtigsten Einflussgrößen auf den Metallbedarf im Fahrzeugbau sind die im Folgenden erläuterte Automobilproduktion selbst, der durchschnittliche Aluminiumeinsatz pro Fahrzeug, der Anteil an Guss- und Knetlegierungen und der Anteil primärer und sekundärer Vorstoffe.

Entwicklung der Automobilproduktion

Im Referenzjahr 1997 wurden in Deutschland 4,7 Millionen Personenkraftwagen und 350.000 Lastkraftwagen produziert. Insgesamt wurden 3,5 Millionen PKW zugelassen und 3,4 Millionen stillgelegt. Abbildung 4 zeigt den Entwicklungszeitraum dieser Werte von 1990 bis heute und die berechnete Projektion bis 2040. Studien, die den in diesem Szenario gewählten Zeithorizont 2040 abdecken, sind nicht verfügbar. Daher wurden auf der Grundlage existierender Abschätzungen für kürzere Zeiträume [10] Annahmen für die Automobilproduktion, die Zulassung und Stillegung sowie das Altautorecycling unter Einbezug ökonomischer und bevölkerungsstatistischer Prognosen getroffen. Diese können aber gemessen an der langen Zeitspanne nur eine von vielen möglichen Entwicklungen darstellen [11]. Folgende Annahmen liegen den Berechnungen zugrunde:

- Das Wachstum der Automobilproduktion wird sich bis etwa 2030 abschwächen und danach in einen leichten Rückgang umkehren.
- Die Bevölkerungszahl wird sich leicht rückläufig entwickeln.
- Die Zulassungszahlen werden schon ab 2010 rückläufig sein.
- Die statistische Lebensdauer der PKW unterliegt einer Normalverteilung mit einem Mittelwert von 12 Jahren.

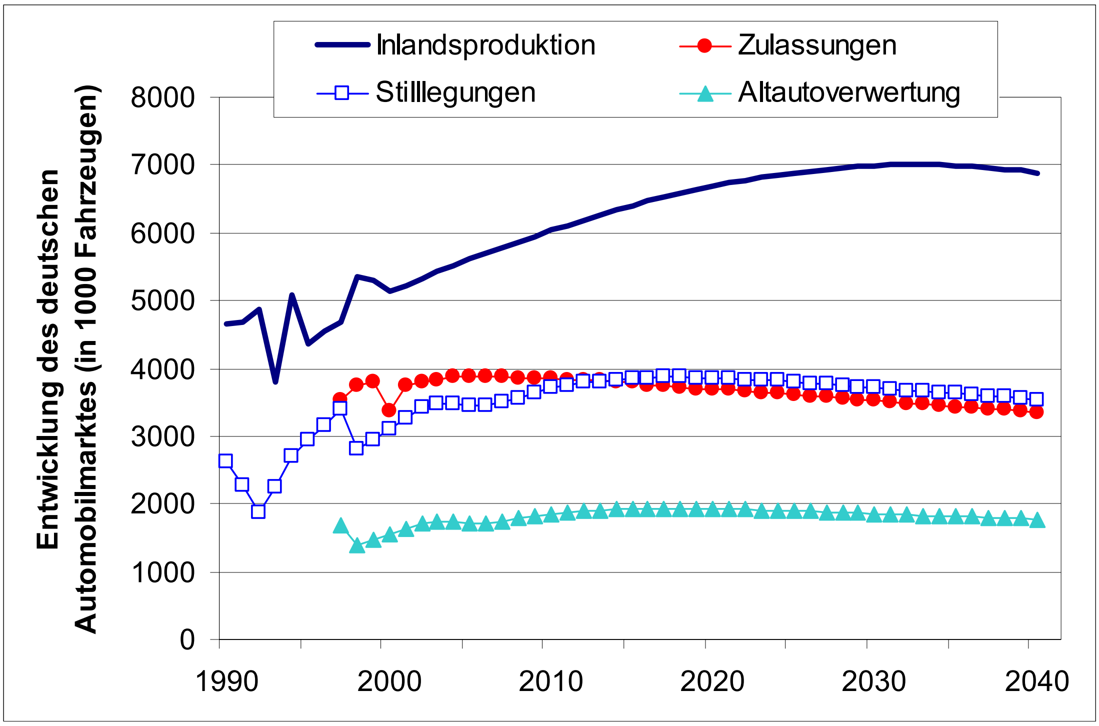

Abbildung 4: Berechnete Entwicklung des deutschen Automobilmarktes

Für das Jahr 2040 wird demnach eine inländische PKW-Produktion von 6,9 Millionen Stück erwartet. 3,6 Millionen PKW aus in- und ausländischer Fertigung werden zu-gelassen und 3,8 Millionen werden stillgelegt, was nur eine geringfügige Veränderung gegenüber 1997 bedeutet. Aus den Stilllegungen und der Exportrate resultiert eine Altautoversorgung des Recyclings von 1,4 Millionen Stück. Diese Entwicklung ist für die Fallbeispiele 2040 und AIV gleich. Aufgrund des hohen Qualitätsniveaus deutscher Fahrzeuge liegt der Exportanteil nach der Stilllegung bei 60 %. Dieser Wert wird voraussichtlich auch unter der europäischen Altautoverordnung konstant bleiben, da diese eine Änderung der Recyclingpraxis aber nicht des Exports von Gebrauchtwagen vorsieht.

Entwicklung des Aluminiumeinsatzes im Automobil

Der Trend des vermehrten Einsatzes von Aluminium bei den Automobilherstellern ist ungebrochen. Dabei werden neben der für viele Fahrzeuge bereits zum Standard gehörenden Anwendung von Aluminiumguss im Kolben, Motorblock, Zylinderkopf oder Getriebegehäuse auch zunehmend Gussbauteile in den Bereichen Fahrwerk und Karosserie eingesetzt. Für Bleche, Strangpressprofile und Schmiedeteile bietet das Automobil ein noch größeres Einsatzpotenzial. Insbesondere Bleche werden vermehrt für sogenannte Anhängteile wie Türen oder Motorhauben verwendet. Profile und Schmiedestücke kommen im gesamten Fahrwerksbereich zum Einsatz.

Aus der Endverbrauchs-Statistik des Aluminiumverbands und einer Vielzahl publizierter Abschätzungen der Aluminiumindustrie (Pechiney, VAW, Alcan-Alusuisse, EAA, GDA) und der Automobilindustrie (PSA Peugeot Citroen, Audi, Ford) wurde die in Abbildung 5 dargestellte Entwicklung des zukünftigen spezifischen Aluminiumeinsatzes zusammengesetzt [12-17]. Das mittlere Aluminiumgewicht der produzierten Fahrzeuge mit konventioneller Stahlkarosserie steigt demnach von heute 100 kg auf 250 kg im Jahr 2040 an. Im gleichen Zeitraum sinkt der Anteil der Gusslegierungen von etwa 75 auf nahezu 50 % ab. Besonders deutlich ist zu erkennen, dass der Hauptanstieg des Aluminiumeinsatzes in den nächsten 10 Jahren erfolgt.

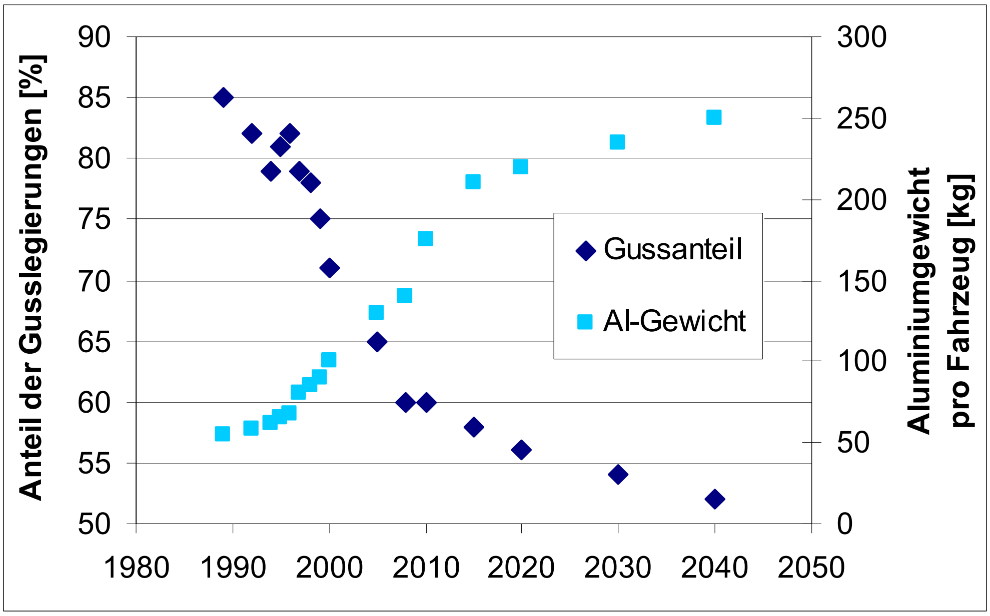

Abbildung 5: Entwicklung des mittleren spezifischen Aluminiumgewichts von Neufahrzeugen und dessen Anteils an Gusslegierungen

Die Betrachtung der mittleren jährlichen Wachstumsraten des Aluminiumeinsatzes der nächsten vier Jahrzehnte in Abbildung 6 zeigt folglich den höchsten Zuwachs für den Zeitraum 2000 bis 2010 von 7,4 %. Für den Fall aluminiumintensiver Fahrzeuge entwickeln sich die Wachstumsraten ähnlich, jedoch mit höheren Absolutwerten (8,8 % von 2000-2010).

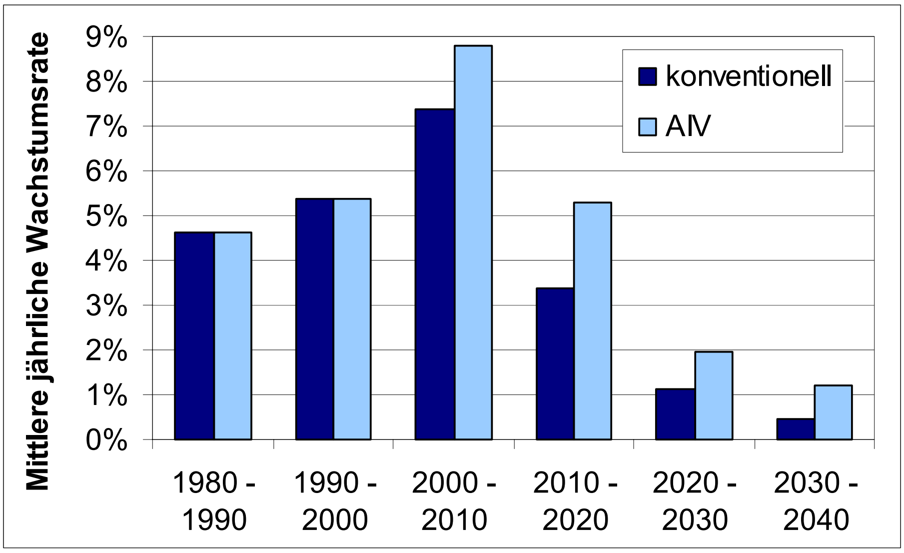

Abbildung 6: Mittlere jährliche Wachstumsraten des Aluminiumeinsatzes von 1980 bis 2040 für konventionelle und aluminiumintensive Fahrzeugkonzepte

Bedarfsentwicklung von Guss- und Knetlegierungen

Der ermittelte Wert von 250 kg Aluminium pro Fahrzeug ist insofern realistisch, da ein theoretisches Gesamtpotenzial von etwa 300 kg im konventionellen Automobil existiert, das sich aus 160 kg Gusslegierungen und 140 kg Knetlegierungen zusammensetzt [5, 8, 17]. Die Differenz kommt dadurch zustande, dass nicht alle Fahrzeuge, insbesondere Kleinwagen, diese Menge erreichen werden. Der Anteil bereits existierender aluminiumintensiver Bauweisen wie etwa das Space-Frame-Konzept von Audi, wird in diesem Fallbeispiel als konstant angenommen, um eine Spannbreite der Ergebnisse im Vergleich mit dem alleinigen Einsatz dieser Konzepte im AIV-Fall aufzuzeigen.

Für den aluminiumintensiven Fahrzeugbau wird bis 2040 von einem Anstieg des Aluminiumgewichtes auf 400 kg ausgegangen, wobei die Karosserie und die Außenhautteile hauptsächlich aus Aluminium bestehen. Die Menge der Gussbauteile bleibt mit 130 kg konstant, wodurch der Gusslegierungsanteil auf 32,5 % absinkt.

Ein Vergleich des berechneten und in der Statistik ausgewiesenen Metallbedarfs zeigt, dass etwa 80 % der eingesetzten Halbzeuge und Gussstücke in den Fahrzeugen selbst zu finden ist. Der Rest sind Ersatzteile sowie Fabrikationsschrotte der Endfertigung. Dieser Anteil wird für die Berechnungen als konstant angenommen, da sich die prozessbedingte Vermeidung von Fertigungsresten und ihre Zunahme durch den steigenden Einsatz von Knetlegierungen kompensieren könnten.

Entwicklung der Metallbereitstellung

Aufgrund fehlender Rohstoffe und hoher Energiepreise wird angenommen, dass die deutsche Elektrolyseproduktion bis 2040 nicht expandiert, sondern bei etwa 700.000 t Jahresproduktion verbleibt. Der Metallbedarf muss somit durch Importe gedeckt werden.

Die Bereitstellung von Recyclingaluminium in Deutschland wird sich dagegen erheblich verändern. Trotz der steigenden Nachfrage wird sich aufgrund der verbesserten Metallausbeuten bei Erfassung, Aufbereitung und Schmelzen der durchschnittliche Recyclinganteil am Inlandsbedarf von 46 auf 56 % erhöhen (AIV 54%) [18]. Mit dem anfallenden Gussschrott und einem Teil Knetschrott kann dann der deutsche Bedarf an Recycling-Gusslegierungen vollständig gedeckt werden. Diese entsprechen wie schon 1997 80 % der gesamten Gussproduktion, für 2040 und AIV. Dies setzt die Serienreife optischer Sortierverfahren voraus, mit denen dann die Aluminiumfraktion der Automobilshredder in Guss- und Knetlegierungen getrennt werden. Tabelle 2 fasst die getroffenen Annahmen zusammen.

Tabelle 2: Annahmen zu Berechnung der Fallbeispiele 2040 und AIV

	1997	2040	AIV
1. Fahrzeugproduktion [Mio. Stück]	4,7	6,9	6,9
2. Aluminiumgewicht pro Fahrzeug [kg]	79	250	400
3. Anteil der Gusslegierungen im Fahrzeug [%]	78	52	32,5
4. Anteil von Primärgusslegierungen an der gesamten Gussproduktion [%]	20	20	20
5. Schrott- bzw. Ersatzteilanteil am Aluminiumbedarf im Automobil [%]	20	20	20
6. Importanteil von Recyclingaluminium [%]	37	0	0
7. Exportanteil von Recyclingaluminium [%]	12	0	0
8. Primäraluminiumproduktion in D [1.000 t]	570	700	700
9. Erfassungsquote von Altautos [%]	40	40	40

Szenarioergebnisse

Die Ergebnisse der Szenariorechnung lassen sich entsprechend den beschriebenen Parametern nach Bedarf und Bereitstellung, primären und sekundären Rohstoffen sowie inländischer und ausländischer Marktversorgung unterteilen. Die Entwicklungen im Automobilsektor sind dabei nicht isoliert vom gesamten System der Aluminiumwirtschaft zu betrachten, das sie sich gegenseitig stark beeinflussen. Zunächst werden daher kurz die erwarteten Veränderungen des gesamten deutschen Aluminiummarktes beschrieben, bevor die speziellen Auswirkungen auf den Automobilbereich diskutiert werden.

Unter der Voraussetzung, dass die deutsche Halbzeugindustrie 2040 unverändert stark exportorientiert ist wie zur Zeit, wird die Halbzeugproduktion insgesamt von 1,8 auf 5,7 Mio. t ansteigen. Für den AIV-Fall wurden entsprechend 7,1 Mio. t berechnet. Der Gussbedarf steigt in beiden Fällen von 0,5 auf 1,5 Mio. t.

Entwicklung des Aluminiumbedarfs im Automobil

Der Aluminiumbedarf im Automobil errechnet sich aus der produzierten Stückzahl multipliziert mit dem spezifischen Aluminiumgewicht zuzüglich 20 % für Rücklauf und Ersatzteilfertigung (Abbildung 7). Aufgrund des verstärkten Einsatzes ist das Wachstum von Knetlegierungen deutlich höher als das der Gusslegierungen, wodurch beide nahezu den gleichen Endwert von etwa 1,1 Mio. t in 2040 erreichen. Das bedeutet den Faktor 3 an Zuwachs für Gusslegierungen und den Faktor 10 für Knetlegierungen in 40 Jahren. Für die aluminiumintensive Bauweise werden 2,33 Mio. t Knetlegierungen benötigt, das entspricht einem Zuwachsfaktor von 22.

Tabelle 3 stellt den gezeigten Aluminiumbedarf der Legierungen und den Gesamtbedarf der Fahrzeugproduktion für die Fallbeispiele des Szenarios zusammen.

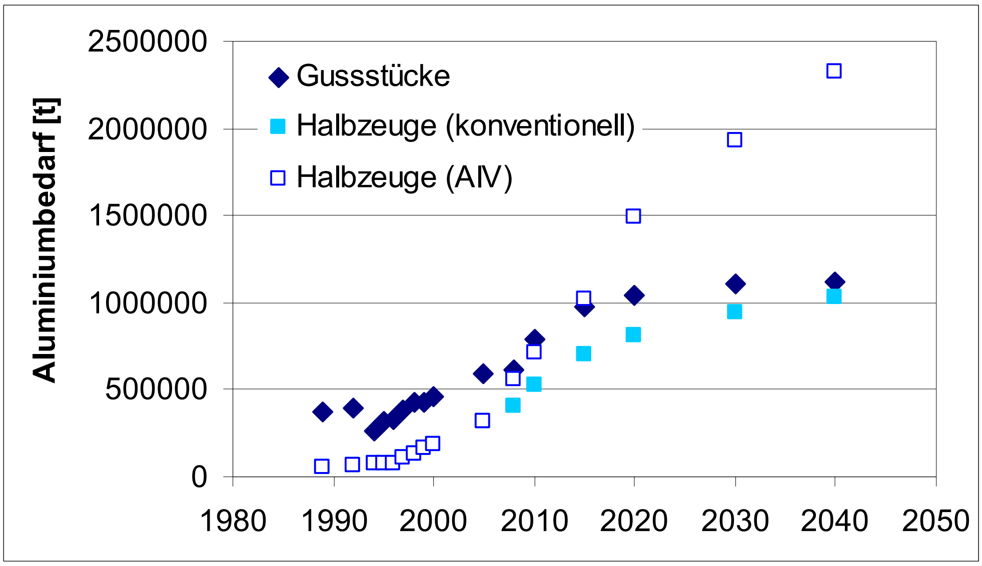

Abbildung 7: Entwicklung des Aluminiumbedarfs im Automobilbau in Deutschland von 1990 bis 2040 nach Guss- und Knetlegierungen

Tabelle 3: Berechneter Aluminiumbedarf für die Automobilproduktion gesamt und nach Legierungsgruppen

		1997	2040	AIV
Gussprodukte	%	78	52	32.5
	1000 t	359	1,121	1,121
Walz- und Pressprodukte	%	22	48	67.5
	1000 t	105	1,035	2,329
Gesamtbedarf	1000 t	464	2,156	3,450

Entwicklung der deutschen Metallversorgung

Die zukünftige Aluminiumversorgung in Deutschland wird insbesondere durch ein steigendes Schrottaufkommen bestimmt sein, da auch in den anderen Anwendungsgebieten des Aluminiums mit einem weiteren, wenngleich deutlich geringeren Zuwachs gerechnet wird.

Für die Herstellung der Recycling-Gusslegierungen bei den Refinern werden daher wie erwähnt zukünftig keine Importe benötigt, da allein die verfügbaren Altschrotte ausreichen werden, um den Vorstoffbedarf zu decken. Dabei wird die Produktion von Recycling-Aluminium von 1997 bis 2040 von 430.000 t auf 1.180.000 t ansteigen.

Darüber hinaus wird wesentlich mehr Schrott bei den Remeltern bzw. in der ersten Verarbeitungsstufe zu Knetlegierungen verarbeitet, und ersetzt somit Primärmetall. Die Versorgung steigt von 190.000 t auf 950.000 t für den Fall 2040 und auf 1.660.000 t für den Fall AIV an. Folglich steigt der Recyclinganteil der in Deutschland produzierten legierten Knetlegierungen von 43 % auf 78 % (2040) bzw. 85 % (AIV) an. Es wird davon ausgegangen, dass diese Anteile für alle Anwendungsbereiche gelten, da keine Einzelinformationen über die verschiedenen Legierungsgruppen vorliegen.

Bei der Betrachtung des Automobilsektors ist neben der Menge des zu erwartenden

Schrottaufkommen interessant, aus welchen Qualitäten, d.h. insbesondere aus welchen Legierungsgruppen sich dieses zusammensetzen wird. Dazu wurden die in Tabelle 4 für die Fälle 2040 und AIV aufgeführten Werte berechnet. Diese berücksichtigen wiederum die Produktionszahlen, den Aluminiuminhalt der Fahrzeuge, die Lebensdauer und die Erfassungsquote.

Tabelle 4: Altschrottaufkommen aus dem Automobilbereich 2040 und AIV

Altschrott	1997	2040	AIV
Gussteile	67.000 t	258.000 t	258.000 t
Bleche	6.000 t	124.000 t	243.000 t
Profile, Rohre, Schmiedestücke	5.000 t	96.000 t	194.000 t

Wie erwähnt, wird der Mehrbedarf an Gusslegierungen, der nicht aus neuen und alten Gussschrotten gedeckt werden kann, mit Knetlegierungen aus dem Automobilbereich aufgefüllt, die bei der Altautoverwertung ebenfalls anfallen. Dieser Mehrbedarf beträgt in beiden Fällen 234.000 t. Für den konventionellen Fall 2040 entspricht der Knetschrott aus den Fahrzeugen in etwa dieser Menge. Berücksichtigt man jedoch, dass die Recyclinghütten neben Schrotten auch einen hohen Anteil an Spänen und Krätzen verarbeiten, ist eine Trennung von Guss- und Knetlegierungen bei der Schrottaufbereitung notwendig, um letztere den Umschmelzbetrieben sortenrein zu Verfügung stellen zu können. Ohne eine solche Trennung müssten Recycling-Gusslegierungen exportiert und im Gegenzug Primäraluminium importiert werden. Für den AIV-Fall entsteht sogar ein Überschuss an Knetschrotten aus Altautos von ca. 200.000 t, wodurch eine Sortierung noch stärkere Notwendigkeit erlangt.

Im Gegensatz zum Gussbereich, muss zur Deckung des zukünftigen Knetlegierungsbedarfs der deutschen Halbzeugproduktion bedeutend mehr unlegiertes und legiertes Primäraluminium importiert werden. Die Importraten steigen im untersuchten Zeitraum voraussichtlich von 55 auf 79 % für unlegierte und von 47 auf 69 % für legierte Knetwerkstoffe. Letztere für die aluminiumintensive Variante sogar auf 76 %.

Theoretisch könnte versucht werden, möglichst viel Knetlegierungsschrott durch geschlossene Recyclingkreisläufe im Automobilsystem zu halten, wodurch dann dort entsprechend geringere Importquoten erreicht würden. Solche Aussagen sollten aber nur zur Ermittlung möglicher Potenziale eines maximalen Schrotteinsatzes genutzt werden. Da die Entwicklungen im Schrotthandel zahlreichen Einflüssen unterliegen, erscheint die Annahme eines gleich hohen Importanteils für alle Anwendungsbereiche auch unter methodischen Aspekten generell sinnvoller.

Heutige und zukünftige Aluminiumversorgung der Automobilindustrie

Bisher wurden die Entwicklungen der Nachfrage im Automobilsektor und die der Aluminiumversorgung in Deutschland getrennt betrachtet. Unter Zuhilfenahme des Prozesskettenmodells können diese nun die Wechselwirkungen dargestellt werden. Dies insbesondere unter dem Aspekt steigender Importquoten von Elektrolysemetall, die ohne eine deutliche Kapazitätserweiterung der inländischen Primärhütten oder ohne einen vermehrten Zukauf von Knetlegierungsschrotten notwendig wird.

Zunächst werden in Tabelle 5 die Auswirkungen der Importe auf die Recyclinganteile für die drei Fallbeispiele verglichen.

Tabelle 5: Angenommene und berechnete Entwicklung der Recyclinganteile für Automobilwerkstoffe ohne und mit Importen für 1997, 2040 und AIV.

	1997		**2040**		**AIV**	
	D	Inkl. Import	D	Inkl. Import	D	Inkl. Import
Primärgusslegierungen	0	0	0	0	0	0
Recycling-Gusslegierungen	100	100	100	100	100	100
Knetlegierungen (legiert)	43	26	78	41	85	44
Gesamtes Automobilsystem	79	70	88	64	90	58

Es ist zu erkennen, das die Recyclinganteile von Primär- und Recyclingguss gemäß den Annahmen konstant bei 0 bzw. 100 % liegen. Das wird auch für die Importländer von Primärguss vorausgesetzt. Bei den Knetlegierungen werden die Recyclinganteile durch die Importe verringert, da 65 % der berücksichtigten Lieferländer aufgrund ihrer Rohstoffsituation keine oder nur unwesentliche Mengen an Schrott zur Herstellung legierter Halbzeuge einsetzen. Im Gesamtsystem steigt der Recyclinganteil der deutschen Legierungsherstellung von 80 auf 90 %, wenn der gesamte anfallende Automobilschrott closed-loop eingesetzt würde. Werden die Importe hinzugezählt, sinkt der Anteil von 70 auf 64 und 58 % für 2040 bzw. AIV, da die Schrottverfügbarkeit zeitlich versetzt ansteigt und der ohnehin schneller wachsenden Bedarf durch Importmetall mit geringem Recyclinganteil gedeckt werden muss.

Die Absolutwerte des Bedarfs an Primär- und Recyclingaluminium für den deutschen Automobilbau und die inländische und ausländische Bereitstellung zeigt Tabelle 6. Der Zuwachs bis 2040 weicht für die betrachteten Subsysteme stark voneinander ab, obwohl die Eigenproduktion und die Importe etwa um den Faktor 6 zunehmen. Wie aus den Importquoten zu erwarten, liefert das Recycling in Zukunft in Deutschland die Hauptmenge der Automobillegierungen wogegen die Importmenge fast nur Elektrolysemetall beinhaltet.

Tabelle 6: Aluminiumbedarf der deutschen Automobilindustrie gesamt, sowie Eigenproduktion und Importe von Primär- und Recyclingaluminium in 1.000 t

		D	**Import**	**Gesamt**
Primäraluminium (legiert)	1997	80	**115**	195
	2040	200	**750**	950
	AIV	250	**1.400**	1.650
Recyclingaluminium	1997	**300**	150	450
	2040	**1.500**	150	1.650
	AIV	**2.000**	250	2.250
Gesamtsystem Automobil	1997	380	265	645
	2040	1.700	900	2.600
	AIV	2.250	1.650	3.900

Insgesamt steigt die im Fahrzeugbau eingesetzte Menge von 645.000 t bis 2040 um das Vierfache auf 2,6 Mio. t bei konventioneller Bauweise und um das Sechsfache auf 3,9 Mio. t für aluminiumintensive Fahrzeuge. In diesen Werten sind im Unterschied zu dem in Tabelle 3 ausgewiesenen Nettobedarf die Fabrikationsabfälle entlang der Prozesskette enthalten.

Fazit

Der verstärkte Einsatz von Aluminiumwerkstoffen in der deutschen Automobilindustrie wird die zukünftige Versorgung des Aluminiumbedarfs aus Eigenproduktion und Importen von Primär- und Recyclingaluminium drastisch verändern. Für die im Jahr 2040 voraussichtlich eingesetzten Mengen von 250 kg pro Fahrzeug bei konventioneller Bauweise und 400 kg bei aluminiumintensiver Bauweise ergibt sich ein zusätzlicher Bedarf von 2 bzw. 3,3 Mio t. In Abbildung 8 wird noch einmal die Größenordnung dieser Veränderung graphisch verdeutlicht.

Im einzelnen bedeutet dies einen Mehrbedarf an legiertem Primäraluminium von 635.000 t für 2040 und 1.285.000 t für AIV, der nicht einfach durch Produktionssteigerungen existierender Anlagen sondern nur durch Kapazitätserweiterung in großem Umfang gedeckt werden kann.

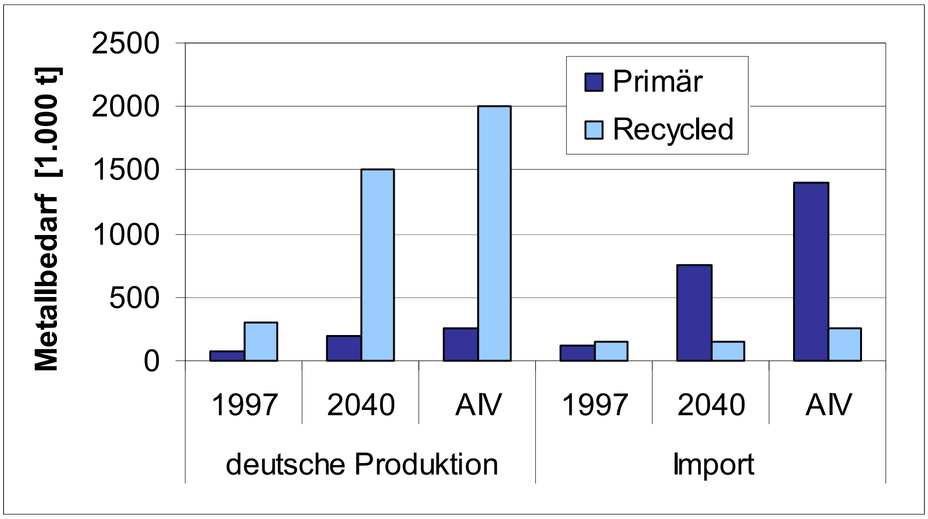

Abbildung 8: Aluminiumbedarf der deutschen Automobilindustrie nach Eigenproduktion und Importen von Primär- und Recyclingaluminium

Bei einer Elektrolysekapazität von durchschnittlich 300.000 t pro Jahr würden folglich zwei bis vier neue Hütten benötigt um allein den Bedarf der deutschen Automobilindustrie zu decken. Berücksichtigt man weiterhin die Entwicklung der Zuwachsraten in Abbildung 6 wird deutlich, dass diese Kapazitäten bereits in den nächsten 10 bis 15 Jahren zur Verfügung gestellt werden müssen. Beabsichtigen die Fahrzeughersteller also tatsächlich, den Aluminiumeinsatz wie gezeigt zu erhöhen, ist die Aluminiumindustrie aufgefordert, möglichst bald entsprechende Versorgungskonzepte zu erarbeiten.

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LONG TERM SUPPLY OF ALUMINIUM TO THE EUROPEAN AUTOMOTIVE INDUSTRY*

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ABSTRACT

This paper points out the effects various developments of the use of Aluminium in the automotive sector will have on the European Aluminium industry with regard to production of primary Aluminium and the use of scrap up to the year 2040. Using a scenario technique the differences between an increasing use of Aluminium in conventional car concepts and in Aluminium-intensive vehicles (AIV) are shown. A variety of parameters influences the availability of old and new scrap and also the demand of primary or recycled metal. Investigated are market developments of new automobiles and collection behaviour for end of live vehicles (ELV) in general. To illustrate the impacts on the different car concepts the automotive Aluminium is classified in casting or wrought alloys, which have to be distinguished with regard to recycling aspects.

KEYWORDS

Automotive application, scrap availability, aluminium-intensity, recycling, end of life vehicle, scenario

* Source: Proceedings of EMC 2003

1 Introduction

The growth of Aluminium and the automotive sector are closely connected. The transport sector was the biggest end use sector of the European Aluminium industry in 2000 accounting for 29% of demand. And it will become even more important. The entire European Aluminium industry is affected by these developments. Within the transport sector car production plays the dominating role. Using more and more extrusions and rolled products beside castings, the automotive sector covers the variety of production paths. On the other hand, the availability of primary and recycled Aluminium is strongly influenced by the car industry being the biggest old scrap-producing sector and the biggest user of new and old scrap at the same time.

During the last two to three years, a lot of changes in the overall Aluminium system and in certain parameters of the metal flows have taken place which are worthwhile to be investigated and which show former studies in a new light [1]. Especially the availability of Aluminium scrap has been matter of lively discussions in different committees like GARC (Global Aluminium Recycling Committee), and working groups of OEA, EAA, and their members. Additionally, the need became obvious to expand the system boundaries from a national to an European or even to a global level due to several reasons. First of all, the international scrap trade makes the determination of recycling quotas and recycled contents of a certain region or country nearly impossible. Here the global approach of GARC will hopefully create better knowledge in the near future. Secondly, the European Union end of live directive sets requirements for the entire European market.

Taking Europe as an economic system where data about demand and supply of Aluminium are already available, interesting developments and their influence on the Aluminium demand and supply can be shown. Major parameters in this context are the development of car production, Aluminium use per car and recycling quotas.

Beside the total amount of Aluminium used in automobiles the share of different alloy groups is of interest since their production follows different process chains. From the modelling point of view the main difference between casting and wrought alloys is the availability and use of secondary raw materials which can vary from 0 to nearly 100% for wrought and casting alloys, respectively.

2 Scenario concept

Looking a good way into the future the amount of produced and used cars, the automotive design and therefore the amount of Aluminium used in cars will change. Additionally, the supply of primary and recycled metal, whether domestic or imported, will alter. To include at least more than one life cycle of cars and to take a long-term view a time span from 2000 to 2040 is modelled. Although the quantification of figures therefore is tainted with a lot of uncertainties a long-term view is necessary as to give a picture of future developments.

To show different developments of the use of Aluminium in cars the scenario approach is carried out in three steps:

- Base case 2000 (**2000**): The base case shows the European market supply for the base year 2000 (including import and export of primary and recycled Aluminium, its pre-products and the recycling of automotive Aluminium).
- Conventional concepts 2040 (**2040 conv.**): For the second case an increasing use of Aluminium in cars for the target year 2040 is assumed, considering the conventional steel-based concepts utilised today. Nevertheless, the portion of Aluminium components is much higher than today.
- Aluminium-intensive vehicles 2040 (**2040 AIV**): The third case reflects a widespread use of Aluminium-intensive vehicles for the target year 2040 also including new car concepts.

The results of all three cases are compared resulting in conventional and Aluminium-intensive demand and supply situations for primary and recycled Aluminium in a long-term time frame.

Beside the different use of Aluminium depending on the different car concepts the assumed parameters of car production and recycling quotas have an influence on the results. To evaluate the influence of these assumptions the production amount and the collection quota for end of life vehicles (ELV) are varied.

3 The overall European Aluminium system in 2000

In a first step the overall material balance for Aluminium for Europe is considered. The total metal demand in 2000 was about 8.4 mill. tonnes. Figure 1 characterises the interconnections of primary and recycled materials which are representative of the automotive sector as well as for every other application. Changes in any of the application areas will have an influence on the overall system and therefore affect the supply situation as well.

Considering the high metal demand of the European Aluminium manufacturing industry, it is obvious that the metal supply is import-dependent. In 2000 26% of the overall Aluminium supply has been imported, for primary Aluminium the import share has been even 36%. The main countries of origin are Russia (37%), Brazil (10%), and Canada (7%) [2].

For scrap only 16% of the raw materials are imported, mainly from CIS (55%). At the same time material is exported to China, Taiwan, and India resulting to a net import of scrap of around 130,000 t. Together with the domestic scrap volume of about 3 mill. t the overall share of recycled Aluminium for semis and foundry production amounts to 32.5%, excluding in-house scrap at this stage of production.

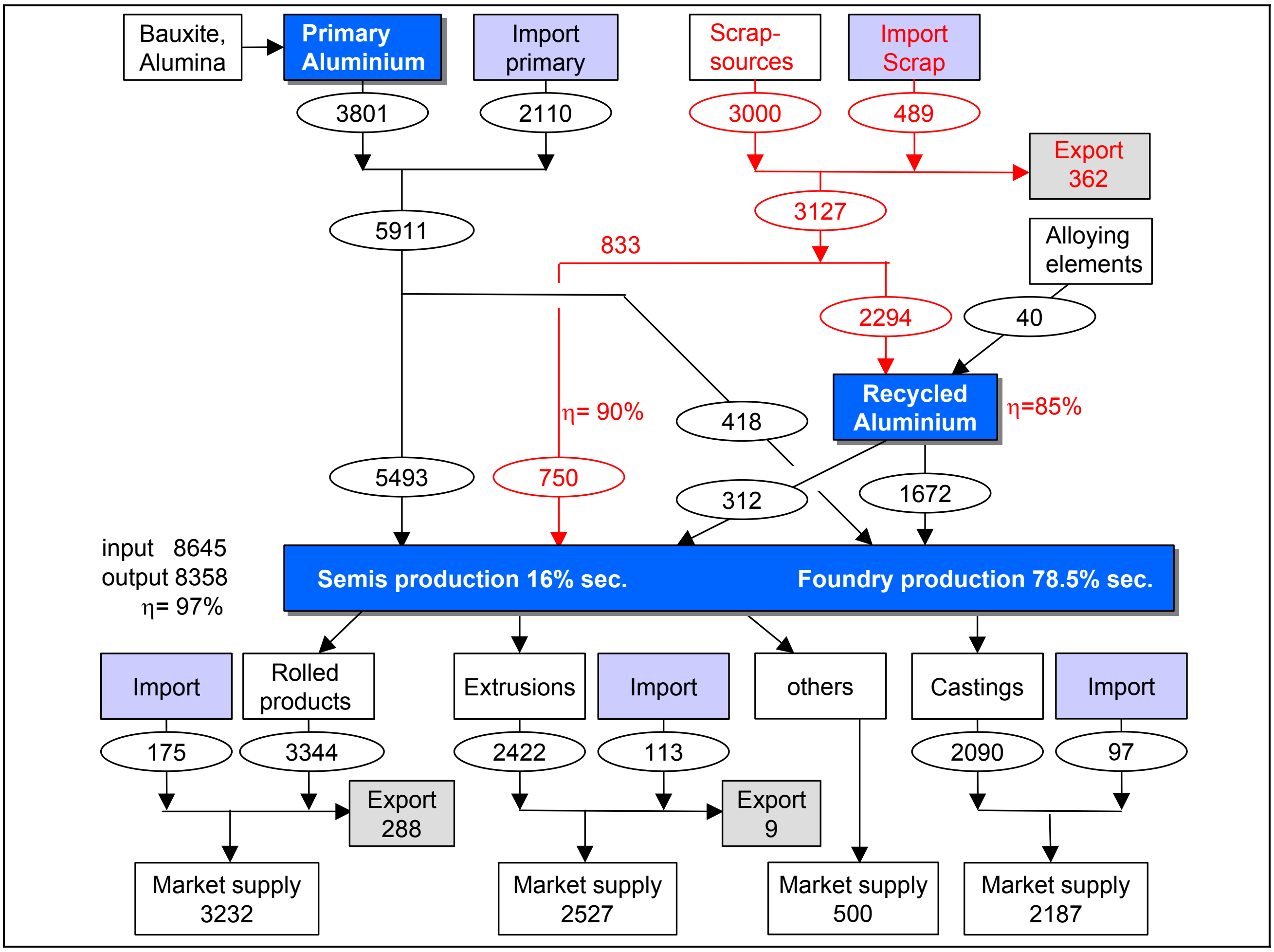

Figure 1: European Aluminium balance 2000 in 1000 t (Data sources: EAA, OEA)

4 The European automobile system

In 2000 European automotive production was the biggest worldwide followed by the USA and Japan [3]. Accordingly, the European supplying industries are quite big as well. To analyse the impacts of the different car concepts on the European Aluminium market the automobile system itself, including production and recycling, has to be described. Concerning the modelled Aluminium system, first the assumptions for the base case 2000 are presented.

4.1 Production of semi-finishes and castings for car components

Automotive Aluminium applications cover nearly the whole range of semi-finished products and castings. Figure 2 illustrates the different production paths for strip or sheet and extrusion production as well as the different casting processes.

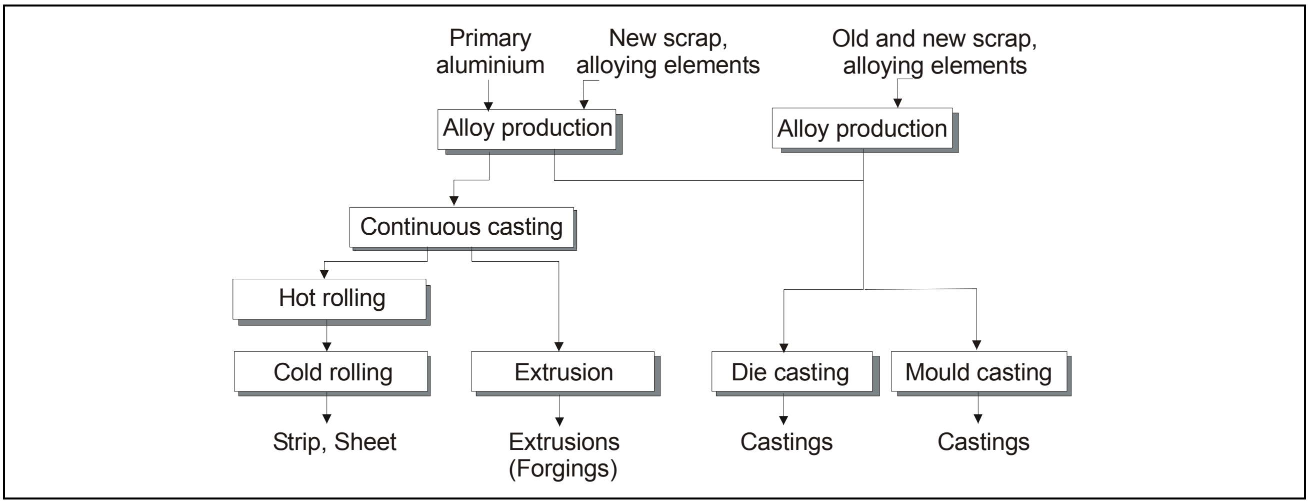

Figure 2: Production scheme for semi-finishes and castings for the automotive sector

In 2000 the main material for automobile components was casting alloys with a share of 71%. 80% of it is produced from recycling material by secondary smelters (refiners). They use old and new scrap, turnings and dross as raw materials to produce casting alloys, so that the recycled content of these alloys is nearly 100%. Table 1 documents the current average input material composition of refiners. The remaining 20% of automobile castings, the so-called primary casting alloys, are supplied by primary smelters and are made of 100% primary material.

Table 1: Average input material of European refiners in %

Old scrap	35-40
New scrap	25-30
Turnings	20-25
Dross	10-15

The picture for wrought alloys, however, is quite complex, due to the different scrap supply for the different materials. For automobile products, the considered recycled metal content can reach up to 50% for rolled and extruded products since here recycling-friendly alloys of the 3000, 5000, and 6000 series are used.

4.2 Recycling of cars

In 2000 11.6 mill. cars were de-registered, of which 65% stayed in Europe for recycling [4]. The rest was exported mostly for further use. For recycling all fluids are removed and the cars are partly dismantled. The rims are sold directly to the secondary smelters. About half of the partly dismantled cars are then completely dismantled. The rest and the dismantled bodies, power trains and radiators are then further processed before being recycled in the Aluminium system. All fractions can then be smelted either for closed loop production of new automobile casting components or casting products of other Aluminium systems.

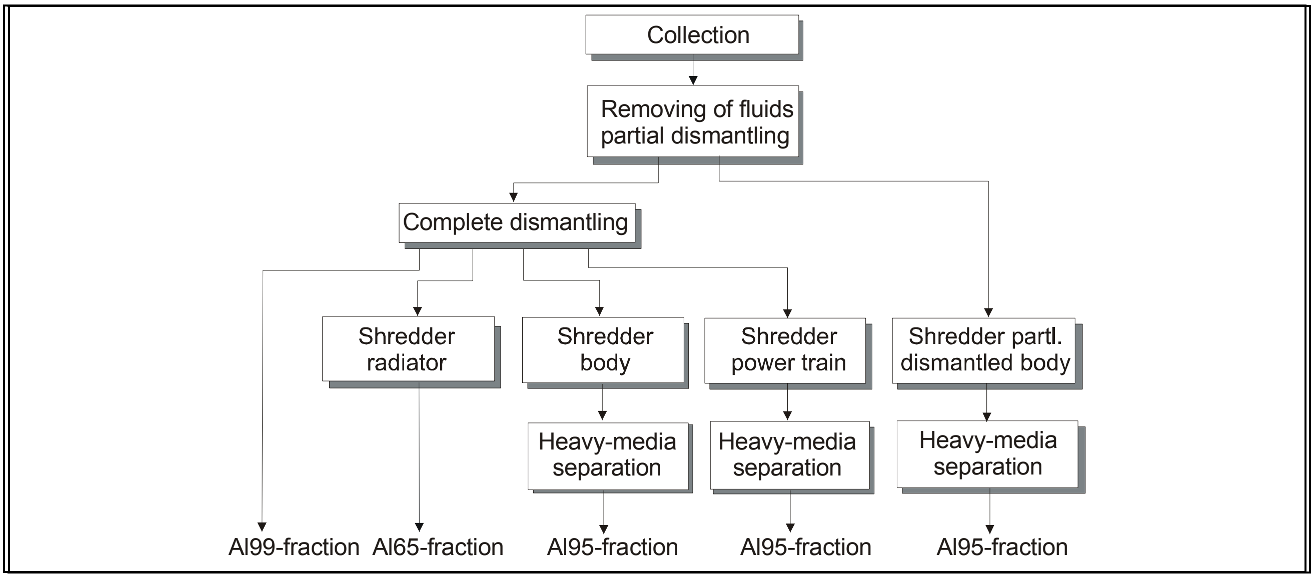

Figure 3: Recycling scheme of ELV

5 Aluminium use in cars

The main parameters of the metal demand in the car industry are car production itself, the average Aluminium content per car, the share of wrought and cast alloys, and the share of primary and recycled material.

5.1 Development of the European car market

Studies of the European automobile market covering the time horizon to 2040 are not available. To develop figures necessary for the analysis, assumptions for automobile production, registration, deregistration and recycling of ELV are worked out. Beside an existing study for the German Automobile market with shorter time horizons from Shell [5] plausible economic and demographic projections form the basis for the estimations for the European system. Figure 4 gives an overview on the current European car production and ELV recycling for the domestic market and on possible developments up to 2040. In 2000 domestic production of cars amounted to 14.8 mill., 14.4 mill. cars from domestic production and imports were registered in Europe and 11.6 mill. cars were deregistered. The Shell study distinguishes between two possible developments for the overall economic development which describe German as well as global markets. The development with higher production figures follows the assumption of further increasing globalisation and liberalisation. The smaller increase in the second case is due to an increasing impact of local governments and less favourable economic parameters.

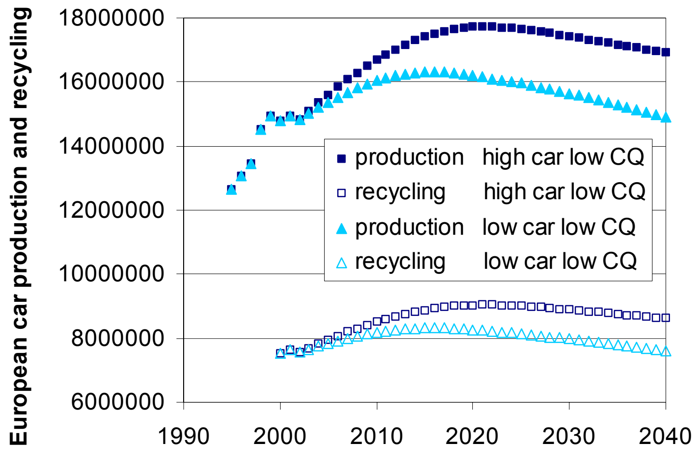

Figure 4: Different development of European car production and respective ELV recycling (Source: Shell [5], VDA Statistics [3], own calculations)

The assumptions to adjust the car market development are as follows:

- European automobile production increases till 2020 and 2015 in the different cases; the following decrease is due to the saturation of the European car market;
- Decreasing population in Western Europe following the current trend;
- The technical lifetime of cars is normally distributed with a median of 12 years;
- In 2000 the share of cars for recycling (net of exports of complete cars or car bodies) equals 65% of de-registered cars. It is assumed that this rate will not change until 2040.

For the scenario of different car concepts the high production case is taken as a basis. This leads to an assumption for domestic production of 17 mill. cars in 2040. The resulting supply of cars for recycling will be 8.6 mill.. This will be the same for the conventional and for the AIV case. The lower production figures for cars are used to show the sensitivity of the results with respect to this parameter (see 6.3).

5.2 Development of Aluminium use in cars

Looking at the average annual growth rates of Aluminium used in conventionally designed cars (figure 5) it is obvious that the highest average growth rate of 6% can be expected for the ongoing decade. This is due to the current trend for car manufacturers to use, besides Aluminium castings for engine, gear box, chassis and suspension, more and more wrought alloys for hang-on parts of the bodywork. For the AIV case the growth rates show a similar trend only with higher values (8.5% in 2000 - 2010).

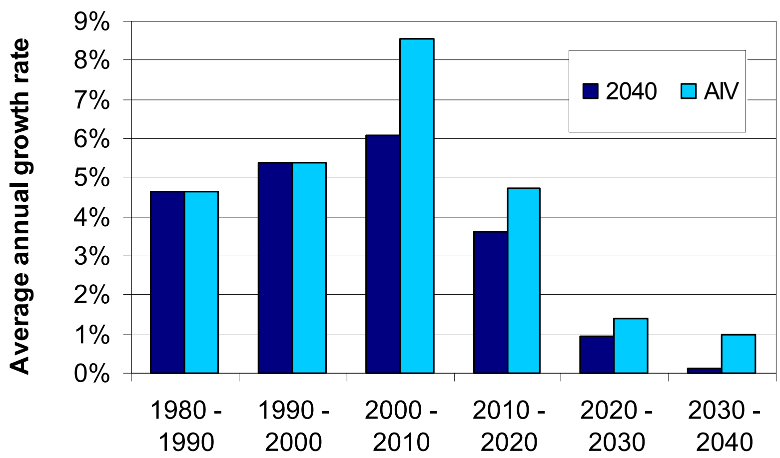

Figure 5: Estimated development of average annual growth rates of Aluminium used in cars

The absolute amounts of Aluminium used in cars for the conventional case in figure 6 underlines the current trend of growth rates described above. Especially the high growth rate between 2000 and 2010 is obvious. The average Aluminium content of a conventional passenger car will increase from 100 kg today to 250 kg within the next few decades, while the share of castings will decrease from about 75% to nearly 50% in the same period.

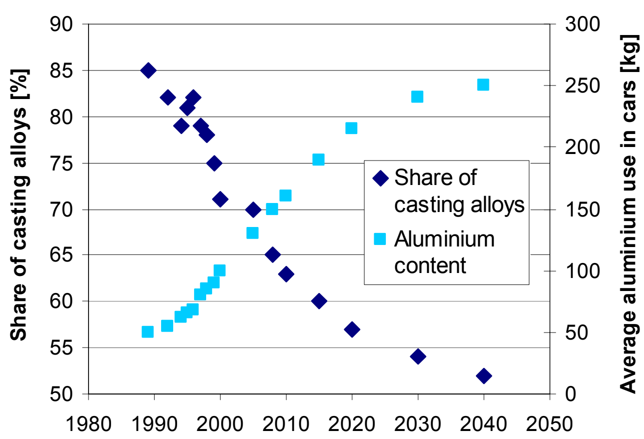

Figure 6: Development of Aluminium used in cars for the conventional case

5.3 Development of wrought and cast products

The amount of 250 kg per car for the 2040 conventional case seems to be achievable considering a total potential of Aluminium parts of about 300 kg for a conventional steel-based car, of which 160 kg are casting alloys and 140 kg wrought alloys [6 - 8]. The smaller amount of 250 kg assumed is due to the fact that especially many small cars will not reach this high Aluminium content. The share of other concepts already existing (such as space frame) is considered to stay the same. They have a significantly higher amount of Aluminium.

For the AIV case the average Aluminium weight of a car is assumed to be 400 kg, whereby the amount of castings remains constant at 130 kg. Using more Aluminium for body and frame, the share of wrought alloys increase to 67.5% in that case.

5.4 Development of primary and recycled material supply

European primary Aluminium production capacity is assumed to grow by about 900,000 t within the next decades. This will be the case if all planned smelter expansions and greenfield projects especially in Iceland will be realised. Further demand for primary material has to be met by a higher share of imports.

For the European situation on cast Aluminium in 2040 no imports and exports of recycled material are considered due to the fact that the production is met by the European supply of new and old scrap. For both 2040 cases the share of primary (20%) and secondary casting alloys (80%) are kept constant.

Table 2 summarises the chosen main assumptions, which determine the overall Aluminium system in general as well as the automobile system in particular.

Table 2: Main system assumptions

	2000	2040 conv.	2040 AIV
1. Cars produced [mill. cars]	14.8	17	17
2. Aluminium content per car [kg]	100	250	400
3. Share of casting alloys in automotive application [%]	71	52	32.5
4. Primary smelter production [1000 t]	3,801	4,700	4,700
5. Collection quota of ELV [%]	65	65	65

6 Results

The scenario results distinguish between demand and supply of primary and recycled material according to the described parameters. Changes of the automobile system cannot be described without discussing their impact on the overall Aluminium system.

To estimate the future demand of castings, rolled products and extrusions in the different fields of application and the availability of according secondary raw materials an existing model considering all application fields [9] has been used with updated parameters.

For this purpose, the effects of the specific variations in the automobile system are shown and the impacts on the overall Aluminium market are described.

6.1 Resulting demand for material in the European automobile market

The particular European metal demand for the automobile market is obtained by multiplying the specific use per car by the annual production figure, figure 7.

Due to the increasing share of wrought product use the growth of these materials is higher than for the castings, reaching nearly the same value of just above 2 mill. tonnes at the end of the calculation at 2040 for the conventional case. This means a doubling for castings and a factor of 5 for rolled, forged and extruded products in 40 years.

In the AIV case the demand for rolled and extruded parts reaches 4.6 mill. tonnes. While the amount of castings doubles, the wrought alloy products increase by a factor of about 10, overtaking the casting demand in 2010.

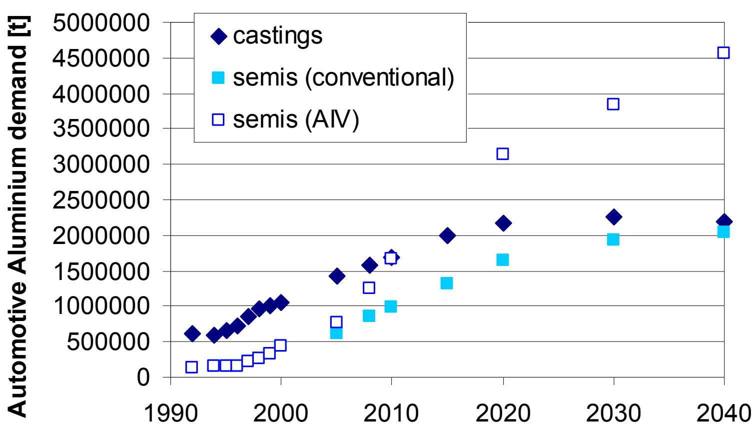

Figure 7: Development of Aluminium use in European cars

To determine the total metal demand for the automobile production (table 3) additional 20% of the product weight itself have to be considered due to fabrication scrap of car part manufacturing.

Table 3: Calculated demand for wrought and casting alloys in 1000 t

Aluminium demand	2000	2040 conv.	2040 AIV
Castings	1,310	2,750	2,750
Wrought products	540	2,540	5,710
Total	1,850	5,290	8,460

Considering also developments of the other sectors of the total European Aluminium system, the wrought alloy demand adds up to 5.8 mill. tonnes today, to 12.1 mill. tonnes for the conventional and 16.7 mill. tonnes for the AIV case in 2040. The casting alloy demand will rise from 2.1 mill. to 5.4 mill. tonnes.

Within this development the meaning of passenger car production will change according to the expected growth rates, figure 8 (see also fig. 5). The other use sectors are assumed to grow constantly. The share of automobile production in total Aluminium production will increase from 21.5% to a maximum of 35% and even 39% for the AIV case. Furthermore, the share of total transport is given which makes another 10% of the Aluminium demand in Europe.

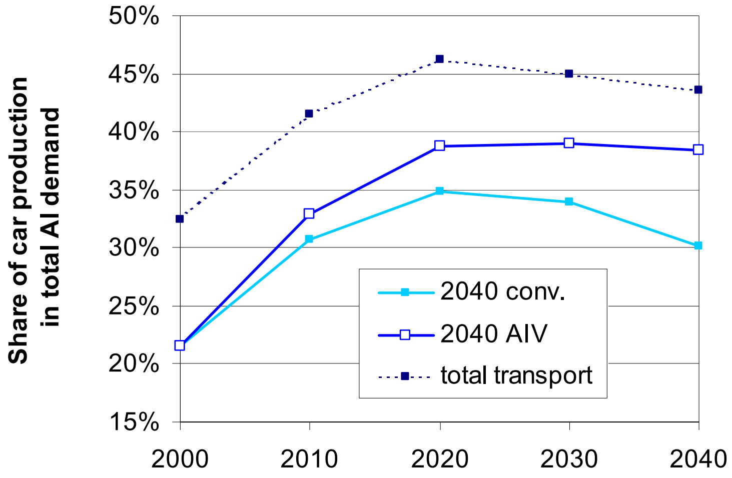

Figure 8: Share of automobile production in total Aluminium production

6.2 Supply of wrought and casting alloys for the automobile market

The supply of recycled material will change significantly by 2040. The improvement of the collection quotas of post-consumer and fabrication scrap and the metal yield of sorting, material processing and smelting will increase the total scrap amount from 3 to over 9 mill. tonnes. In figure 9 the development describing the different use sectors is shown for the conventional case. To handle this amount of scrap the refining and re-melting capacities (excl. in-house re-melting of semi fabrication) have to be more than tripled.

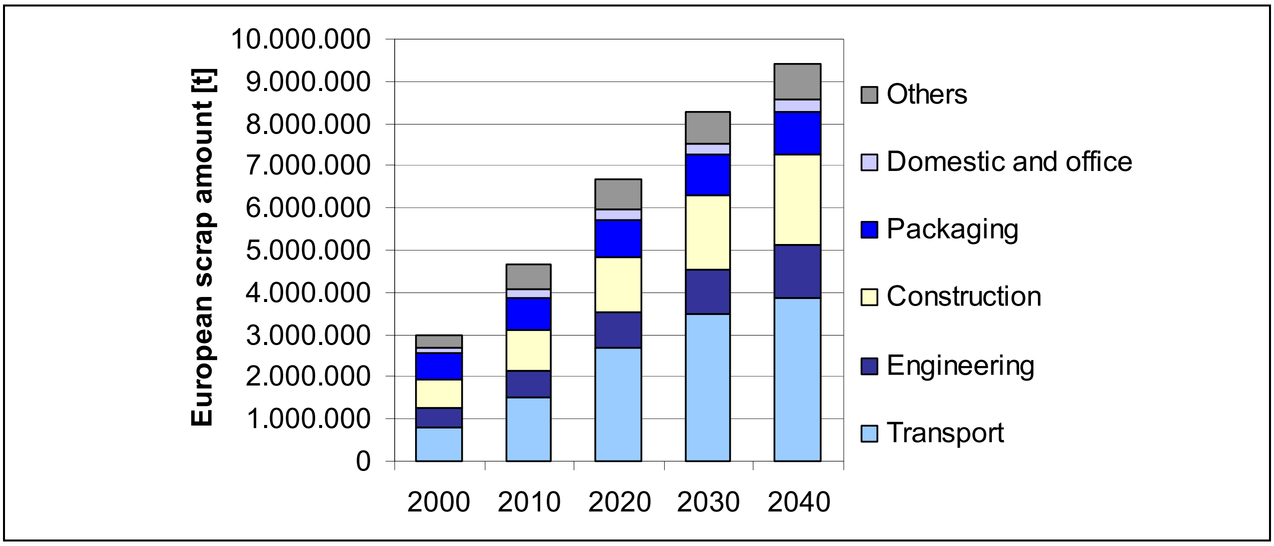

Figure 9: Development of European scrap amount for the conventional case

The supply of secondary raw material from the automotive application consists of new and old scrap. Main parameters are the car production itself, the lifetime of cars, and the amount of Aluminium used in cars. Additionally the amount of old scrap is depending on the collection quota (portion of recycled ELV of total de-registration) and the sorting technology. Table 4 shows the potential amount of old scrap from the automobile sector considering pure sorted fractions.

Table 4: Old scrap from the automobile sector in 1000 tonnes

	2000	2040 conv.	2040 AIV
Casting scrap	633	875	875
Rolled scrap	200	421	804
Extrusion scrap	170	324	662

Since closed loop recycling of Aluminium does only exist in some special cases, all scrap from fabrication and use is reused at its highest possible quality level to produce new alloys. Today, the automotive industry is the main “consumer” of recycling Aluminium.

To describe the effects of the different developments of demand and supply figure 10 compares the future casting demand with different scrap amounts. It can be seen, that the casting demand is exceeded by the old scrap amount due to its decreasing portion in automotive applications. Today about 50% of the casting demand could be covered by the available old scrap (de facto 35-40%, see also table 1). This potential will rise to 105% for the conventional and up to 125% for AIV case in 2040.

Adding the new scrap of foundry production, turnings and dross which can only be used for new casting alloys, the exceeding would take place much earlier. As a consequence the adequate use of post-consumer material will require effective sorting technologies. The amounts of casting scrap (new + old) and ELV scrap alone will also play a significant role of raw material supply, which is shown in figure 10 as well.

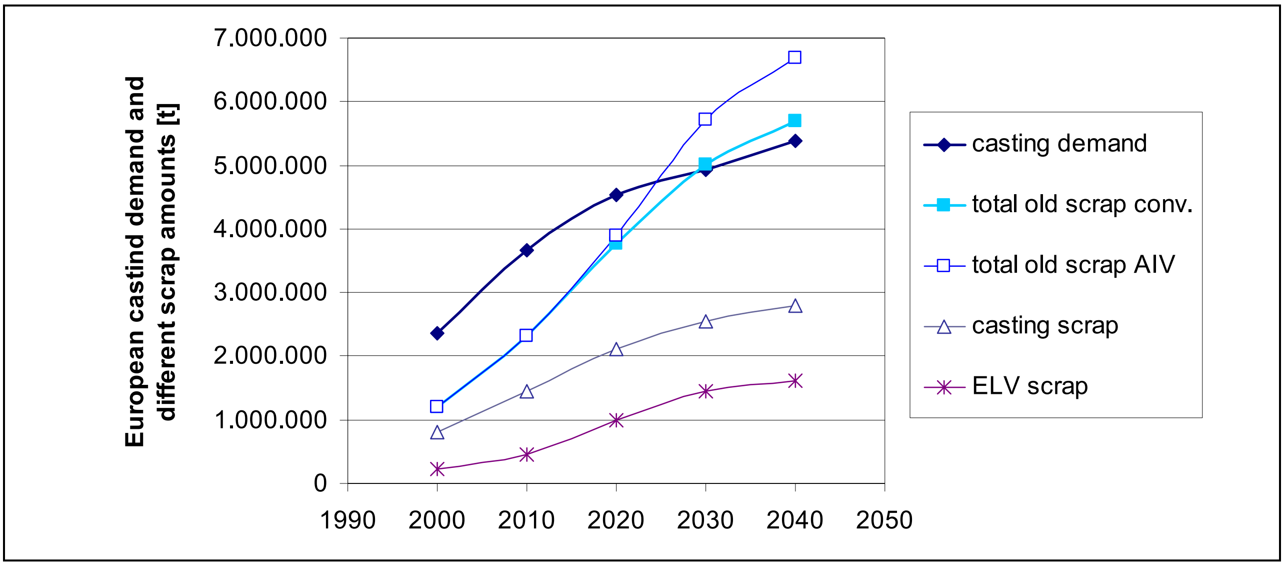

Figure 10: Comparison of the future casting demand with different scrap amounts

Another important measure of the recycling potential is the recycled content of Aluminium production which increases during the investigated period from 32.5 to 48% (46% AIV), see figure 13. This value is also strongly dependent on the growth of the other applications beside the automobile. The recycled content will increase even further if their growth rates will be lower than assumed, like the current situation in the building and construction industry indicates.

Finally, using all the available scrap sources within Europe, the change of import of primary Aluminium has to be discussed. Having the planned smelter expansions in Europe in place a remaining Aluminium demand of 5 mill. tonnes in 2040 (nearly 8 mill. t for AIV) has to be covered by imports, compared to 2.1 mill. tonnes primary import today. This will increase the import share of primary material from 36% to 51% for the conventional concept and 62% in the AIV case in 2040.

6.3 System's sensitivity

To evaluate the obtained outcomes a sensibility study is carried out by varying the main parameters for the 2040 conv. case. All results are mainly depending on the assumed parameters for car production and ELV collection. For the first appraisal the low production figures (fig. 4) are chosen (2040 conv. low pro.). In contrast to the high production case with max. 17 mill. produced cars in 2040 production is assumed to equal 15 mill. cars in 2040. In a second analysis the collection quota of ELV's is varied. It is assumed that the collection system improves and less ELV's leave the

European market (2040 conv. high coll.). Consequentially the collection increases to an implied quota of about 80% of de-registered cars.

The demand for material is only influenced by the change in production amount . In figure 11 the total demand for Aluminium for the automobile sector is compared. The lower car production of 2 mill. cars in 2040 leads to a decrease in the metal demand of nearly 30% accounting equalling 1.3 mill. tonnes material.

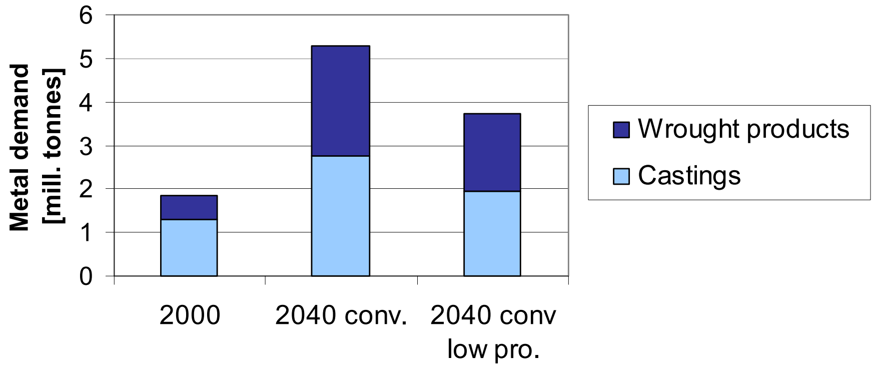

Figure 11: Metal demand of the automobile sector for different production amounts

The scrap supply is depending on both, the collection quota and the production amount. The development of the different cases and assumptions is compared in figure 12. It can be seen that the variation in the collection quota has an even higher influence on the results than the a change in production. A smaller production of 2 mill. cars but constant collection quotas reduces the scrap amount by 5% (430 thousand tonnes) in 2040. A higher collection quota but the same production development increases the occurring ELV scrap by 8% (800 thousand tonnes). Nevertheless, the difference between the conventional and the AIV case is bigger than the influence of the variation in parameter.

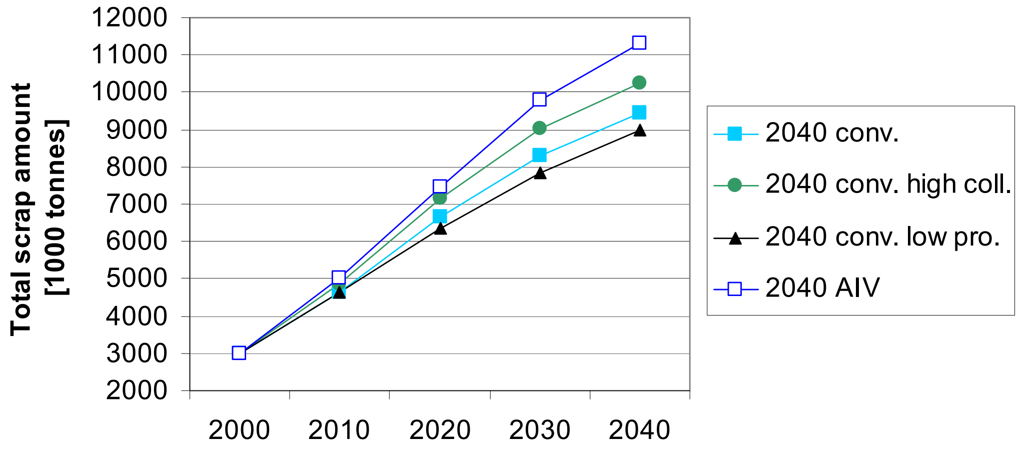

Figure 12: Development of total scrap amount

The change of total scrap amount will also have an effect on the recycled content of the European Aluminium supply. In figure 13 the development of the recycled content for the different calculations are presented. It is obvious that the analysis is highly sensitive to the assumption of the collection quota. Assuming the high collection quota the recycled content increases by 4%-points in 2040.

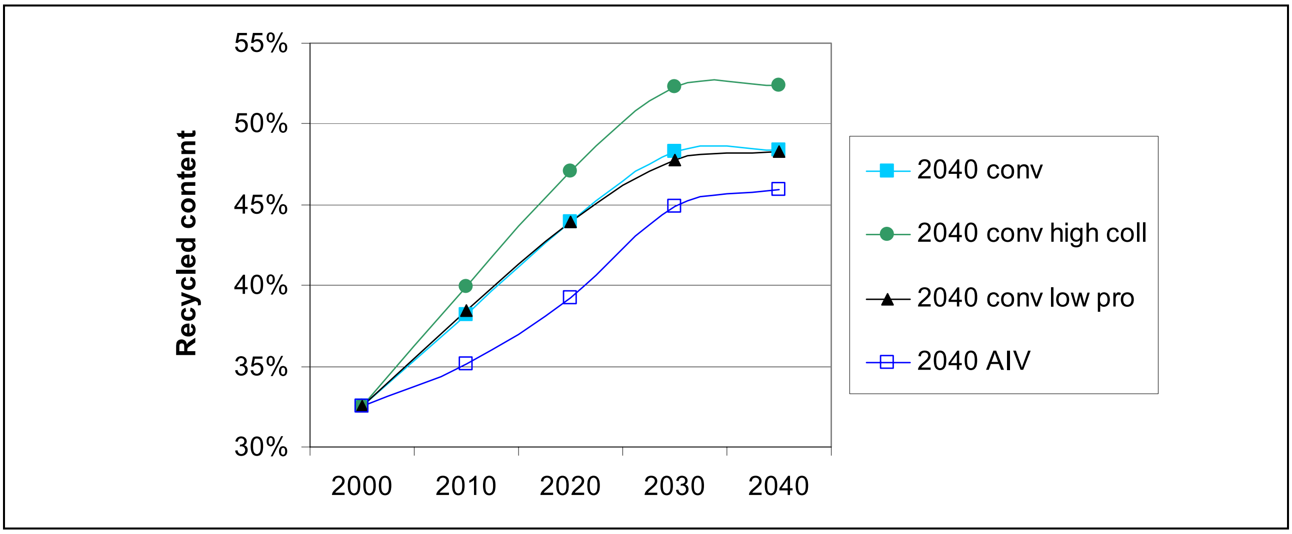

Figure 13: Development of the recycled content

Whereas the variation of production amounts has no influence on the content due to correlation of less generated new scrap and proportionally more old scrap in a lower car production system. Furthermore, the Aluminium content per car has a big influence. The higher amount in the AIV case leads to a smaller increase of the recycled content due to a super-proportional growth of Aluminium demand.

7 Conclusions

First of all, the long term developments of the European car industry show an increasing demand for Aluminium from 1.9 mill. tonnes today to 5.3 mill. tonnes and even to 8.3 mill. tonnes in 2040 considering the different developments in car concepts, of which casting alloys account for 2.8 mill. tonnes. Concerning the total Aluminium demand in Europe the share of car components will increase from 20 to 30%, while the growth of the other applications is constant and on a lower level. The estimated Aluminium content for the different car concepts dominates the trend of the results.

Like the demand primary and secondary metal supply will change significantly. Even though the European smelter production is assumed to grow by nearly one mill. tonnes imports of primary metal have to increase from 2 to 5 mill. tonnes in 2040 to cover the demand. For the AIV case even 8 mill. tonnes will be required. At the same time the scrap volumes will be tripled and the changing composition will make a sorting of at least wrought and cast alloys necessary.

A variation of the two parameters car production and ELV collection shows the sensitivity of the obtained results. As this two parameters are only roughly estimated further analysis is necessary to evaluate the results.

For the demand the system is less sensitive to car production than to the Aluminium content per car. The scrap availability acts similar and additionally the ELV collection quota has a smaller influence on the results than the Aluminium content of the cars. For the recycled Aluminium content of the overall system the car production has only a small influence but the calculations are strongly sensitive to the ELV collection quota (with similar effect) and the Aluminium content per car (with reverse effect).

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THE FUTURE OF AUTOMOTIVE ALUMINIUM*

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ABSTRACT

This paper presents different possible developments for aluminium in automotive applications describing the resulting impact on aluminium production and recycling. Based on detailed process chain modelling, the use of aluminium in the German car industry is analysed along the entire life cycle chain. To identify major innovations in the automotive industry several life periods of cars have to be covered, which was achieved by choosing 2040 as the target year. A variety of parameters influence the demand for metal (primary and/or recycled) and the availability of aluminium scrap. Investigated are market developments of automobiles in general, and design strategies for car components differentiating between conventional and aluminium-intensive constructions. For the analysis the automotive aluminium is classified into casting or wrought alloys, which have to be distinguished with regard to recycling aspects.

KEYWORDS

Automotive applications, recycling, process chain model, demand for metal, availability of scrap, aluminium-intensity, alloys

* Source: Proceedings of TMS 2002

Introduction

The growth of aluminium and the automotive sector is closely connected. The transport sector was the biggest end use sector of the European aluminium industry in 2000 accounting for 29% of demand. And it will become even more important. Within this sector the automobile plays the domination role (95% of the metal demand). Beside, the growth rate of the future automobile market, which will probably be moderate, the specific amount of aluminium used in cars is expected to increase much faster.
The entire German aluminium industry is affected by the developments. Using more and more extrusions and rolled products beside castings, the automotive sector covers the variety of production paths.
The facet of greatest concern for this paper is the availability of primary and recycled aluminium. This is strongly influenced by the car industry being the biggest old scrap-producing sector and the biggest user of new and old scrap at the same time. In 1997 about 40% of the total amount of scrap (without in-house scrap) was reused in the automotive sector.
This paper points out the effects various developments of the use of aluminium in the automotive sector will have on the German aluminium industry with regard to production of primary aluminium and the use of scrap up to the year 2040. Using a scenario technique the differences between an increasing use of aluminium in conventional cars concepts and in aluminium-intensive vehicles (AIV) are shown. According to the scenario technique, the results should not be interpreted as a prediction of the automotive market in the future but rather as 'what would happen if' case studies for the aluminium supply chain.

The "automotive aluminium" scenario

Looking a good way into the future the amount of produced and used cars, the automotive design and therefore the amount of aluminium used in cars will change. Additionally, the supply of primary and recycled metal, whether domestic or imported, will alter. To show the impact of different possible developments on the German production situation a scenario technique is used. The investigations consider the aluminium supplying industry with semi-finished products and castings, and also the existing recycling industry for end of life vehicles (ELV). For the chosen example, the changes of primary and recycled aluminium both in demand and supply and the resulting import situation is modelled. To show different developments the scenario approach is carried out in three steps:

1. Base case 1997 (**1997**): The case shows the domestic market supply for Germany for the base year 1997 (including import and export of primary and recycled aluminium, its pre-products and the recycling of automotive aluminium).
2. Conventional concepts 2040 (**2040**): For the second case an increasing use of aluminium in cars for the target year 2040 is assumed, considering the conventional steel-based concepts utilized today. Nevertheless, the proportion of aluminium components is much higher than today.
3. Aluminium-intensive vehicles 2040 (**AIV**): The third case reflects a widespread use of aluminium-intensive vehicles also including new concepts.

The results of all three cases are compared resulting in conventional and aluminium intensive demand and supply situations for primary and recycled aluminium in a long-term time frame.

The investigated aspects comprise 'German car market', 'Aluminium use in cars', 'Wrought and cast products', 'Primary and recycled material'.

The overall German aluminium system in 1997

To analyse the material and energy flows of aluminium a process chain model has been developed [1]. Within this model production, use and recycling of aluminium products is divided into individual processes which are represented by technology-specific and location-independent modules. They can be seen as entities of a production system, each of which has specific inputs and outputs of materials, energies, emissions and products taking distinct natural and technical properties into account. The process chain model describes the aluminium flow from bauxite mining to the production of aluminium products including primary smelting and recycling of fabrication and post-consumer scrap.
Considering the high metal demand of the German aluminium manufacturing industry, it is obvious that the metal supply is strongly import-dependent. In 1997 casting alloys had an import rate of 38%, alloyed primary aluminium 47%, and unalloyed primary aluminium 55%, respectively.
The main exporting countries for alloyed wrought material used in the investigated system are Norway (43%), UK (26%), Iceland (10%), France (8%), Russia (7%), Canada and Brazil less than 5 %. Only for alloyed aluminium imported from the UK and France is a recycled content of 43% estimated. The other countries produce alloyed material mainly from primary aluminium with added alloying elements.

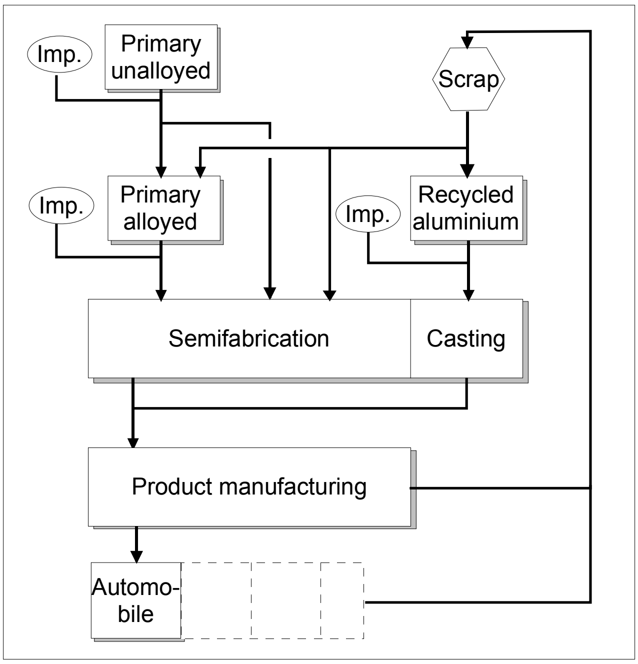


Figure 1: Schematic German aluminium system and its implications for the automotive market

For the explicit analysis of the German automotive system only a few of the technology modules available in the process chain model are necessary. Nevertheless, the overall material flow of aluminium for domestic use and export has to be considered. The total metal demand in 1997 was about 2.5 million tonnes and domestic end-use more than 1.3 million tonnes. Figure 1 charac-

terises the interconnections of primary and recycled materials which are representative of the automotive sector as well as for every other application. Changes in any of the application areas will have an influence on the overall system and therefore affect the supply situation as well.
New scrap or alloying elements are added to unalloyed primary aluminium produced from bauxite in primary smelters and either cast into rolling slabs for strip and sheet production, extrusion billets or used for primary casting alloys (see also figure 2). Another group of wrought alloy producers are the remelters using mainly fabrication scrap and primary ingots. Strip and sheet production is done by conventional hot and cold rolling. Extrusion processes are used to produce the various extrusion products (forgings are not considered exclusively and are included in the extrusion process flow). The picture for wrought alloys, however, is quite complex, due to the different scrap supply for low, middle and high alloyed materials. In particular, for 1997, the following recycled contents have been calculated from German industry and literature data: extrusion and forging alloys 47%, low alloyed rolling material 35%, middle 80% and high 65%. Unalloyed material usually has no recycled content.
A third group, the secondary smelters (refiners), use old and new scrap, turnings and dross as raw materials to produce casting alloys, so that the recycled content of these alloys is nearly 100%. On the other hand, primary casting alloys are made of 100% primary metal. The cast processes considered are die and mould casting.

The German automotive system

In 2000 German automotive production was the third biggest worldwide only outnumbered by the USA and Japan [2]. As a consequence, the German supplying industries are quite big as well. First the modelled system, including the assumptions for the base case 1997, is presented.

Production of semi-finishes and castings for car components

Automotive aluminium applications cover nearly the whole range of semi-finished products and castings, figure 2.

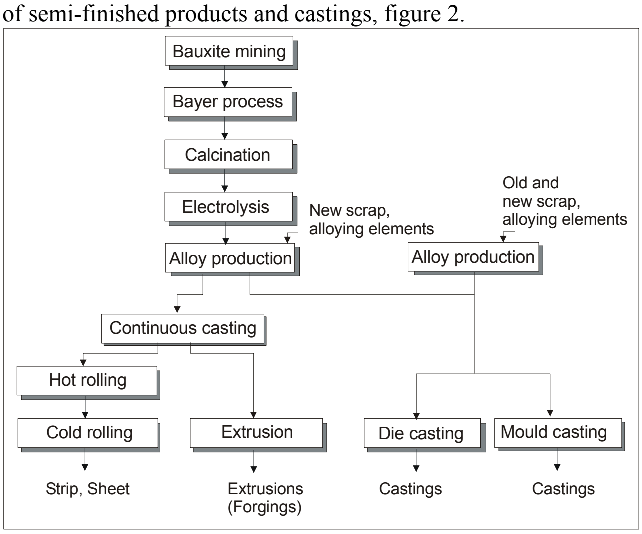


Figure 2: Production scheme for semi-finishes and castings for the automotive sector

In 1997 the main material for automobile components was casting alloys with a share of 78%. 80% of which is produced from recycling material by the refiners. The remaining 20%, the so-called primary casting alloys, are supplied by primary smelters.
The most widely used casting alloy for nearly all kinds of automotive applications is the AlSi9Cu3 alloy with a share of about 50% of all castings. In addition, the eutectic AlSi12 and the AlSi10Mg are the most important alloys with a share of 16 and 12%, respectively. The latter has nearly doubled in the last 4 years.
In the case of the primary casting alloys there is an increasing application of the AlSi7Mg alloy for safety components like wheels and brake parts. Table I shows some typical automotive alloys and their application share [3-5].

Table I Alloy composition of automotive aluminium

Alloy type	AA No.	Notation	Share
casting alloys (78%)	A 359	AlSi9Cu3	48%
	A 356	AlSi7Mg	20%
	A 361	AlSi10Mg	12%
	-	AlSi12Cu	9%
	A 413	AlSi12	7%
	A 332	AlSi12CuNiMg	4%
wrought alloys (22%)			
of which - extrusions	6060	AlMgSi0.5	35%
- forgings	6082	AlMgSi1	11%
- rolled	3003	AlMn1	10%
products	5182	AlMg4.5Mn0.4	9%
	5754	AlMg3	14%
	6016	AlSi1.2Mn0.4	15%
	7020	AlZn5.4Mg1	6%

Table I also shows the most representative wrought alloys used for example for radiators (3003), forged wheels (6082), bumper beams (7020), internal (5182, 5457) and external (6016) structural parts [4-8]. The wrought alloys used for the calculation are divided into extrusions (46%), low alloyed rolled products (25%) and high alloyed rolled products (29%).

Recycling of cars

In 1997 3.4 million cars were deregistered, of which only 40% remained in Germany for recycling (figure 3).

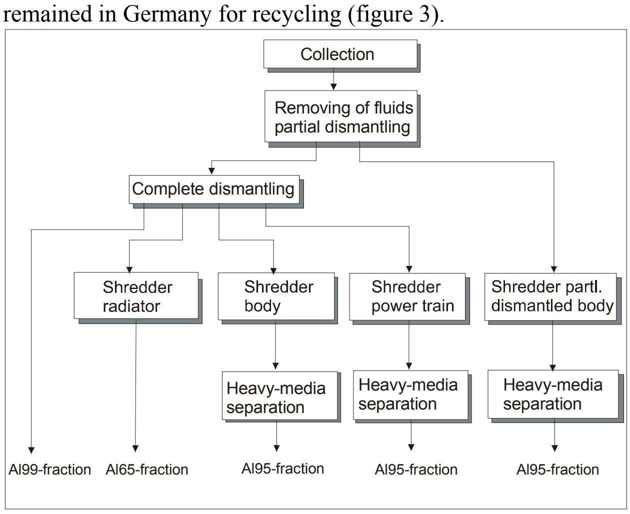


Figure 3: Recycling system of ELV in Germany

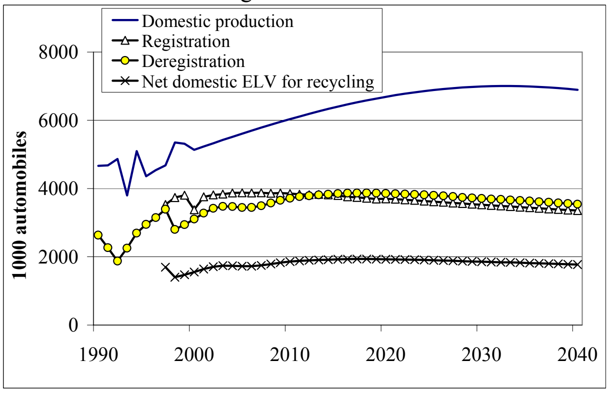
The rest was exported mostly to Eastern Europe for further use [9]. After removal of all fluids the cars are partly dismantled. Tyres together with rims, batteries and the catalysts are removed. The rims are sold directly to the secondary smelters. About 60% of the partly dismantled cars are completely dismantled. The other 40% partly dismantled and the dismantled bodies, power trains and radiators are then shredded. Except the radiators, whose copper-aluminium mix is directly used as alloying material in recycling plants, the other shredder outputs are further processed in a subsequent heavy-media separation to reclaim the aluminium. So far no distinction between wrought and cast alloys can be made. All fractions can then be smelted either for closed loop production of new automobile casting components (8%) or casting products of other aluminium systems.

Development of metal demand and supply

The main parameters of the metal demand in the car industry are car production itself, the average aluminium content per car, the share of wrought and cast alloys, and the share of primary and recycled material.

Development of the German car market

Figure 4 gives an overview of the current development of the German car market and a projection up to 2040. In 1997 domestic production of cars amounted to 4.7 million, 3.5 million cars from domestic production and imports were registered in Germany and 3.4 million cars were deregistered.



Source: VDA Statistics [2], own calculations
Figure 4: Development of German car market

Studies of the German automobile market covering the time horizon to 2040 are not available. To develop figures necessary for the analysis, assumptions for automobile production, registration, deregistration and recycling of ELV were worked out, based on plausible economic and demographic projections and existing studies with shorter time horizons [10]. Nevertheless, the figures should be used with caution and should not be interpreted as a prediction, because in the long time span until 2040 different developments are possible.
The assumptions for car market development are as follows:

- Domestic automobile production growth, but decreasing growth rates up to 2040;
- Decreasing population;
- Decreasing registrations after 2010;
- The technical lifetime of cars is normally distributed with a median of 12 years;
- In 1997 the net domestic supply of cars for recycling after export of complete cars or car bodies equals 40% of deregistered cars, because of the high quality level of used German cars and the resulting export potential. It is assumed that this rate will not change until 2040, although recently initiatives to change the regulations of ELV in the European Union have been undertaken.

For the year 2040 domestic production of cars is assumed to be 6.9 million. 3.4 million cars from domestic production and imports will be registered and 3.5 million cars will be deregistered, representing only a minor shift from the 1997 situation. Resulting net domestic supply of cars for recycling will therefore be 1.4 million. This assumed development will be the same for the conventional case and for the AIV case.

Development of aluminium use in cars

Looking at the average annual growth rates of aluminium used in conventionally designed cars (figure 5) it is obvious that in the ongoing decade the highest average growth rate of 7.4% can be expected. This is due to the current trend for car manufacturers to use, besides aluminium castings for engine, gear box, chassis and suspension, more and more wrought alloys for hang-on parts of the bodywork. For the AIV case the growth rates show a similar trend only with higher values (8.8% in 2000 - 2010).

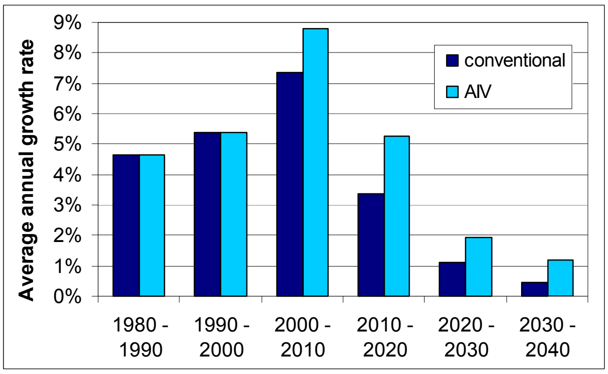


Figure 5: Estimated development of average annual growth rates of aluminium used in cars (own calculations)

The absolute amounts of aluminium used in cars for the conventional case in figure 6 underlines the current trend of growth rates described above.

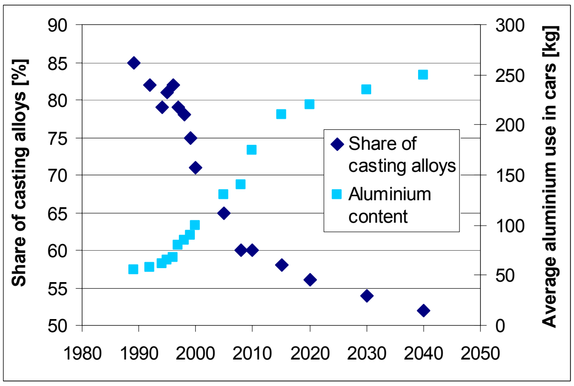


Figure 6: Development of aluminium used in cars for the conventional case

Especially the high growth rate between 2000 and 2010 is obvious. The average aluminium content of a passenger car will increase from 100 to 250 kg from today's amount within the next few decades, while the share of castings will decrease from about 75% to nearly 50% in the same period. The figures were assembled from the end-use statistics of GDA up to 2000 [11] and many different estimations from the aluminium industry (Pechiney, VAW, Alcan-Alusuisse, EAA, GDA) and the car industry (PSA Peugeot Citroen, Audi, Ford) [12-16].

Development of wrought and cast products

The amount of 250 kg per car for the 2040 conventional case seems to be achievable considering a total potential of aluminium parts of about 300 kg for a conventional steel-based car, of which 160 kg are casting alloys and 140 kg wrought alloys [5, 8, 16]. The smaller amount of 250 kg assumed is due to the fact that especially many small cars will not reach this high aluminium content. The share of other concepts already existing (such as space frame) is considered to stay the same. They have a significantly higher amount of aluminium.
For the AIV case the average aluminium weight of a car is assumed to be 400 kg, whereby the amount of castings remains constant at 130 kg. Using more aluminium for body and frame, the share of wrought alloys increase to 67.5% in that case.
A comparison of statistics and the calculations of metal demand show that about 80% of the metal supply of the automobile industry can be found as aluminium products in the car itself. The other 20% is mainly necessary because of the occurrence of fabrication scrap during end-product manufacturing and the supplementary production of spare parts. This ratio is assumed to remain constant in spite of improved production technologies, because the increasing share of wrought alloys application with higher scrap rates will compensate this trend.
The particular German metal demand is then obtained by multiplying the adapted specific demand per car by the annual production figure, figure 7. Due to the increasing share of wrought product use the growth of the semi-fabricated products demand is higher than for the castings, reaching nearly the same value of 1,100,000 tonnes at the end of the calculation in the year 2040 for the conventional case. This means a factor of 3 of growth for castings and a factor of 10 for rolled, forged and extruded products in 40 years.
In the AIV case the demand for semis reaches 2,330,000 tonnes. While the growth for castings stays constant at the threefold amount, the wrought products increase by a factor of 22, overtaking casting demand in 2015.

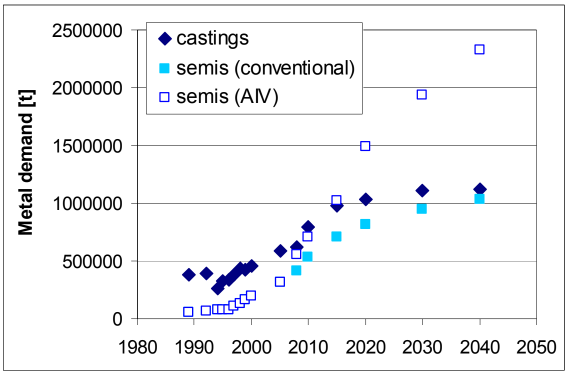


Figure 7: Development in aluminium demand of German car manufacturers

Development of primary and recycled material supply

German primary aluminium production is assumed not to exceed 700,000 t in 2040 due to the lack of raw materials and cheap (hydro) power for both the conventional and the AIV case. Further demand for unalloyed and alloyed material has to be met by a higher share of imports.
The supply of recycled material will change significantly by 2040. The improvement of the collection quotas of post-consumer scrap and the metal yield of sorting, material processing, and smelting will increase the average recycled content of aluminium alloys for the domestic market supply from 46 to 56% (54% AIV) [17]. For 2040 no imports and exports of recycled cast aluminium are considered due to the fact that the production is met by the German supply of new and old scrap. For both 2040 cases the share of primary (20%) and secondary casting alloys (80%) are kept constant at that of 1997. To satisfy the secondary casting demand, besides the total cast scrap amount, which can only be remelted into casting alloys, additional wrought scrap has to be used. For automotive alloys the latter is taken from end of life vehicles. Using improved sorting technologies wrought and cast material will be obtained separately.

Table II summarises the chosen main assumptions, which determine the overall aluminium system in general as well as the automobile system in particular.

Table II Main system assumptions

	1997	2040	AIV
1. Cars produced [million cars]	4.7	6.9	6.9
2. Aluminium content per car [kg]	79	250	400
3. Share of casting alloys in automotive application [%]	78	52	32.5
4. Share of primary casting alloys in total foundry production [%]	20	20	20
5. Material spare parts, scrap [%]	80	80	80
6. Import share of recycled aluminium [%]	37	0	0
7. Export share of recycled aluminium [%]	12	0	0
8. Primary smelter production [1000 tonnes]	570	700	700
9. Collection quota of ELV [%]	40	40	40

Results

Taking all the described developments of the various parameters into account the impacts on the system can be determined. Changes of the automobile system cannot be described without discussing their impact on the overall aluminium system. Therefore, the effects on the overall aluminium market are described first before the specific impacts on the automobile system are shown. The various connected results are then described.

Resulting demand of material for the German automobile market

If the German aluminium industry in the sector of semi-finished products remains strongly export-oriented as it is today the production of these products in the overall aluminium system will increase from 1.8 to 5.7 million tonnes by 2040 and to as much as 7.1 million tonnes in the AIV case, while the castings production arises from 0.5 million to 1.5 tonnes in both cases.

The metal demand for the automotive system is mainly determined by the assumptions of car development and the amount of aluminium in cars (see table II). Table III shows the resulting demands for aluminium products.

Table III Comparison of 1997 and 2040 systems parameters and calculated demand for wrought and casting products

		1997	2040	AIV
Casting products	%	78	52	32.5
	1000 tonnes	359	1,121	1,121
Wrought products	%	22	48	67.5
	1000 tonnes	105	1,035	2,329
Total demand	1000 tonnes	464	2,156	3,450

464,000 tonnes of aluminium products were necessary for the production of 4.7 million cars in Germany in 1997, bearing in mind that 20% of the material is either scrap from end product manufacturing or used for spare parts production. With the estimated production of 6.9 million cars in 2040 the material demand for the two cases varies between 2.2 and 3.5 million tonnes of aluminium because of the different aluminium content of the cars. While in both 2040 cases the demand for castings increases from nearly 360,000 tonnes in 1997 to 1,121,000 tonnes, the situation for wrought material differs. The demand increases from about 100,000 tonnes in the base year to 1,035,000 tonnes in the conventional case and to 2,329,000 tonnes in the AIV case.

Resulting supply of wrought and casting alloys for the automobile market

The domestic supply of the German market in 2040 will be determined by the production capacity of primary smelters and the supply of scrap for secondary smelters. Since, like the market for automobiles, the other aluminium markets will increase the total scrap amount available in Germany will increase as well.

For secondary castings it is assumed that no imports of cast products will take place because the German demand can be satisfied by these amount of scrap. This implies that the 1997 German production must be nearly tripled by 2040 from 430 to 1,180 thousand tonnes.

At the same time, the amount of surplus scrap which goes to the remelters increases significantly and substitutes primary metal. The supply increases from 190 thousand tonnes in 1997 to 950 thousand tonnes for the conventional case, and 1,660 thousand tonnes for the AIV case, respectively. This yields a higher recycled content of wrought material produced in Germany because the production of primary metal is assumed only to increase slightly from 570 to 700 thousand tonnes.

For the 1997 base case, it was possible to determine the recycled content differentiating between the various wrought alloy groups (low/medium/high alloyed, rolled/extruded) (table IV). The detailed information necessary to obtain the different amounts is not available for the 2040 cases. Therefore only overall results for wrought products are obtained, considering the German primary production and scrap supply. Table IV shows the various recycled contents of wrought products, due to the small growth of primary capacity and significant increase in fabrication and post-consumer scrap.

Table IV Recycled content of wrought material for the German aluminium system in %

	1997	2040	AIV
Rolled (low)	35		
Rolled (medium)	80		
Rolled (high)	65		
Extruded (low)	47		
Average	43	78	85

These are the average shares of recycled aluminium for the entire German wrought aluminium system. The specific values for the automobile production or other applications cannot be separated. It is assumed that the supply from the German system to the automotive sector is prorated according to the share of demand.

Besides the changing demand, the described developments of the automobile systems also yield different amounts and qualities of old scrap. Table V shows the estimated old scrap from the automobile sector for the different 2040 cases, considering car production itself, the lifetime of cars, and the amount of aluminium used in cars.

Table V Old scrap from the automobile sector in 2040 in 1000 tonnes

	2040	AIV
Casting scrap	258	258
Rolled scrap	124	243
Extrusion scrap	96	194

As described earlier, the wrought old scrap from the automobile sector is used to fill the gap between the demand for cast alloys and the supply of cast new and old scrap. For both 2040 cases this gap is 234 thousand tonnes. For the conventional case, wrought old scrap just meets this amount. Looking at the scrap supply of the German secondary smelters [18], turnings and dross are also main input materials and can only be handled by the smelters. Consequently the old scrap has to be separated into cast and wrought scrap. Without strictly differentiated sorting into wrought and cast alloys there would just be mixed scrap only reusable to produce cast alloys. The German demand for secondary castings would not be high enough to handle the resulting amount of old scrap plus turnings and dross. The oversupply of cast alloys would have to be exported, but at the same time more wrought alloys would have to be imported. With a higher wrought alloy amount in cars for the AIV case this separation becomes even more essential.

Resulting import shares for the automobile market

While the German castings demand will be met by the German scrap supply, wrought unalloyed and alloyed material has to be imported to satisfy demand. The import rates will increase from 55 to 79% for unalloyed primary aluminium, and from 47 to 69% for alloyed primary aluminium, and 76% for AIV, respectively, for the overall German aluminium sector. The share of recycled content for the exporting countries France and UK will also increase to 50% while the other countries will still produce the alloyed aluminium at primary smelters.

Looking exclusively at the automotive sector, a separate picture emerges. Mainly alloyed components are used for car production. Figure 8 shows the import shares for the 1997 system but also those for 2040 resulting from the assumed production capacities for primary and recycled aluminium and the demand for car production.

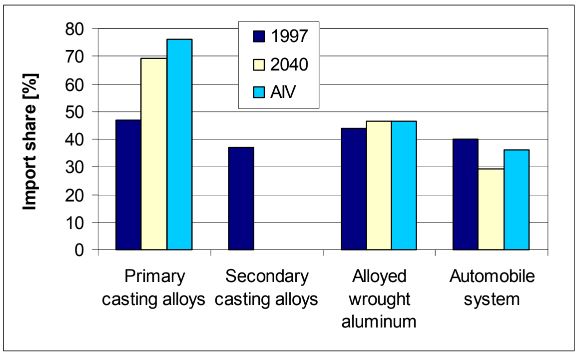


Figure 8: Import shares for the 1997 and the 2040 cases in % for materials used in German automobile system

German primary aluminium production is assumed not to follow the increasing demand. Therefore the import shares for the production of primary castings produced at primary smelters must increase in the same way as the imports of primary alloys. For secondary castings no imports were assumed in the future. To determine the import share for alloyed wrought aluminium besides the change in the import situation of primary alloyed material the increasing supply of scrap on the German market has to be considered. The import share, however, still has to increase less than for primary alloys. It can be seen that for the total automobile system the import share decreases by 2040 (from 40 to 29%) for the conventional case because the domestic produced secondary castings are still dominant. In the AIV case the wrought alloyed components with their high share of 67.5% cause a smaller decrease of the import share (36%).

Material flows of the total automobile system today and in the future

So far the impacts of the assumed developments on the overall aluminium system and the automobile system in particular have been described. Using the process chain model material flows of the total automobile system are obtained. Therefore, changes of the German automobile system and the adapted import situation must be combined. In table VI the shares of recycled aluminium from the domestic German automotive system are compared to those including the necessary imports.

Table VI Recycled content for the 1997 and 2040 cases in % for the Germany automobile system with and without imports

	1997		2040		AIV	
	FRG	Incl. Imp	FRG	Incl. Imp	FRG	Incl. Imp
Primary castings	0	0	0	0	0	0
Secondary castings	100	100	100	100	100	100
Wrought alloys	43	26	78	41	85	44
Total autom. system	79	70	88	64	90	58

The situation for Germany and the countries which export primary castings to Germany are similar with no recycled content. In 1997 secondary castings are produced by using exclusively scrap in all countries considered. The two 2040 cases have no imports and exports for secondary castings, so that the German situation equals the overall casting system. For the wrought alloys recycled content including the imports is smaller than the German one due to the fact that more than 65% of the countries exporting wrought alloys to Germany produce their alloys only from primary metal. Looking at the total automobile system in Germany, the recycling share increases due to the higher amount of available scrap and only a moderate increase in the production of primary metal. Also including imports the effects are reversed. The increase of scrap cannot compensate the increasing demand due to the time lag in occurrence, so that wrought aluminium has to be imported (with low recycled content). Assuming that the production of recycled aluminium needs less energy, an increase in aluminium in cars would yield a reduced specific energy demand for the domestic German system but a rising specific energy demand for the total automobile system, due to the import countries.
The absolute amounts of primary and recycled alloys of the automobile system in Germany and the import countries are shown in table VII for all three cases. The growth rates for primary or recycled material vary for the different subsystems (Germany/import countries). While the German increase of a factor of 5.9 from 1997 to the AIV case is mainly due to increasing scrap availability, for the import countries the growth of 6.2 can only be met by higher primary production.

Table VII Demand of primary and recycled aluminium for the automobile system from the German market and resulting imports in 1000 tonnes

		FRG	Imports	Total
Primary alloyed	1997	80	115	195
	2040	200	750	950
	AIV	250	1,400	1,650
Recycled alloyed	1997	300	150	450
	2040	1,500	150	1,650
	AIV	2,000	250	2,250
Total automobile system	1997	380	265	645
	2040	1,700	900	2,600
	AIV	2,250	1,650	3,900

The total automobile system considering Germany and the import countries has a growth rate of 4 for the conventional case and of 6 for the AIV case. While the automobile system had a total demand of 645,000 tonnes in 1997 in Germany and those countries which supply Germany with alloyed material, the system needs 2,600,000 tonnes for the conventional steel-based concepts in 2040. Aluminium-intensive vehicles would even yield a demand of 3,900,000 tonnes. In contrast to the calculated demand for products in table III, fabrication scrap of the entire processing chain is included here. In figure 9 it can be seen that the German system increases more than that of the import countries. This is expected because the additional amount of scrap is supplied only to the domestic system.

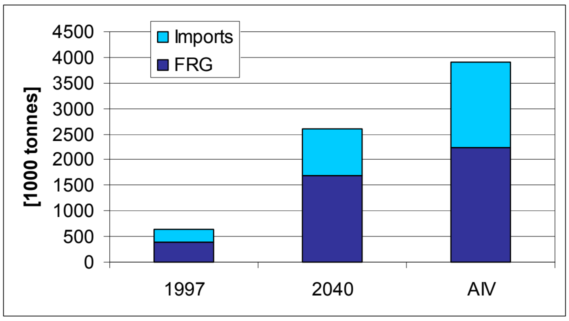


Figure 9: Total amount of material for the German automobile sector including imported material

This is also obvious in figure 10 where the particular primary and recycled amounts are shown for the domestic and the import situation for the three cases. It also shows the dimension of the necessary extension of capacity, especially for the German refiner and remelter industry. However, the additional demand for primary alloyed material of 635 thousand tonnes for the conventional case or as much as 1,285 thousand tonnes for the AIV case cannot easily be satisfied by the existing system. With recently implemented new smelters having a capacity of about 300 thousand tonnes that would mean between 2 to 4 additional new smelters entirely used to supply the German automobile market. Keeping the growth rates in mind (figure 5), this capacity expansion has to happen within the next 10 – 15 years.

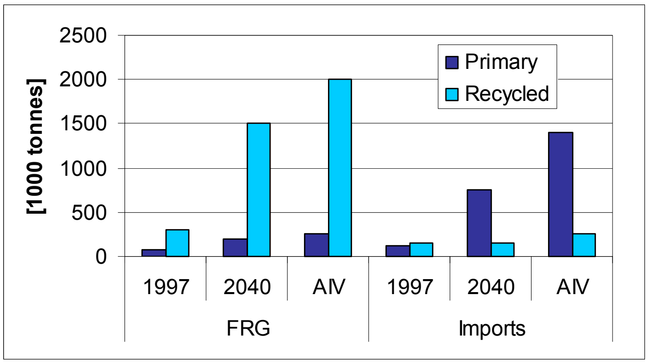


Figure 10: Primary and recycled material for the automotive system distinguishing between domestic and foreign supply

Conclusion

Different developments in the use of aluminium in cars are possible. A scenario approach has been used to show the effects various concepts would have on demand and also on the supply of wrought and casting alloys in the German aluminium industry in general and the automotive industry in particular. A differentiation was made between the conventional steel-based and an aluminium-intensive concept. By choosing 2040 as the target year it was ensured that enough time for changes within the system was considered. The development of the main parameters, car production itself, the average aluminium content per car, the share of wrought and cast alloys, and the share of primary and recycled material had to be described first.
The increasing production of automobiles from 4.7 to 6.9 million cars and the different concepts will yield a higher demand of aluminium products in 2040 rising from about 460 at present to 2,160 and 3,450 thousand tonnes. At the same time the scrap amount usable for the German system will increase. Nevertheless, with an increasing share of aluminium-intensive vehicles an improvement in sorting technology is necessary to separate wrought and casting alloys because the absolute amount of old scrap is higher than the casting demand. While the higher scrap availability benefits the German market, the recycled content of the overall system decreases. The demand for wrought alloys is increasingly satisfied by imports.
The total automobile system will grow fourfold for the conventional case and sixfold for the AIV case. This can only be met by extending both the secondary smelting system in Germany and the primary production in countries exporting to Germany.

The results should be considered to show trends and orders of magnitude for automotive metal demand based on the scenario technique used. They should not be misunderstood predictions.

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GRUNDLEGENDE ENTWICKLUNGSTENDENZEN IM WELTWEITEN STOFF-STROM DES PRIMÄRALUMINIUMS*

(BASIC TRENDS IN THE GLOBAL MATERIAL FLOW OF PRIMARY ALUMINIUM)

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ABSTRACT

The Collaborative Research Center 525 „ A Resource-Orientated Analysis of the Metallic Raw Materials Flows“ aims to develop operative recommendations for a resource-sensitive utilisation of metallic raw materials. The objects of research are the primary production processes of metallic raw materials, secondary production processes (recycling) and disposal. The survey will take particular account of economic and environmental factors alongside technical considerations.

For this purpose, among other models a computer-based partial equilibrium model of the global aluminium industry is developed to demonstrate the cause-and-effect relations behind the resource flows. The model simulates a competitive global market for primary aluminium and intermediate products. Allocations depend on demand, resource endowments, technologies, and instruments of economic policy. The model contributes to give an explanation of empirical observations on global level with regard to production structures, industry relocation, technological progress and environmental impacts. Besides investment, production and international trade, the global model as well assesses future developments of emissions for all main processes and regions.

The model describes the global aluminium industry from bauxite mining to primary aluminium smelting. Assuming different growth rates of primary aluminium demand, its impacts to the investment and production allocation of the global aluminium industry, as well as energy use and correspondig emissions of carbon dioxide (CO_2) and emissions of perfluorinated hydrocarbons (CF_4, C_2F_6) are demonstrated.

KEYWORDS

Global aluminium industry, energy use, GHG, CO_2, CF_4, C_2F_6, partial equilibrium model

* Source: Schwarz, H.G.: Grundlegende Entwicklungstendenzen im weltweiten Stoffstrom des Primäraluminiums. Schriftenreihe des Forschungszentrums Jülich, Reihe Umwelt, Bd. 24, 2000.

ALUMINIUM
- SUPPLY AND INTERNATIONAL TRADE -*

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ABSTRACT

Primary aluminium processing is characterised by multistage processing in production locations, which are predominantly geographically distant from demand centres. While, for example, large primary aluminium production facilities are located in Canada or Australia, the main demand regions are the USA, EU-15, and the Far East. Consequently, at each processing stage international trade is important to link demand and supply. The importance of trade differs not only between each processing stage. Also, the importance of international trade varied in the last century and will presumably change in the future. The relevance of international trade is influenced firstly by the ability of exporting regions to competitively supply their output. On the demand side, preferences and politics in demand regions also affect the importance of international trade.

The objective of the paper is to analyse the determinants influencing the production of and trade in bauxite, alumina, and primary aluminium. In the discussion we differ between determinants which are given for firms, but are not set by the government, and those which are set by policy-makers either on a local or national level. Using simulation technique the presumable development of production and trade in the current decade is analysed, although not all the determinants mentioned are considered.

KEYWORDS

Primary aluminium, international trade, imports, exports, subsidies, tariffs, electricity prices, partial equilibrium model

* Source: STE-preprint 14/2002

1. INTRODUCTION

Primary aluminium processing is characterised by multistage processing in production locations, which are predominantly geographically distant from demand centres. While, for example, large primary aluminium production facilities are located in Canada or Australia, the main demand regions are the USA, EU-15, and the Far East. The principal production processes consist of bauxite mining, alumina refining, and primary aluminium smelting. Consequently, at each processing stage international trade is important to link demand and supply.

The importance of trade differs not only between each processing stage. Because of its low added value the share of internationally traded bauxite in world bauxite mining is rather low, compared to that of traded primary aluminium: in 1995 30% compared to 45%. Also, the importance of international trade varied in the last century and will presumably change in the future. In 1960 one fifth of world primary aluminium production was internationally traded; in 1999 slightly less than 50%.

The relevance of international trade is influenced firstly by the ability of exporting regions to competitively supply their output. The capacity to do so depends on several determinants, which can be influenced either by firms (e.g. management of chosen technology) or by government (e.g. taxation). Moreover, the resources of a region (e.g. bauxite deposits) are essential. On the demand side, preferences and politics in demand regions also affect the importance of international trade.

The aim of the paper is to analyse the determinants influencing the production of and trade in bauxite, alumina, and primary aluminium. The considered factors are beyond the control of firms. In the discussion we differ between determinants which are given for firms, but are not set by the government, and those which are set by policy-makers either on a local or national level. The former include the availability of bauxite and energy carriers. The latter consist of trade, tax and environmental policy. Using a simulation technique the presumable development of production and trade in the current decade is analysed, although not all the determinants mentioned are considered.

The paper is organised as follows: In Section 2 a short overview of the main inputs and the costs of processing of primary aluminium is given. Section 3 outlines the main trends in production, demand and international trade in primary aluminium. Section 4 deals with the incentives for trade. In the first part of the section theoretical considerations are presented. In the second part relevant determinants of competitiveness are analysed. Section 5 explores a demand-driven scenario and discusses resulting production and trade in the current decade. In Section 6 a summary is given.

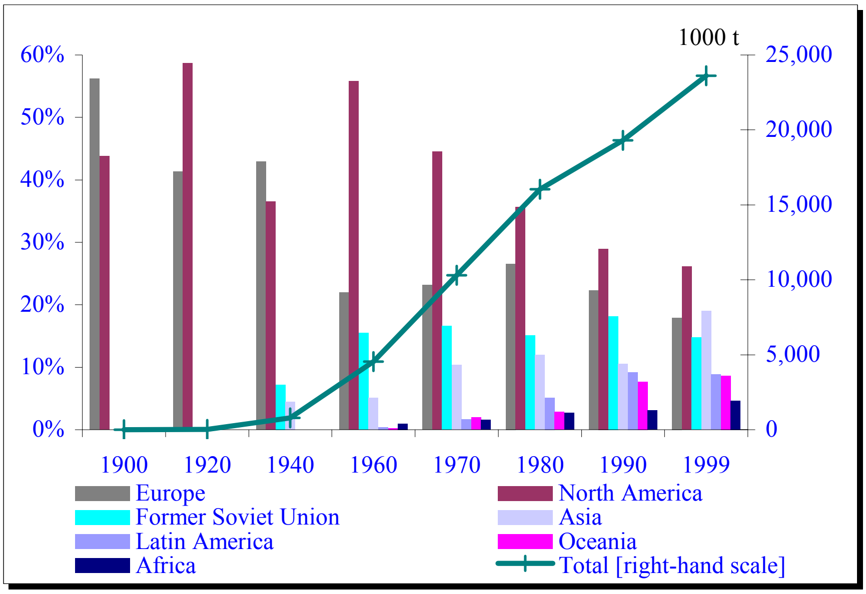
2. COSTS AND INPUTS OF PRIMARY ALUMINIUM

In 1995 worldwide operating costs of mining one tonne of bauxite were US$ 15, of which 43% were labour costs and 11% energy costs. To refine one tonne of alumina in that period cost a firm US$ 150. The main cost factors were bauxite, with 34% of total operating costs, thermal energy (22%), labour and caustic soda (each accounting for 12% of operating costs). Production of one tonne of primary aluminium gave rise to costs of US$ 1350. The main cost component was alumina with a share of 33%. In 1995 electricity and labour had a share of 24% and 10% respectively (Schwarz 2000).

3. TRENDS IN PRIMARY ALUMINIUM SUPPLY AND TRADE SINCE 1900

The world production of primary aluminium amounted to just 6700 t in 1900. Today one of the smallest European smelters could produce this volume. In 1995 the Hoyanger 1B smelter in Norway fabricated 7000 t (CRU 1997).[1] By 1999 world production had risen to 23.6m t.

With rising production the geography of production has changed. Not only did the number of countries increase from five in 1900 (USA, Switzerland, France, Germany, and the United Kingdom) to more than 40 in 1999, but the centres of production also shifted away from these five countries (Figure 1).



Sources: Own calculations based on Metal Statistics and Aluminium-Taschenbuch.

Figure 1. Production of primary aluminium, 1900-1999

The trend in the variation of production geography began quite early in the first half of the last century. But in 1940 still more than 80% of primary aluminium was produced in North America (now including Canada) and Central Europe. At the end of World War II, with the rise of socialism and decolonisation the change in production geography sped up dramatically.

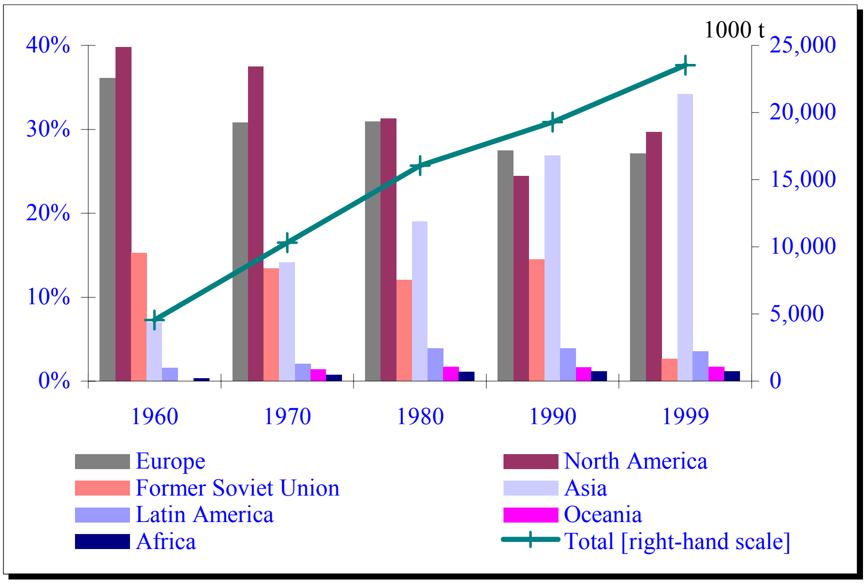
Following the example of the Soviet Union in the period before World War II a broad industrialisation of the economy was the main development strategy in many newly established countries in Africa and Asia and as well as in the, until then mainly agrarian countries, in Latin America and also in Australia. Another motive, predominantly in socialist economies, was to become independent of the supply of industry products from “capitalist” countries. As a part of the strategies and motives these countries began to build, more or less systematically, new production facilities, thus reducing the importance of the five “original” producing countries. In 1999 these five economies shared about one fifth of total output.

Looking at production geography in 1999 the most important regions were North America (26% of total output), Asia (19%), and Europe (18%).

In the longer run, the world supply and world demand of primary aluminium are balanced. Consequently, the consumption of primary aluminium developed in a manner comparable to production, reaching about 23.6m t in 1999.

In the pre-war period no important centres of industrialisation existed outside North America, Europe, and Soviet Union. Therefore, consumption of primary aluminium was centred in these regions. In keeping with production geography, with the end of World War II the distribution of demand to different regions changed. In the following only the period after 1960 is discussed, as from that year onwards detailed data were available. Since 1960 the old centres of consumption (Europe and North America) have lost their importance as main demanders and they have been mainly replaced by Asian countries.

In 1960 North America consumed about 40% of world production. By 1990 this share had dropped to just 25%. But, due to a long-lasting economic boom in the USA, until 1999 an edging up of the share to 30% can be observed (Figure 2).



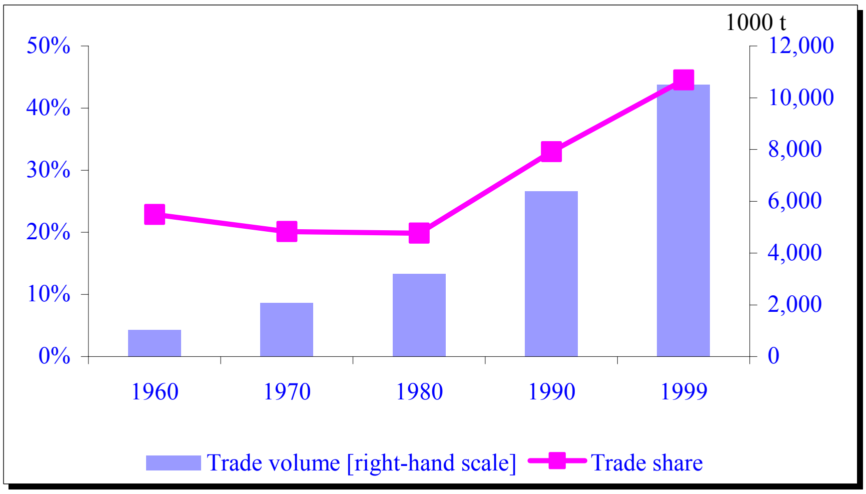
Source: Own calculations based on Metal Statistics.

Figure 2. Demand for primary aluminium, 1960-1999

The development in Europe is apparently comparable to the one in North America. Europe's share dropped to 27% in 1999 from 36% in 1960. But the decline is not as dramatic as in North America. And no recovery of the share is observable. One reason for this is the collapse in demand in the transition countries. A drastic decline of demand is evident in the Former Soviet Union (FSU) as well (Figure 2).

Asia is the only region where demand increased above the world average. In 1960 only 7% of primary aluminium was consumed in that region, in contrast to more than 37% of world production in 1999. The driving "forces" of that development were Japan (since the 60s), the newly industrialised countries in Southeast Asia (in the 80s and 90s) and China (since the 80s). The consumption in the other regions, Latin America, Australia, and Africa, did not change much (Figure 2).

Trade volume also increased in keeping with production and demand. However, in the last 40 years growth in trade volume has been more than twice as high as in production. Since 1960 trade volume has grown on average annually by 30%, and production by 13.3% (Figure 3).



As trade data were not available, the difference between domestic production and domestic consumption was used as a proxy for trade volume. Trade volume is defined as half of the sum of import and export of all countries. Trade share is the share of world trade volume in world production.

Source: Own calculations based on Metal Statistics.

Figure 3. Trade in primary aluminium, 1960-1999

Although trade volume has grown continuously since 1960, the importance of trade, measured by the share of trade volume in production, has not. Until 1980 the share dropped from 23% to 20%. That means until 1980 production increase occurred mainly in those countries where demand escalated. This changed in the 80s and 90s. In the two decades, the trade share exploded from 20% to more than 44.5%. Thus, in that period regional production and regional demand grew apart.

Looking at the changing pattern of trade relationships two developments seem to emphasise the increasing importance of trade:

- Exploitation of comparative advantages in exporting and importing regions.
  A typical example is the development of the Australian primary aluminium industry. Australia has comparative advantages (the underlying theory will be discussed in the following section) in producing primary aluminium. Bauxite is abundant in Australia. As since the 60s demand in Southeast and Far East Asia has grown considerably, and smelters in that region could not satisfy the demand, in the 80s the Australian aluminium industry became an important exporting industry. Today Australia produces mainly for the world market and not for domestic consumption which, in relation to the output, is almost negligible.

  Another example is the USA. Until the 80s American industry exported primary aluminium. This changed in the 80s. Since then supply conditions in the USA in relation to those abroad have worsened. Consequently, production capacity has dropped even though demand, especially in the 90s, increased considerably. In 1999 nearly 40% of domestic demand was imported.
- Collapse of the FSU.
  In the aftermath of the collapse of the FSU and the following economic decline in that region, domestic demand for primary aluminium slumped completely. Since production did not change considerably compared to 1990, a rising gap between production and domestic demand emerged. The excess supply was exported. In 1999 domestic production outstripped domestic demand by nearly 2.8m t. The respective figures for 1980 and 1990 were 570,000 t and 730,000 t.

In 1999 the main exporting countries were Russia (24.6% share of world export volume in 1999), Canada (15.4%), and Australia (12.9%). The main importing countries respectively regions were the EU (27.3% of world import volume in 1999), USA (23.1%), and Japan (19.9%).

4. INCENTIVES TO TRADE ALUMINIUM GLOBALLY

4.1 Driving forces for trade: Theoretical considerations

The figures presented above reveal the increasing and now overwhelming importance of trade. Our in-house simulation for the current decade confirms this trend (cf. Section 5), even though the change of trade volume will be not as drastic as in the last twenty years. In the section above two suggestions were offered explaining the rising relevance of trade, at least in primary aluminium. As the second one – the collapse of the FSU – is rather intuitive, the sources on which the first one is based are derived from the theory of international trade.

From the theoretical point of view countries[2] engage in international trade for two basic reasons:

- Countries trade because they differ in supply conditions,[3] and
- Countries trade in order to achieve economies of scale in production.

4.1.1 Comparative advantage

Nations, like individuals, can benefit from trade by reaching an arrangement in which each supplies the things it produces relatively well, as long as they differ in supply conditions. The outcome is traded between participating countries. All economies can gain from such an agreement even if one of them can produce all the goods more efficiently than all the others. It is sufficient that a country produces predominantly those goods where it has a comparative advantage over foreign competitors. The main reason why in such an arrangement all economies benefit is that economies are constrained by resources, factors, and time. However, such a deal will not ensure, that all economic agents in an economy will necessarily profit from trade.

A country has a comparative advantage in supplying a good if the comparative costs of producing that specific good are lower than abroad. Comparative costs are the costs of one domestically produced good with respect to the costs of other domestically produced goods. Due to the concept of comparative advantage, each country should produce at least one good with a comparative advantage.

A simple numerical example will clarify the concept of comparative advantage. The world is divided in two countries, which produce with one factor – labour – two goods, cheese and wine.[4] The home country has lower unit labour requirements, i.e. higher labour productivity, in both industries. The home country needs 1 unit labour to produce one pound of cheese and 2 units to produce one gallon of wine. The corresponding figures for the foreign country are 6 and 3. Thus, the comparative costs of cheese production are at home ½, abroad 2. But the comparative costs of wine production at home are 2, abroad ½. The home country has a comparative advantage in cheese production in the same way as the foreign country has one in wine production. That means a worker at home would earn only half as much producing wine as he does producing cheese, while the reverse is true for a worker abroad. Following the theory, trade should progress along this comparative cost pattern.

In accordance with the traditional theory of international economics we assume perfect competition in all markets. Thus, the market price of cheese in terms of wine is determined by the opportunity costs of cheese. The opportunity costs are determined by the unit labour requirements in cheese production per unit labour requirement in wine production. Due to this in case of no trade the relative market price of cheese at home is ½, abroad 2. Since in a trade situation the relative price of cheese should be identical in both countries, the world price must lie between these values. For the sake of argumentation, the world price is set at one: a pound of cheese trades for a gallon of wine on world markets.

Both countries gain from trade as both countries can use labour more efficiently than without trade. At home one hour's labour produces only ½ gallon of wine. The same hour could be used to produce one pound of cheese, which can be traded for 1 gallon of wine. It is obvious that the home country would not profit if it exported wine, i.e. the product where the foreign economy has a comparative advantage. The reverse is true for the foreign country.

The so-called Ricardian world is far too simple to give a complete analysis of either the causes or the effects of international trade. It was just used to explain the essential concept of comparative advantage. Although differences in labour productivity explain the existence of foreign trade, divergences in countries' resources is seen in traditional international economics as a main push factor for international trade. This is emphasised in the Heckscher-Ohlin-Samuelson approach. The main finding does not contradict the concept of comparative advantage. A country should tend to export those goods whose production is intensive in factors with which they are abundantly endowed, compared to the foreign country. The relative price of a factor will be lower in that country in which it is plentiful, compared to the foreign country.

The development in primary aluminium trade in the second half of the last century could be explained according to the Heckscher-Ohlin-Samuelson approach. Canada and Australia are abundantly endowed with intermediate goods and factors (Australia: bauxite and consequently of alumina, and cheap coal; Canada: hydropower). Thus, their becoming leading suppliers of aluminium worldwide follows the logic of the model.

4.1.2 Economies of scale

Traditional theory centres on divergences in production conditions. But a great deal of trade worldwide is carried out between countries with rather small divergences in resource and factor endowments. This is inter alia a consequence of the increasing opening of economies and continuous flow of knowledge in research and development of products and processes at least among industrialised countries. The latter is a result of the former. And the former was a starting point for the "internationalisation" of firms, i.e. the willingness of enterprises to trade and, in a second step, to produce goods internationally.

Modern production of important final and intermediate goods is characterised by firm specific economies of scale.[5] Rising production leads to decreasing average costs. If a supplier has an innovative edge, he can expand his monopolistic profits. If a firm has to compete in a market with almost identical products, decreasing average costs permit it to reduce prices and to improve competitiveness.

On the assumption that a producer wants to expand his profit, notwithstanding that in economic theory profit maximising behaviour is generally assumed, he will expand his production level up to the point the average costs are minimised. If the produced amount is larger than domestic demand the producer has to supply part of the production abroad, generating international trade.

In a changing world with integrating economies comparative advantages of regions can and will change. For this reason firms who are engaged in international production will make use of the comparative advantage of distinct regions by focusing new production centres in such regions. A consequence could be that production in countries with high demand will migrate to regions with comparative advantage but low demand, for example in the case of primary aluminium from the USA to countries like Canada. Consequently, trade between economies will increase.

4.2 Determinants of competitiveness of processing primary aluminium

The theoretical considerations as well as the examples have shown the relevance of supply conditions for the development of production in a country and the pattern of international trade. As the argumentation was rather theoretical, in the following Section 4.2.1 some conditions will be discussed which are relevant for the competitiveness of primary aluminium processing. The section focuses on the availability of natural resources such as bauxite and energy carriers for electricity production.

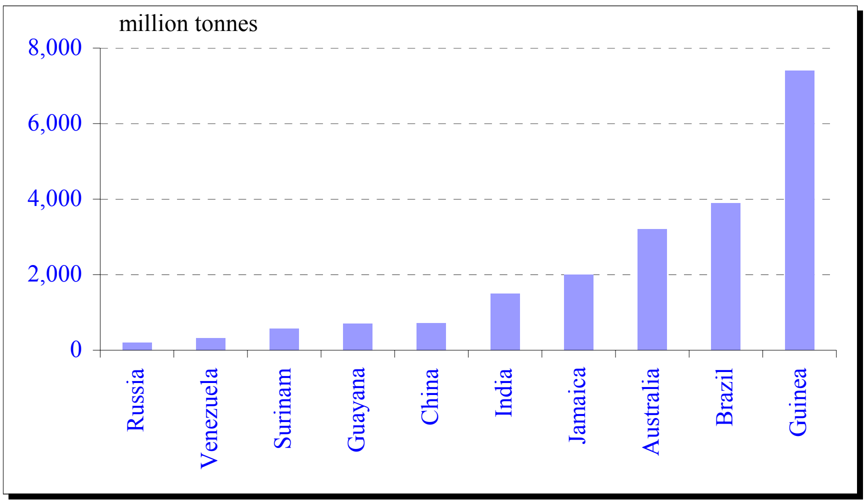
The world depicted in the traditional theory of international trade is characterised by the assumption of perfectly functioning markets. This assumption implicitly assumes that all firms compete in an identical political framework since only the supply conditions differ between regions. Looking at the "real world" this is an idealistic assumption. Without going into detail, policy-makers heavily influence the economic environment of a firm by e.g. raising import duties. In Section 4.2.2 some of the most important features for the primary aluminium industry will be analysed. These aspects comprise electricity prices, import tariffs, taxation regimes, internalisation of external effects as part of environmental policy and export dumping policies.

Although the chapter cannot supply a fully detailed discussion of this wide range of aspects and their relevance for specific countries, it serves to give a picture of the present aluminium industry and its forces for structural change and adaptation of global trade.

4.2.1 Factors determined by natural environment and market organisation

Bauxite availability

Although factor endowment with respect to natural resources was not the focal point in trade theory, obviously bauxite must be available to be traded. For 1999 world bauxite reserves[6] are estimated to be 25bn t. There are numerous bauxite deposits mainly in tropical and subtropical areas, but also in Europe and elsewhere (Figure 4).



Source: U.S. Geological Survey (2000).

Figure 4. World bauxite reserves, 1999

Reserves are unevenly distributed throughout the world with Guinea, Brazil, Australia, Jamaica and India ranking as the five richest countries, possessing 75% of worldwide reserves. Average static lifetime (ratio between present reserves and annual production) indicates an adequate bauxite supply for nearly 200 years. Country-specific lifetime is unevenly distributed, with Greece, Brazil, Guinea and India as countries with static lifetimes of more than 200 years (Hausberg et al. 2001).

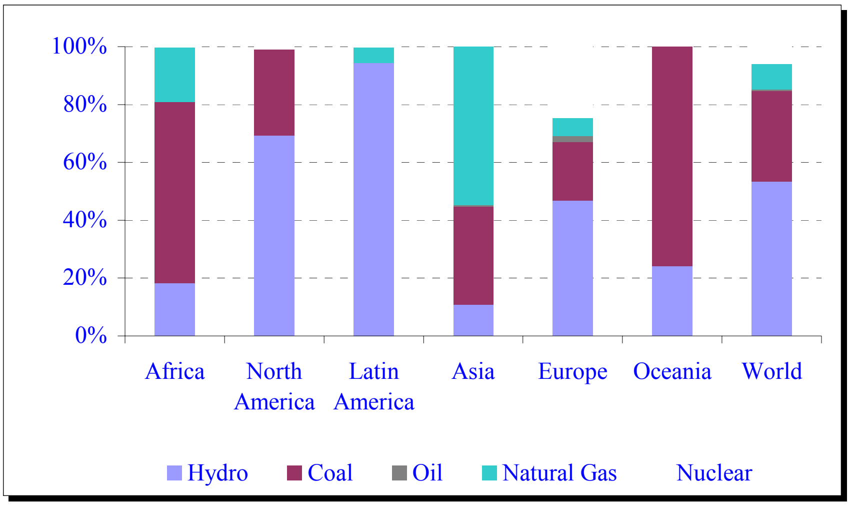
Global bauxite resources are estimated to be 55-75bn t (U.S. Geological Survey 2000) mainly located in Latin America (33%), Africa (27%), Asia (17%) and Oceania (13%).

Energy source for electricity

To produce aluminium large amounts of energy, particularly electricity, are necessary. As electricity transport over long distances is not profitable, investment in smelters requires sufficiently cheap local energy sources. According to IPAI statistics, 53% of smelters worldwide are supplied by hydropower and 31% by coal-based power. Gas-based power, nuclear electricity, and oil-based power contribute 9%, 6% and 1% (IPAI 1999).

Hydropower is regarded worldwide as the cheapest among the alternatives, respectively. Therefore, new smelter capacities very often result in combination with sufficient availability of hydropower, e.g. in Canada, Latin America, Norway, and Iceland. But other countries with sufficient availability of cheap fossil-based electricity show an increase in capacity, too, e.g. Australia, India, and China.

As Figure 5 indicates, for Asia (India), Oceania (Australia) and Africa fossil-based sources of electricity are dominant. Only Europe (Germany, France) shows a high share of nuclear energy.



Source: IPAI (1999).

Figure 5. Electrical power used in primary aluminium production, 1998

In North America, Latin America (Venezuela, Brazil) and partly in Europe (Norway) hydropower dominates. Although some countries did not report to IPAI (e.g. China, Poland, Russian Federation), Figure 5 gives instructive information on the structure of the electricity supply world wide.

Low and variable electricity prices

Due to the high specific electricity demand per tonne of primary aluminium the price of power is a very sensitive parameter. High-electricity-price aluminium producers pay twice as much as low-electricity-price producers. In 1997 the aluminium industry average worldwide was US$ 20.7/MWh. Canada had the lowest tariffs, and Asia and Eastern Europe the highest (CRU 1997).

61% of the electricity supply in 1996 was based on contracts with fixed prices and 39% on contracts with metal-linked variable electricity prices (CRU 1997). Contracts with variable electricity prices are orientated towards the price of aluminium on the London Metal Exchange.

The two price regimes differ in risk sharing between the aluminium industry and electricity suppliers (Craul 2000). Aluminium companies with fixed electricity prices take the full risk of falling metal prices, but also take full advantage of rising prices. In the case of metal-linked electricity prices, the aluminium industry and energy industry share the risks and advantages since with falling aluminium prices the price of electricity drops as well, and vice versa. Analysts interpret this price regime as offering competitive advantages for parts of the aluminium industry. Canada, Latin America and Australia are the regions with the highest share of metal-linked electricity prices.

4.2.2 Policy-induced determinants

Subsidies

Very often, low and variable electricity prices are considered to reflect a special kind of subsidy (Kirchner 1988, Adams 1990). This assessment requires a subtle analysis. For example, price differentiation with low prices for aluminium processors or risk-sharing based on metal-linked variable electricity prices could be means of securing markets for the energy suppliers (Spies 1990). In these cases the assessment of subsidies is not tenable. In certain cases, e.g. Venezuela in 1998, due to high metal prices the aluminium industry even pays higher electricity prices than private consumers (Pinto 1998).

A local or governmental body can affect the electricity prices for aluminium processing firms directly, by subsidising the price, or indirectly, inclining the policy of a power-generating enterprise. A specific influence of local or gonvermental policy can be assumed if either a power-generating enterprise has monopolistic power or the existence of that firm is politically guaranteed. In both cases, policy-makers additionally have to have the capability to directly or indirectly influence decisions by that firm. Monopolistic power is crucial for having the opportunity to offer different prices to different groups of consumers (Kirchner 1988). If the existence of a company is guaranteed, it is not pressured to set prices according to the constraint of profit making. Hence, the appointed prices can follow some other, e.g. social or political, considerations. Certainly, these conditions are not generally fulfilled. Worldwide, the electricity sector is structured very differently, ranging from a government controlled and monopolistic to private and competitive power supply. In the course of the deregularisation of electricity markets in several countries, e.g. EU, the power supply is organized more and more privately and competitively. Hence, affected power suppliers lose their ability to vary prices among consumer groups. Additionally, governmental ability to control the power supply is diminishing.

Deregularisation and privatisation is, however, no obstacle for policy authorities to arrange price schemes for selective industries and lessen the effects of these policies on electricity prices paid by these industries. For example, in the Australian state Victoria a long range contract – running from 1984 to 2016 – between smelters located in Victoria and the then state-owned electricity provider was fixed leading to a decoupling of electricity prices paid by smelters from market prices for electricity. In the year 2001 the state agency in charge makes losses of about $ 17.50/MWh of power demanded by smelters, filling the gap between electricity price paid by smelters of $ 13.50-15.50/MWh and market price of $ 31-33/MWh. Another way of subsiding the price is used in the Northwest of the USA. In that region an agency of the US Department of Energy provides to there situated smelters power claiming a price of about US$ 8/MWh below market price (Turton 2002).

Import tariffs

In general, import tariffs serve to protect domestic industries against foreign competition. Whether they result in gains for the total domestic industries depends on some conditions not discussed here.

A lot of countries charge tariffs on imports of bauxite, alumina, and aluminium. Before the Uruguay Round the only alumina-producing countries levying tariffs on bauxite imports were India (45%) and Venezuela (5%). Alumina imports were taxed by India (65%), China (20%), Poland (10%), EU (5.5%), Argentina (5%), and the Russian Federation (5%).

With 4.4% to 9% generally low, although significant, tariffs on unwrought aluminium were levied by China, the European Union and others. For India tariffs were 60%. Tariffs on waste and scrap were normally zero (with a few exceptions), while tariffs on powders were generally higher than on unwrought aluminium. Tariffs on semi-fabricates were significant in most countries (for details cf. UNCTAD 1996).

Except for India, tariff concessions, negotiated during the Uruguay Round, were generally small. For bauxite and alumina Indian tariffs were reduced to 25% and 40%. However, compared to other countries, Indian tariffs remained high. In total the Uruguay Round tariff concessions are unlikely in themselves to lead to major changes in trade patterns (UNCTAD 1996). For the tariffs themselves this conclusion cannot be drawn. At present, the discussion on the necessity and efficiency of tariffs for aluminium products or rather on further concessions is still going on.

Mining taxation policy

Taxation is the main source of income for any government. Unlike other industries, natural-resource-based industries such as bauxite mining are affected not only by capital taxes but by royalty taxes as well. Raising royalty taxes expresses the government's desire to benefit from the presence of bauxite deposits on its territory and resulting scarcity rents.

There are quite a number of mining taxation regimes (Mining Journal 2000). They are structured differently with respect to income taxation and royalty taxation, optimally reflecting a kind of balance between stakeholders' needs, as expressed by the government and the mining industry.

In some cases analysts agree that tax regimes reduce the comparative advantage countries once enjoyed over their competitors. Jamaican mining tax policy is an example (Nappi 1992). The government raised a uniform royalty tax on each tonne of bauxite mined on its territory and a production levy on bauxite mined linked to the average world market price of aluminium ingots. Fiscal reforms in the seventies raised the total taxes collected by the government on each tonne of bauxite mined from US$ 1.77 to US$ 15.08 in 1977. A further fiscal reform in 1979 introduced a two-tiered system of tax on bauxite production, differing between a basic production of 13m t and incremental production with a lower tax rate.

This rapid increase of specific taxes accompanied a development where Jamaican producers were confronted with competitors supplying higher quality, but cheaply processed bauxites, e.g. Guyana and Australia. To some extent the unequal fiscal treatment of mining activities explains the decline in competitiveness of Caribbean countries like Jamaica in favour of countries like Brazil or Venezuela (Nappi 1992).

Environmental policy: Internalisation of external effects

The phenomenon of external effects is theoretically well understood and documented and well accepted in practical terms. Modern environmental economics and policy offer a number of instruments to deal with this phenomenon and to internalise external effects, ranging from negotiations, the property-rights approach to Pigou taxes. More practical approaches comprise the price-standard-approach and specific environmental regulations.

From a theoretical point of view, it is important to define the Pareto-efficient level of external effects and level of internalisation, and vice versa. The Pareto-efficient level of external effects is determined by a situation where the sum of all agents' profits (or utilities) is maximised. In practice it is clear that due to the lack of information and the number of agents involved and for several other reasons it is very difficult to determine Pareto efficiency. Therefore, practical solutions reflect a stakeholder's ability to impose his interests (including governmental interests).

In any case the internalisation of external effects – whether negative or positive – has an influence on comparative advantage, as it influences production costs. Selected external effects have been studied for aluminium production in Venezuela (Pinto 1998), and for bauxite mining in Bintan, Indonesia, (Kölfen 1999) and Jamaica (Happel et al. 1999). Although a clear picture of external effects of the aluminium industry and of the level of internalisation does not exist, it is agreed that the present situation is in favour of countries which do not have far-reaching environmental standards and therefore no sufficient internalisation of external effects. From the viewpoint of foreign trade the lack of environmental legislation might be regarded as an advantage over competitors.

Export dumping

Export dumping is seen as a situation where on a foreign market a domestic firm supplies a product at a price below its own production costs. Hence, the chances of a firm penetrating a market or at least staying in a market will be enhanced. A profit-maximising firm will run this strategy if either the losses are, directly or indirectly, financed by the government or to crowd out competitors. In the latter case this will generally happen only for a short time. A badly functioning internal auditing system can lead to the same situation, i.e., that goods are sold below costs. Irrespective of the reasons for export dumping, economies with competing enterprises will try to hinder such imports.

In the course of the transformation of centrally planned economies, the aluminium industry in the FSU was confronted with a lot of problems (McDonald 1994). Traditionally, there was hardly any foreign trade with Western countries. But domestic markets collapsed in the early nineties. In total, demand for the FSU aluminium industry dropped by 82% by 1995 (Dobozi 1996). As a result of inflation and price control policy for nonferrous metals the domestic price fell below export prices for aluminium.

As a consequence the FSU aluminium industry raised its exports to Western markets from 0.7m t in 1990 to 2.4m t in 1995. An increase in exports cannot necessarily be qualified as export dumping. In this case the reproach of dumping was based on the aspect that FSU export prices did not reflect real production costs. As a consequence, Western producers cut their production and shut down capacities. The EU imposed an import quota of 15,000 t per month on unwrought aluminium from the states of the FSU from August 1993 to February 1994. The quota was abolished as a result of the memorandum of understanding concluded in January 1994 between Australia, Canada, Norway, the Russian Federation, the USA and EU. Under the memorandum of understanding, the Russian Federation undertook to reduce its output of primary aluminium by 500,000 tonnes by July 31, 1994.

5. MODEL-BASED PROJECTION OF GLOBAL PRIMARY ALUMINIUM TRADE IN 2010

Considering some of the determinants discussed above, in the following the longer-run trend of production of and trade in bauxite, alumina, and primary aluminium will be analysed. Using a simulation technique, the research is based on the partial equilibrium world trade model GlobAl, which contains the complete production process for primary aluminium.[7] The version used is a slightly revised variant of the model developed by Schwarz (2000; cf. Schwarz et al. 2000). The model is based on work by Brown et al. (1983), Nichols et al. (1992) and Manne et al. (1994).

The motivation for developing a world trade model is to give a clue to the longer-run trends in trade, considering the main determinants of competitiveness. But since a model cannot handle all features, some simplifications are generally made. Bearing this in mind, the GlobAl model takes into account policy-induced determinants of trade tariffs. Additionally, bauxite availability in the countries and the diverging mix of energy carriers and prices between the regions are modelled.

5.1 The model GlobAl

GlobAl belongs to the group of partial equilibrium world trade models and is linear in nature. The model gives a simplified picture of the processing of primary aluminium. Primary aluminium is processed in three steps, beginning with the mining of bauxite. Mined bauxite is processed to alumina, and the latter to primary aluminium.

Technologies simulated in the model follow in a stylised way the one used in reality. For mining only one technology is modelled, which is not altered until 2010. But, due to technical progress, requirements for all input goods decrease between 1995 and 2010 by 20%. Alumina is refined in the model by six types of processing: three types of digestion – low- and high-temperature autoclaves and tube reactors – are combined with two types of calcination – rotary kiln and fluidised bed processes. Four technologies are distinguished for smelting – Söderberg (VSS&HSS), side-worked pre-baked (SWPB), centre-worked pre-baked (CWPB) and point-feeder pre-baked (PFPB) technology. Installing new equipment, which generates higher energy efficiency, reveals technical progress in refining alumina and smelting aluminium.

Demand for and production of all goods are separated geographically. Recognising this, the world is divided into 15 regions.

On the basis of minimising the total costs of production, investing and transport, the model calculates the production of the different goods in each region as well as trade flows between regions. Irrespective of this, since in all markets perfect competition is implemented, the model is demand-driven. That means, total output of each good is determined by demand for this good. Demand for primary aluminium is exogenously given. Demand for alumina and bauxite is derived from the demand for primary aluminium and alumina, respectively. The assumption of perfect competition ensures that the bauxite, alumina, and primary aluminium produced in a region is completely distributed domestically and abroad. The chosen objective function implies profit-maximising economic agents. The model is static and depicts the development between 1995 and 2010 in one period.

The data in the base year refer to 1995 (cf. Schwarz 2000). Prices of various input factors – i.e. labour, electricity, thermal energy carrier, caustic soda, lime – converge between regions until 2010, leaving the world price of each input good constant. Relative world prices of input factors are constant throughout the period. Nevertheless, relative prices in the regions as well as between the regions will change. Transport tariffs will decrease by 10% (cf. Schwarz 2000).

Tariffs for bauxite, alumina and primary aluminium differ regarding traded good and region. In general more highly processed goods are taxed more highly than less processed one. In 1995 tariffs for bauxite were spread between 0% and 10%, for alumina and aluminium between 0% and 25%. For the model it is assumed that tariff rates in each region will decline by 20%.

The above made projections base on consideration discussed in literature or put forward by experts. Contrasting this, the possible future macroeconomic and microeconomic environment is seldom discussed in a way, which could be implemented into the model. Thus, additional changes of the macroeconomic and microeconomic environment are not modelled. In particular no variation of tax rates are considered.

5.2 Scenario: Cases and results

The model is used to analyse the effects of changed demand for primary aluminium on production and trade of all demanded goods. Using the scenario technique three cases are analysed which differ regarding the demand level for primary aluminium in the regions in 2010:

- Base case (or case 1): On the basis of projections regarding the development of income, the final aluminium intensity of the entire output of an economy as well as of the primary aluminium intensity of final aluminium products for each region demand for primary aluminium was calculated,
- Case 2: In this case a higher income growth than in case 1 is predicted, leading to a higher demand for primary aluminium compared to case 1,
- Case 3: In this case development of income is identical to case 2. But, because of increasing innovation rate and structural change in aluminium production a lower final aluminium intensity of the entire output of the economy and of primary aluminium compared to that in case 1 and 2 is predicted. Consequently, the world demand for primary aluminium is below that in the other cases.

The world demand for primary aluminium, alumina, and bauxite was calculated on the basis of the estimations. The figures are shown in the following Table 1.

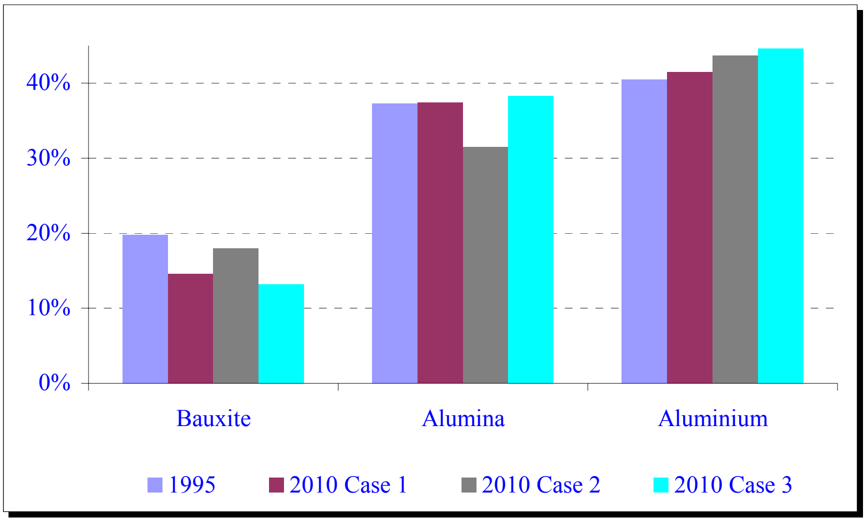
Table 1. World demand for bauxite, alumina, and primary aluminium, in million tonnes

	1995	2010		
		Case 1	Case 2	Case 3
Bauxite	115.57	167.25	183.02	152.82
Alumina	42.99	60.93	67.73	54.39
Aluminium	20.22	27.94	31.08	24.95

Demand for primary aluminium in 2010 is estimated according to the assumptions presented in the text. Demand for alumina and bauxite is derived from demand for primary aluminium.

Source: Own calculations.

The importance of foreign markets to meet domestic demand differs between the three goods. As the value-added of processing steps increases, the share of foreign trade rises too. That means the share of externally traded bauxite in world production is the lowest: in 1995 it was 19.8%; the share of alumina at that time was 37.3%, that of aluminium 40.5%.[8] A main reason is the low value added of bauxite, thus reducing the incentive to trade outside the region (Figure 6).



Source: Own calculations.

Figure 6. Share of net trade balance in domestic demand

Until 2010 the “hierarchy” of relevance of trade with bauxite at the top, i.e. the lowest share, and aluminium at the bottom, i.e. the highest share, will not change; but the shape of the hierarchy will. That means the importance of trade on different process levels will alter as well as between the cases (Figure 6).

Irrespective of the assumed case, the openness of domestic bauxite markets declines considerably. The largest shrinkage will be in case 3, the smallest in case 2. The deterioration of the share in case 3 is accompanied by a decline of total volume of trade by 11.8%.

This is due to a shift of alumina production to bauxite mining regions. In the four most important mining regions alumina output will grow more quickly than bauxite mining, irrespective of the assumed case (Table 2). In these regions alumina output in relation to bauxite mining will increase at least by four per cent (case 2). In case 1 and 3 the relative growth rate is more than twice as high compared to case 2. To meet rising demand for alumina new capacities have to be installed. Due to cost considerations this will be done first in the main bauxite mining regions. If demand for alumina surpasses a particular level, costs in non-mining regions will exceed investment costs in mining regions. The particular demand level seems to be beyond that calculated in case 1. In contrast to mining regions, on the world level alumina production decreases compared to bauxite. Given the conditions in the markets, investments in alumina in bauxite mining regions are profitable, with a weak linkage to demand for primary aluminium.

Table 2. Development of alumina production relative to bauxite mining[1]

	Share[2]	Case 1	Case 2	Case 3
Four most important mining regions[3]	79.6%	9.4%	3.9%	10.6%
World	100.0%	-4.4%	-2.9%	-6.6%

1 The change of output of alumina between 2010 and 1995 is set in relation to output change of bauxite mining between 1995 and 2010.
2 Share of world bauxite mining.
3 Africa, Australia, Brazil, and Rest of Latin America.
Source: Own calculations.

A quite different picture is given in the alumina market. Irrespective of the fact that the share of traded alumina is about twice as high as that of bauxite, the specific trend contrasts with that of bauxite. With increasing output of alumina the share of traded alumina decreases. In case 3, with the lowest output increase, the share is 38.3%; in case 2 only 31.5% of alumina is traded externally. Thus, as long as the demand increase of alumina is quite low, capacities of smelters are mainly expanded in importing regions or – to a lesser degree – new ones are constructed. If demand level is high, i.e. in case 2, additional capacities are installed mainly in exporting regions.

The “openness” of primary aluminium markets is greatest. In 1995 about 40.5% of aluminium produced was traded externally. Irrespective of the assumed case, the relevance of foreign trade will increase. The trend, however, has an interesting pattern. The highest figure is realised in case 3, the lowest in the base case. As demand for aluminium rises to the level assumed in case 3 new smelting capacities are mainly build up in the most important exporting regions, such as Canada and Rest of Western Europe. When demand increases to the level of case 1 additional capacities will be installed to a greater extent in importing regions like the USA, compared to case 3. In this case investment volume in importing regions slightly exceeds that in exporting regions. Demand above the level of case 1 is met mainly by new capacities in minor exporting regions, like the Middle East. This pattern results from the diverging costs in production between the regions.

5.2.1 Regional trends in bauxite mining, demand and trade

Irrespective of the chosen case, Australia and Rest of Latin America will keep their position as world's leading bauxite miner; although they will lose market shares in some of the cases (Table 3). The importance of both regions is due to large deposits of bauxite in the respective regions combined with low costs of mining. The total costs will reach in 2010 US$ 7.70/t (Australia) and US$ 8.10/t (Rest of Latin America) per mined tonne of bauxite on the average of all cases. The costs are denominated in US dollars for the base year 1995.

Table 3. Supply of and demand for bauxite, in million tonnes

	Supply				Demand			
	1995	2010			1995	2010		
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
N America	*0.00*	*0.00*	*0.00*	*0.00*	*11.72*	*15.19*	*20.84*	*13.78*
USA	0.00	0.00	0.00	0.00	9.36	11.75	15.94	10.33
Canada	0.00	0.00	0.00	0.00	2.36	3.44	4.90	3.44
Latin America	*32.20*	*43.85*	*45.95*	*42.59*	*27.55*	*39.99*	*39.99*	*37.31*
Brazil	10.20	11.76	11.76	11.76	7.93	11.59	11.59	8.91
Rest of L America	22.00	32.09	34.19	30.83	19.62	28.40	28.40	28.40
Europe	*9.70*	*21.05*	*23.13*	*18.44*	*20.95*	*29.29*	*35.28*	*24.63*
EU-15	2.20	6.25	6.25	6.25	9.68	10.76	11.76	8.72
Germany	0.00	0.00	0.00	0.00	1.72	2.47	2.22	2.47
Rest of W Europe	0.00	0.00	0.00	0.00	0.00	0.00	1.46	0.00
FSU	6.10	10.40	10.40	10.40	8.13	14.13	15.58	14.13
CEEC	1.40	4.40	6.48	1.79	3.15	4.40	6.48	1.79
Africa	*14.90*	*17.11*	*25.21*	*8.52*	*1.74*	*2.54*	*4.25*	*2.54*
Asia	*13.40*	*21.47*	*22.79*	*19.57*	*13.12*	*22.49*	*22.79*	*19.60*
Middle East	0.60	1.36	1.36	0.80	0.40	1.36	1.36	0.58
India	5.20	8.16	8.16	7.42	5.03	8.16	8.16	7.42
China	6.50	9.75	9.75	9.15	5.30	9.75	9.75	9.15
Rest of Asia	1.10	2.20	3.52	2.20	2.38	3.22	3.52	2.45
Australia	*42.70*	*63.77*	*65.94*	*63.70*	*40.49*	*57.75*	*59.86*	*54.96*
World	112.90	167.25	183.02	152.82	115.57	167.25	183.02	152.82

Source: Own calculations.

Even though both regions were major mining regions in 1995 and will be in 2010 they were not the world's leading exporting regions in 1995. Only in case 3 will Australia have the largest market share. Both regions have the world's largest alumina industry, which will satisfy the rising demand for alumina by the primary aluminium industry until 2010. Thus, in neither case will more than 15% (Australia) and 18% (Rest of Latin America) of mined bauxite be exported.

The world's leading export region in 1995 was Africa and will be in 2010, at least in cases 1 and 2. In both cases about 60% of exported bauxite worldwide will be supplied by Africa's mines (Table 3). Some mines in Africa operate on the competitive fringe. As companies operating in Africa do not have the endowment to extend refining capacities exceeding the growth of world demand for bauxite, they have to supply the resource worldwide. But as mining costs in Africa are on average rather high – in 2010 they will be at US$ 20 per mined tonne of bauxite –, they can only satisfy the "residual" world demand. That means the demand which other bauxite exporting regions are not willing to meet. Consequently, as worldwide demand for bauxite is rather low, i.e. in case 1, the market share drops below 30% from 61% in 1995. The drop will be accompanied by a drastic decline of exported bauxite by 54.6%, compared to 1995.

In 2010 about half of traded bauxite will be shipped to the USA, irrespective of the assumed case. Thus further increasing its importance as a leading bauxite market. In 1995 firms located in the USA imported 38.6%.

In 1995 EU-15 was the other main importing region involving 30.8% of worldwide imported bauxite. This will change dramatically by 2010. In case 1 and 2 the share decreases to about 17%, in case 3 to 12.2%. This development is a consequence of new mining capacities in Greece, which will nearly triple between 1995 and 2010. The additional capacities in Greece will be mainly used within the EU-15, replacing foreign imports. Consequently, the total volume of bauxite imported by the EU-15 will be lower, compared to 1995, irrespective of the assumed case.

- Australia will remain the world's leading bauxite mining and demanding region.
- Africa's mines, in 1995 an important exporting region, on the competitive fringe, satisfy the "residual" world demand for bauxite. Thus, in the low demand case it will lose its position.
- The USA will remain the world's leading bauxite importing region.

5.2.2 Regional trends in alumina refining, demand and trade

Comparable to bauxite, in 1995 Australia and Rest of Latin America were leading producers of alumina; and this will not change until 2010, according to the results of the calculations. The market share of Australia will not change considerably, varying between 28.9% (case 2) and 32.1% (case 3), compared to 30.5% in 1995. In 1995 Rest of Latin America produced about 15% of world alumina. The share will vary between 14.5% and 18.1% (Table 4). Both regions profit from low refining costs, compared to the world average, and large capacities, established before 1995. In the model the capacities in 1995 predetermine the maximum possible enlargement of new production facilities. In 2010 average refining costs in Australia will amount to US$ 126 per tonne of alumina, in Rest of Latin America US$ 118/t. The world average costs will be about US$ 130/t. Because of low capacities, regions with lower costs like Africa or Brazil could not displace the two leading regions. In each region firms will gather costs for refining of US$ 114 per refined tonne of alumina.

Table 4. Supply of and demand for alumina, in million tonnes

	Supply				Demand			
	1995	2010			1995	2010		
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
N America	*5.60*	*7.14*	*9.70*	*6.16*	*12.18*	*18.01*	*18.01*	*16.29*
USA	4.50	5.49	7.35	4.51	7.38	10.39	10.39	8.67
Canada	1.10	1.65	2.35	1.65	4.80	7.62	7.62	7.62
Latin America	*8.50*	*13.99*	*13.99*	*13.00*	*4.36*	*6.34*	*7.73*	*5.83*
Brazil	2.10	4.16	4.16	3.17	2.62	3.17	3.17	3.17
Rest of L America	6.40	9.83	9.83	9.83	1.73	3.17	4.56	2.66
Europe	*10.50*	*12.30*	*15.07*	*10.35*	*14.49*	*18.70*	*20.22*	*16.15*
EU-15	5.30	5.04	5.64	4.06	4.77	6.25	6.25	5.99
Germany	1.00	1.06	1.06	1.06	1.30	1.61	1.61	1.34
Rest of W Europe	0.00	0.00	0.70	0.00	2.18	3.88	3.88	3.88
FSU	4.50	5.63	6.33	5.63	6.88	7.75	9.27	6.29
CEEC	0.70	1.62	2.39	0.66	0.65	0.82	0.82	0.00
Africa	*0.60*	*0.94*	*1.64*	*0.94*	*1.30*	*2.75*	*2.75*	*2.75*
Asia	*4.70*	*7.76*	*7.76*	*6.47*	*7.19*	*10.68*	*12.95*	*8.93*
Middle East	0.20	0.65	0.65	0.28	1.95	2.50	3.57	2.50
India	1.70	2.56	2.56	2.30	1.09	2.56	2.93	2.30
China	2.10	3.25	3.25	2.96	3.72	4.17	4.99	2.96
Rest of Asia	0.70	1.30	1.30	0.93	0.43	1.45	1.45	1.18
Australia	*13.10*	*18.80*	*19.58*	*17.47*	*3.47*	*4.45*	*6.07*	*4.45*
World	43.00	60.93	67.73	54.39	42.99	60.93	67.73	54.39

Source: Own calculations.

As the USA, FSU, Canada and the EU-15 are leading primary aluminium producers about half of the alumina produced worldwide was used in these regions in 1995. This will not change until 2010 (Table 4).

The main producers of alumina were and will be the main exporters, as their primary aluminium industries cannot absorb the domestic alumina production. Australia's market shares in world export vary between 62.5% (case 3) and 63.3% (case 2), compared to 60.0% in 1995. In 1995 Rest of Latin America supplied 29.1% outside the region. In 2010 this will alter between 24.7% (case 2) and 34.4% (case 3) (Table 4).

Canada and the USA were the main importing regions receiving in 1995 23.1% and 17.9% respectively, of net traded alumina worldwide. With the exception of case 3 in the case of the USA, both countries will expand their shares and thus the demand for alumina above the world average. Both regions are important aluminium producers. Canadian smelters will expand their production facilities above the world average, as domestic alumina refineries cannot meet the rising demand for aluminium. US American smelters will grow at a rate below the world average. But since domestic alumina producers cannot fulfil the demand of domestic smelters, the latter have to expand imports. Necessary investments in extending production capacities beyond those presumably realised in the US alumina industry would lead to prices higher than the one of imported alumina. The only exception is case 2. In that case, firms in the USA expand their production facilities above the world average. Due to a worldwide high demand, the price of domestic alumina will be less than that of imported alumina. Consequently, the share in the world market drops.

In addition to the two North American countries, the FSU, Rest of Western Europe, Middle East, and China were important importers in 1995, with shares of between 14.8% (FSU) and 10.1% (China) with Rest of Western Europe and the Middle East in between (13.6% and 10.9%, respectively) (Table 4). According to the calculations, China will lose market shares. In case 3 it will rather stop importing alumina. Also in case 1 the fall in market shares is accompanied by a decline in import volume. Chinese industry is not competitive with foreign suppliers due to high production costs. Only in case 2 does the import volume increase slightly by 7.4%. A similar pattern can be expected for enterprises in the FSU. The higher world demand for alumina is, the higher import demand will be, but only exceeding the 1995 level in case 3 by 23.5% (Table 4). The motives of smelting firms in Rest of Western Europe are apparently the same as in Canada. The companies will expand their smelting capacities above the world average, as they have a comparative advantage in processing aluminium. Since they have no domestic alumina industry they have to enlarge the import of alumina. Only in case 2 will the establishment of alumina production facilities be profitable. Because the extension of smelting capacities is the same in all cases, the import volume will be the same as well, except in case 2. The share variation is a consequence of changing world trade volume.

The Middle East is a minor aluminium producer. In contrast to Canada and Rest of Western Europe, companies in that region expand their capacities above the world average only in case 2. Since the domestic alumina industry is rather negligible, smelters have to expand their import market share in that case.

- Neither regional dispersion of producer nor of demander will change considerably.
- Thus, no significant changes occur in the distribution of exporting and importing regions.

5.2.3 Regional trends in aluminium smelting, demand and trade

In 1995 regional centres of primary aluminium production were the USA and Canada (17.3% and 11.2% of world production, respectively) and on the Eurasian continent, FSU and EU-15 (15.7% and 11.2% respectively) (Table 5).

The importance of these four regions will tend to decline by 2010, continuing the trend evident since the 60s of a "de-concentration" of production on the world level.[9] And with increasing demand "de-concentration" is edging up. The higher demand for primary aluminium is mainly met by increasing output in regions with small market shares in 1995: Africa, India, Middle East, Rest of Asia, and Rest of Latin America. These five regions had a joint market share of 15.2% of world production in 1995. In all three cases the share will be higher: highest in the high demand case 2

(22.6%) compared to 18.3% (case 1) and 21.0% (case 3), respectively (cf. Table 5). The regions are those where an "aluminisation" of the economy can be stated. With the exception of India, these regions have the lowest production costs, together with Canada. In all these regions the operating costs are below the world average by nine per cent at least. Divergences of production costs are determined by operating costs, since in the model investment costs do not differ between regions. India's firms produce at high costs on an average of all smelters, irrespective of the fact that some production facilities processing primary aluminium are internationally competitive (cf. Vasudevan 1999). Due to the highest duties worldwide domestic industry is protected. In the model Indian tariffs in 2010 will exceed those on world average by 185% (bauxite), 320% (alumina), and 290% (aluminium).

Table 5. Supply of and demand for primary aluminium, in million tonnes

	Supply				Demand			
	1995	2010			1995	2010		
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
N America	*5.60*	*8.27*	*8.27*	*7.48*	*5.64*	*6.44*	*7.27*	*5.82*
USA	3.40	4.78	4.78	3.98	5.06	5.77	6.56	5.25
Canada	2.20	3.50	3.50	3.50	0.59	0.67	0.71	0.57
Latin America	*2.00*	*2.91*	*3.56*	*2.68*	*0.88*	*1.34*	*1.43*	*1.15*
Brazil	1.20	1.45	1.45	1.45	0.50	0.70	0.74	0.60
Rest of L America	0.80	1.46	2.10	1.22	0.38	0.65	0.69	0.55
Europe	*6.60*	*8.54*	*9.24*	*7.38*	*6.09*	*6.88*	*7.28*	*5.82*
EU-15	2.20	2.88	2.88	2.76	4.87	5.40	5.62	4.49
Germany	0.60	0.74	0.74	0.62	1.50	1.67	1.74	1.39
Rest of W Europe	1.00	1.78	1.78	1.78	0.41	0.45	0.48	0.38
FSU	3.10	3.50	4.20	2.84	0.53	0.60	0.69	0.55
CEEC	0.30	0.38	0.38	0.00	0.29	0.42	0.49	0.39
Africa	*0.60*	*1.26*	*1.26*	*1.26*	*0.26*	*0.37*	*0.48*	*0.39*
Asia	*3.30*	*4.90*	*5.94*	*4.11*	*6.97*	*12.48*	*14.08*	*11.35*
Middle East	0.90	1.15	1.65	1.15	0.45	0.70	0.84	0.67
India	0.50	1.17	1.35	1.05	0.57	1.27	1.41	1.14
China	1.70	1.90	2.28	1.36	1.86	4.15	5.40	4.37
Rest of Asia	0.20	0.67	0.67	0.54	4.09	6.35	6.44	5.17
Australia	*1.60*	*2.05*	*2.80*	*2.05*	*0.38*	*0.42*	*0.53*	*0.42*
World	19.70	27.94	31.08	24.95	20.22	27.94	31.08	24.95

Source: Own calculations.

The USA, EU-15, and the Rest of Asia (Japan) are the leading users of primary aluminium worldwide, demanding in 1995 about 70%, in 2010 about 60% of aluminium produced worldwide. As the first two have important aluminium industries, the most significant importing region is Rest of Asia. In 1995 this region accounted for 46.1% of net traded primary aluminium; EU-15 had 31.6%, the USA 19.6%. Thus, the three regions accumulated 97.3% of worldwide net traded primary aluminium. This will change in 2010, according to the calculations. Chinese import demand will explode from 0.16m t in 1995 to 2.25m t at least (case 1). China's market share will vary in 2010 between 19.4% (case 1) and 27.1% (case 3), compared to 1.9% in 1995. The exploding demand of China partly crowds out other demanders from the market, inducing dropping market shares. In case 2 and 3, Rest of Asia shares fall to 42.4% and 41.5% respectively. Thus, in 2010 about two thirds of traded aluminium will be shipped to the Far East and Southeast Asia (Table 5).

The EU-15 share declines by nearly one third. In 2010 in either case 1 or 2 presumably one fifth of net traded aluminium will be imported by EU-15, in case 3 only 15.6%. In case 1 and 3 the drop is accompanied by a decline in imported volume from 2.67m t to 2.52m t and 1.73m t, respectively. In the same way as EU-15, the USA will lose market shares. In case 1 and 3 import volume falls considerably to 1m t (case 1) and 1.27m t (case 3) from 1.66m t in 1995 (Table 5).

One remark should complete the discussion on import demand. Industries in China as well as in the Rest of Asia are rather small, compared to the size of demand. In the case of China this is not surprising, taking operating costs into consideration. China has, next to Germany, the highest operating costs. They exceed the world average by 23%.[10] In case of Rest of Asia historically low capacities constrain the building up of new capacities, even though the operating costs are 18% below world average.

In 1995 nearly one third of worldwide net traded primary aluminium was supplied by firms operating in the FSU, followed by Canadian (20.4%) and Australian enterprises (15.4%). Companies from the FSU will experience market share losses between 6.6%-points (case 2) and 11.9%-points (case 3). In case 3 the drop is accompanied by a fall in export volume of 10.9%. An insignificantly increasing domestic demand is contrasted by a drop in production. Contrary to the share losses of enterprises in the FSU, Canadian aluminium traders will expand their market share, however, in case 2 only slightly. As mentioned above Canadian firms will enlarge their production facilities above the world average. Since domestic demand drops in comparison to the world average increase – in case 3 Canadian demand will fall absolutely, compared to 1995 – the additional production has to be supplied to world markets. Australian producers will more or less maintain their 1995 position in the world market.

- The trend of regional "de-concentration" of production plants will presumably continue.
- Far East and Southeast Asia will considerably increase their importance as leading demanding and importing regions, due to exploding import demand by China.

6. SUMMARY

Since 1960 the average growth rates of production and trade volume have been 13.3% and 30%, respectively. Whereas trade volume has grown more or less continuously its growth rate was smaller compared to production until 1980. Therefore, the importance of trade, measured by the share of trade volume in production, did not grow continuously. This share dropped from 23% in 1960 to 20% in 1980. The reason was that until 1980 production increase occurred mainly in those regions where demand had risen. Beginning in the 80s the situation changed radically. From 1980 to 1999 trade share doubled from 20% to 44.5%. The reason was that regional production and demand diverged. The driving forces behind this development were the realisation of comparative advantages in trading countries and at the beginning of the 90s the collapse of domestic demand in the FSU.

Supply conditions are particularly important for the development of production in a country and the pattern of international trade. With respect to the competitiveness of primary aluminium processing, natural environmental and market organisation factors as well as policy-induced determinants are discussed. The former comprise availability of bauxite and primary energy sources and the contractual basis of electricity prices, whereas the latter include subsidies, import tariffs, mining taxation, internalisation of external effects and export dumping. Although this wide range of determinants is not discussed in full detail in its relevance for specific countries, the overview serves to give a picture of present aluminium industry and its forces for structural change and of adaptation of global trade.

Having analysed past trends in production and trade in primary aluminium and its pre-products, a projection of future development is explored. Using a process-based partial equilibrium world trade model of primary aluminium, a demand-driven scenario of production and trade in the current decade is discussed. The analysis shows that the importance of foreign markets for meeting domestic demand differs between primary aluminium and its pre-products bauxite and alumina. In particular, the share of externally traded bauxite in world production is the lowest and the share of primary aluminium the highest. That means as added value of processing steps increases the share of foreign trade rises. For the current decade, model results show no dramatic change of existing trends. Australia will remain the leading bauxite mining and demanding region. Africa's mines satisfy the residual world demand for bauxite, acting on the competitive fringe. The USA will remain the leading bauxite importing region. In the case of alumina neither the regional dispersion of producers nor of demanders will change considerably. For primary aluminium, the trend towards a regional de-concentration of production plants will presumably continue. Far East and Southeast Asia will probably considerably increase their importance as leading demanding and importing regions. This is mainly due to projected exploding imports by China.

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NOTES

1 There are smaller smelters in China, which, however, are not considered by CRU.

2 Countries generally do not act as economic agents who decide directly on the distribution of production to domestic markets and to foreign ones as well as on domestic demand, at least in market economies. Since in the theoretical literature the notion of “country” is typically used, we will do the same. But one should be aware that on the supply side firms (or the boards of firms) are the one who decide on production plans and thus, on demand for input goods and factors as well on output level and regional distribution of the output. On the demand side, private and public households decide on their own, following their own decision calculus.

[3] Differences in demand conditions are seldom discussed, even though they can generate trade as supply conditions in countries are much the same.

[4] The example is drawn from Krugman and Obstfeld (1988).

[5] Another variation of economies of scale is sector-wide economies of scale. In this case, on the firm level the marginal earning could remain constant as output grows. But activities outside the sector could generate external profits to the sector, with the consequence that the sector as a whole achieves economies of scale. For example, human capital accumulation in a sector of which upstream and downstream sectors can gain.

[6] A resource is simply the identified or probable physical presence of minerals in the earth, which may or may not be exploitable economically with presently available technology. Reserves represent that portion of the resources that has been precisely measured and which is, or might be, available for production over a specified time period.

[7] The whole section draws heavily on Poganietz (2001).

[8] Data consider only net trade of each good in relation to domestic demand. Transit trade is excluded. Data are not comparable with those used in Section 3. In the following, trade between model regions is presented, and not trade between all the countries in the world.

[9] This should not be confused with a de-monopolisation of production. The model says nothing about the number of firms and their development. Since most aluminium-producing companies are multi-nationals, a regional "de-concentration" can mean either a monopolisation or a de-monopolisation of production on the company level.

[10] This result reveals a shortcoming of the model. In the model a cost minimising calculus is assumed. Since China is still a country with a strong socialist tradition, decisions regarding the production of important as well as large-scale industries are still under the supervision of the ruling party. It is doubtful, whether this will change completely in the next ten years.

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Future carbon dioxide emissions in the global material flow of primary aluminium

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Abstract

This study assesses the future carbon dioxide emissions in the global material flow of primary aluminium. The model of the global aluminium industry (GlobAl model) is used for scenario calculations. It simulates a market economy and allows an integrated analysis of the material flow and the corresponding carbon dioxide emissions. 1995 is the base year and the future horizon of the scenario calculations is 2010. The critical parameter 'global demand for primary aluminium' is varied. According to the scenario calculations, the absolute carbon dioxide emissions in the global material flow of primary energy will not increase until the growth rate of demand reaches 2% per year. World average specific emissions will decrease remarkably, especially due to the reduced energy-related emissions for smelting. There are three reasons for this. In the first place, the lower CO_2-emission factor of electricity generated from fossil fuels leads to reduced emissions. Secondly, modern point-feeder pre-baked plants need less electricity than the Soderberg plants they replace. And, thirdly, the production of primary aluminium is being shifted to regions in which the production of electricity is mainly based on hydropower.

1. Introduction

In 1995, about 1% of the worldwide energy-related carbon dioxide (CO_2) emissions was caused by the production of primary aluminium. Far more than half of the CO_2 arising from the flow of primary aluminium is due to electricity supply for electrolysis. Moreover, energy-related emissions

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from alumina production and the process-related emissions caused by anode consumption during electrolysis play a major role.

This study estimates the future CO_2 emissions due to bauxite mining, processing alumina and producing primary aluminium, including all transport processes. Estimates are made by scenario calculations, with the future horizon being the year 2010, based on the model of the global aluminium economy (GlobAl model). The GlobAl model simulates a competitive market. It allows an integrated analysis of the material flow and the corresponding CO_2 emissions. The critical parameter ‘future global demand for primary aluminium’ is varied.[1] The base year of the scenarios is 1995. An extensive data basis, describing the material flow (e. g. production or cost figures of single mines or smelters) in a very detailed manner was developed. The 1995 figures are necessary to compare expected future developments with the present situation and to recognise changes within the material flow and of the associated CO_2 emissions. In addition, the figures form the primary basis for the assessment of the parameters of the GlobAl model.

The paper is organised as follows: In Section 2, the GlobAl model is described as analytical instrument. In Section 3, scenario assumptions and model parameters are discussed. After a survey, the figures of important model parameters are represented. The scenario results for future final energy consumption due to the flow of primary aluminium are described in Section 4. Their assessment is necessary because most CO_2 emissions are energy-related. In Section 5, the estimated future CO_2 emission figures are shown. The reasons for the decline of emissions in smelting are discussed in detail. Finally, in Section 6, the results are summarised.

2. GlobAl model

2.1. Model classification

The GlobAl model is a further development of previous approaches [4–6]. It is a so-called process model which considers the different process steps of the material flow as well as transport processes [7]. It is computer-based and uses a linear programming technique. Total costs of global primary aluminium production including transport are minimised under the auxiliary conditions of a given demand for primary aluminium and capacity constraints. The model is static. All model parameters and all variables (production and transport quantities) refer to the year 2010. The assessment of model parameters for the year 2010 is based on figures for 1995 or a period including 1995. The implemented mathematical algorithm calculates a long-term market equilibrium with perfect competition [8]. It is, therefore, implicitly assumed that the producers of bauxite, alumina and primary aluminium maximise their profits decentrally, that they accept the market price as given and adjust their production quantities according to their marginal costs.[2]

[1] A detailed description of the model structure and calculation results is to be found in [1]. Some aspects of the model are also discussed in [2]. The data basis and methodology for determining the parameters relating to the CO_2 emissions from electricity supply are systematised in [3].

[2] The primary aluminium industry is in fact today seen as a workably competitive one. “The oligopolistic pattern of the post-Second World War era had been largely eroded before 1970. (...) Even if the major companies are still dominant in the sense of controlling a large share of world’s capacity, they are not able to control the price. The market outcome is hardly distinguishable from that of a competitive industry” [6].

Consequently, the flow of primary aluminium is understood to be *economically determined*. Human needs and market processes are responsible for the extent, technical configuration and ecological impacts of the flow of primary aluminium. Thus, the demand for primary aluminium causes the material flow. Various technologies and regions compete to meet the demand for primary aluminium and its preliminary products. It is the market process that decides which one will win the competition, and therefore simultaneously governs the energy demand and the extent of emissions.

2.2. Material flow modelling

Within the GlobAl model the process of technical transformation is reflected in three process steps: mining, refining and smelting. The chemical and mineralogical heterogeneity of bauxite is considered in 18 bauxite types which differ in their contents of aluminium oxide and reactive silica. The content of aluminium oxide defines the maximum yield of alumina extraction, while the content of reactive silica determines the extent of chemical loss during digestion. Monohydrated and trihydrated bauxite are also differentiated. Mineralogy decides the technology that has to be used for digestion. Alumina and aluminium are each treated as homogeneous goods.

On the three different process levels, the existing technical options are merged into a few technologies, six of which are differentiated in alumina production. A distinction is made between low- and high-temperature autoclaves and the tube reactor for digestion which can be combined with rotary kiln or fluidised bed calcining. Four technologies are specified for the production of primary aluminium: one Soderberg technology and three technologies with prebaked anodes: centre-worked pre-baked (CWPB), side-worked pre-baked (SWPB) and point-feeder pre-baked (PFPB) (Fig. 1). These technologies are employed in four different investment strategies: existing plant, upgrading, brownfield and greenfield expansion. Upgrading of existing plant means improving the technical parameters of the implemented technology (e.g. energy demand) by replacing components. Obsolete technologies are normally replaced by new ones within this measurement. The adding of new autoclaves, tube reactors or electrolytic cells to any existing plant is called brownfield expansion, which includes a capacity expansion of the existing site. In contrast to this, greenfield expansion means the establishment of an entirely new site. Considering the investment strategies, we have to bear in mind that existing plant and new plant may use the same technique, but do not as a rule have the same technical parameters. Normally, the new plant will be superior to the old one. Conversely, the new plant, as well as upgrading and brownfield expansion, causes investment costs whereas the (former) investment costs of existing plants are 'sunk costs' and therefore not relevant from the model perspective.

Conveyor belts, trucks, railway, inland waterways or ocean vessels are the means of transport involved. Fifteen world regions are considered, functioning as sites for the production processes of the three process stages: USA, Canada, Brazil, Rest of Latin America, Germany, Rest of the European Union, Rest of Western Europe, Former Soviet Union, Rest of Eastern Europe, Africa, Near and Middle East, India, China, Rest of Asia and Australia.[3]

[3] Because of the consideration of different bauxite types, process steps, technologies, investment strategies and regions, the GlobAl model is relatively large: 4335 production processes and 4500 transport processes are taken into account. The linear model therefore consists of altogether 8835 variables (cp. [1]).

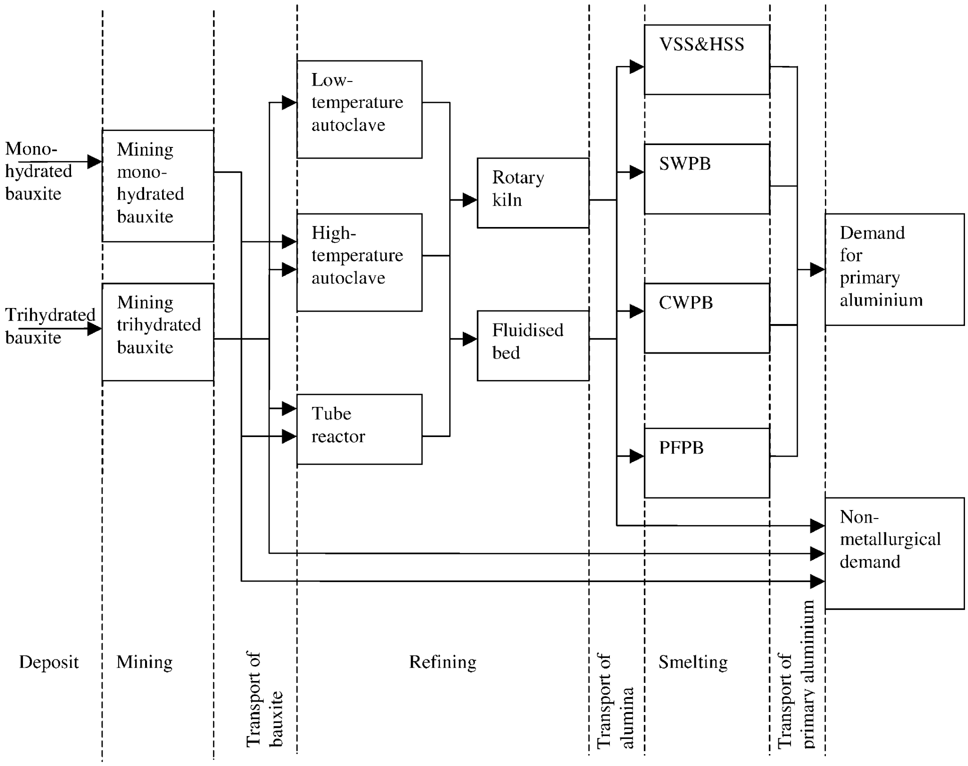

Fig. 1. Simplified flow chart of the GlobAl model

2.3. Steps of CO_2 emissions assessment and CO_2 emissions considered

The GlobAl model primarily provides an explanation of the regional distribution of the production of bauxite, alumina and primary aluminium and of transport between the production stages for the given future year. Production and transport quantities correspond to the activity levels of the structural variables of the optimisation problem. They are modelled as a function of cost, capacity constraints and demand.

In a second step the final energies are determined. The process-specific technical parameters of the energy inputs are assigned to the regional production quantities, the distances spanned by the respective means of transport and the respective specific final energy consumption are allocated to the transport quantities. Thus, it is possible to calculate the regional electricity consumption and the consumption of other final energy carriers. The energy-related CO_2 emission is finally the result of assigning the regional CO_2 emission factors of the entire electricity production to the regional electricity consumption, and the allocation of the CO_2 emission factors of thermal energy production to the consumption of other final energy carriers (Fig. 2).

In addition to the energy consumption and the associated CO_2 emissions in the main process chain, the energy consumption and emissions for the production of caustic soda and anodes are taken into account. Caustic soda is an essential material input in alumina production. Baked anodes are used in primary aluminium production by prebaked technologies. Moreover, the direct CO_2

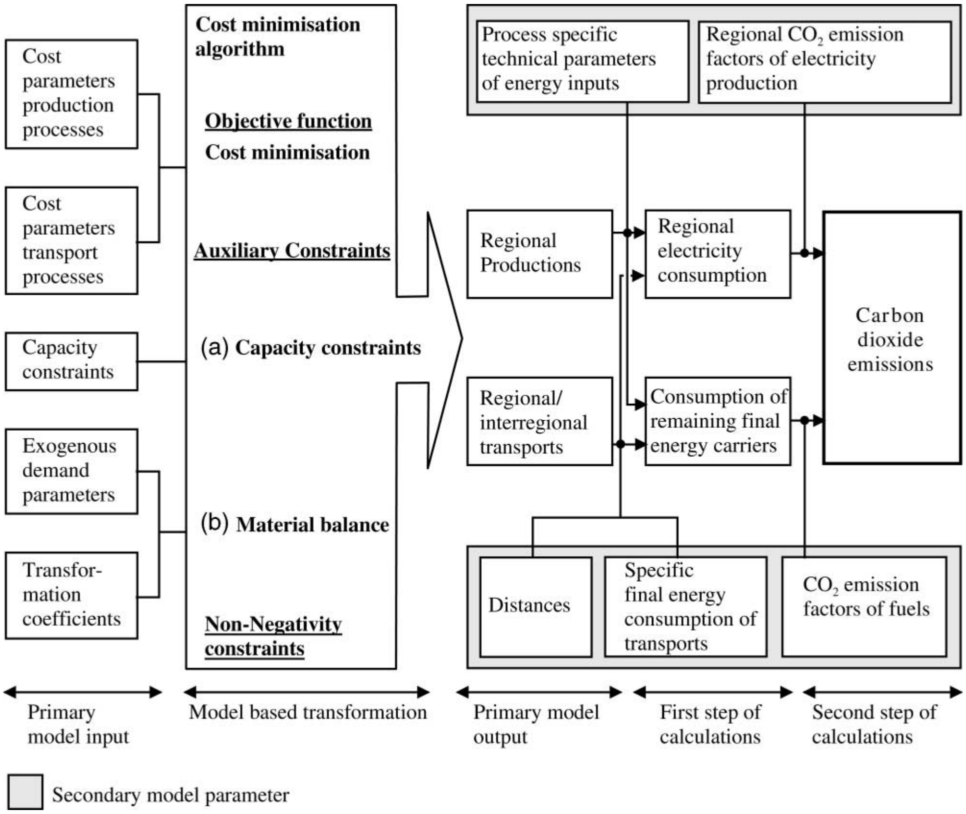

Fig. 2. Calculation of the energy-related CO_2 emissions of the main process chain within the GlobAl model.

emissions from electrolysis are included: the oxygen formed at the anode due to the electrochemical reduction of alumina reacts with the carbon of the anode to form CO_2 (and carbon monoxide). This reaction is characteristic of the electrolytic processes considered. The resultant CO_2 emissions are therefore regarded as process-related emissions within the model, although the underlying exothermal reaction has a considerable influence on the heat balance and energy requirements of the electrolytic cell and, strictly speaking, can thus also be understood in part as energy-related.[4]

[4] CO_2 emissions are not the only greenhouse gas emissions caused by the flow of primary aluminium. Perfluorinated hydrocarbons (CF_4, C_2F_6) result from the anode effects. The extent of perfluorinated hydrocarbon emissions strongly depends on the smelting technology used. Perfluorinated hydrocarbons can be and are considered within the GlobAl model. The assumptions for specific emissions and the scenario results are discussed in [1]. The supply of electricity from hydropower is connected with methane emissions (CH_4). Especially shallow tropical reservoirs often release large quantities of methane from decomposing biomass because of anoxic conditions. Methane emissions are not yet considered within the GlobAl model. The reason is that each reservoir's emissions vary considerably, for example due to geography, size, depth and hydrological fluctuation (see e.g. [9,10]). More investigations are necessary to determine reservoir-type-specific methane emission due to electricity production from hydropower.

3. Scenario assumptions and important model parameters

3.1. Survey

Table 1 presents the model parameters, their sources and the assumptions for their assessment. There are a large number of model parameters because of the consideration of different process steps, bauxite types, technologies, investment strategies and regions within the GlobAl model.

The assumption of progressing globalisation and worldwide deregulation is essential for the projections of most model parameters. For example, globally identical technical parameters are assumed for the future operations of upgrading, brownfield and greenfield expansion for alumina and primary aluminium production. In addition, a progressive adjustment of the regional prices is assumed for the tradable input goods (e.g. caustic soda, lime) as well as decreasing import duties for bauxite, alumina and primary aluminium.

In the following, the very important parameters of the present analysis are discussed in more detail: global primary aluminium demand, cost parameters of production processes, process-specific technical parameters of energy inputs and the regional CO_2 emission factors of electricity production.

3.2. Global demand for primary aluminium

The global demand for primary aluminium in the year 2010 is a crucial model parameter because of its great importance for model results and the existing projection difficulties. These difficulties are due to the fact that future global primary aluminium demand will depend greatly on the future development of the world economy. Moreover, competition with other raw materials and the recycling quota additionally influence demand. Therefore three scenarios are distinguished. Firstly, the base scenario assumes a moderate growth rate of demand for primary aluminium of 1.9% per year from 1995 to 2010. This is the growth rate which was valid for the period from 1980 to 1995. The low-demand scenario assumes a growth rate of 1.4% per year and the high-demand scenario a growth rate of 2.4%.

3.3. Cost parameters of production processes

The decision on whether, for example, an existing refinery or smelter in one region is to be closed, upgraded and/or expanded and/or new facilities are to be built depends within the GlobAl model only on the comparative cost situation of these alternatives. Therefore, the cost parameters are essential. The future specific operating costs of one alternative (e.g. using an existing plant without technical change) are estimated by projecting the future technical parameter of that alternative (e.g. electricity consumption) and the relating input prices (e.g. electricity tariff). Capital costs have to be considered for upgrading, brownfield and greenfield expansion. They are assumed to be globally identical.

Because of the large number of technical parameters and input prices that determine the future operating costs of the different production processes, only world average cost figures for the year 1995 are presented here. They can give a first impression of the cost situation of the global primary aluminium industry. Total operating costs per tonne of output were USD^{1995} 15 for min-

Table 1
Model parameters and their sources or/and assumptions for assessment

Parameter	Sources or/and assumptions for assessment
Regional demand for primary aluminium	Scenarios with a moderate, low and high growth rate of *global* demand are distinguished. Regional shares according to adjusted figures of [11].
Capacity constraints	
Initial capacity (specified for the different process steps, technologies and regions)	Defined for the year 1995 according to [12–15].
Capacity constraints brownfield expansion (specified for the different process steps and regions)	Calculations for maximum permissible expansion based on figures for current brownfield expansions and planned projects ([15,16] and others).
Capacity constraints greenfield expansion (specified for the different process steps and regions)	Calculations for maximum permissible expansion based on figures for current greenfield expansions and planned projects ([15,16] and others).
Specific operating costs	
Technical parameters of old plants (specified for the different process steps, technologies and regions)	Based on figures for 1995 according to [13–15]. Assuming that the difference in the technical parameters of an old plant, compared to those of the most efficient plant with the same technology, decrease by 50% until 2010.
Technical parameters of upgrading, brownfield and greenfield expansion (specified for the different process steps)	According to [17,18] and others. Worldwide the same figures are assumed.
Regional input prices	Based on figures for 1995 ([12] and others). Assumptions: (a) progressive adjustment of regional prices for tradable goods until 2010, (b) only slight changes in the comparative regional electricity tariffs, (c) highest growth rates of wage rates in regions with the lowest level in that respect.
Specific capital costs (specified for the different process steps and investment strategies)	The method of net present value is used to calculate the specific capital costs. Assuming an interest rate of 5%, the known investment costs per tonne of capacity according to [15,16,19] are spread as an annuity over the economic life. Twenty years are assumed as the economic life of mining, refining, and smelting plants.
Specific transport costs	
Regional/interregional transport distances (specified for the different means of transport)	According to [4] and others.
Transport tariffs (specified for the different means of transport)	Based on the tariffs for 1995 according to [20]. Assuming that the tariffs are globally identical and decrease by 10% until 2010.
Regional import duties	Based on figures for 1995 according to [21] and others. Assuming that the import duties decrease by 20% until 2010.
Specific final energy consumption	
Specific final energy consumption of production processes	Compare technical parameters.
Specific final energy consumption of transport processes	Assuming that figures for 1995 according to [22] will not change until 2010.
CO_2 emissions	
Regional CO_2 emission factors for thermal energy (specified for different process steps)	They are a function of the regional mix of energy carriers used for thermal energy production on the different production steps and the associated CO_2 emission factors of the energy carriers. It is assumed that the regional mix of energy carriers used for thermal energy production on the different production stages will not change until 2010 and that the associated CO_2 emission factors of the energy carriers are globally the same.
Regional CO_2 emission factors for electricity production	Calculated in sub-model for 1995 and 2010. Country-specific CO_2-emission factors were calculated based on [23–26] and others and weighted by their national share of regional electricity production. Projection for 2010 considers increase or decrease of national electricity production, changes of the energy carrier's contribution as well as replacement and upgrading of power plants. Technical parameters (efficiency) of new and upgraded plants are set to be globally identical for coal, oil and gas power plants, repectively. The regional mix for 2010 is also calculated by weighting the country-specific CO_2 factors by the national share of total regional electricity production. The sub-model structure is described in [3].

ing, USD[1995] 150 for refining and USD[1995] 1350 for smelting. The importance of the single cost components is shown in Table 2(a), whereas Table 2(b) illustrates the capital costs for upgrading, brownfield and greenfield expansion. In relation to total operating costs, refining has the highest capital costs for new plants. For refining and smelting upgrading amounts to about one quarter of the capital costs of new plants and brownfield expansion about half.

3.4. Process-specific technical parameters of energy inputs

The assumption of globally identical technical parameters for the future operations of alumina and primary aluminium production also concerns the specific final energy consumption. The ‘process-specific technical parameters of energy inputs’ are both primary and secondary model parameters. In their attribution as cost parameters they have an influence on the activity levels and are used for balancing purposes, too.

Table 3 shows the world average specific final energy consumption for mining, refining and smelting and the capacity-weighted world average figures for the individual technologies in 1995, as well as the model assumptions for future operations for 2010. In 1995, the consumption by all three process steps varied widely according to region and technology. These 1995 figures adjusted for a ‘natural progress rate’[5] are assumed for the old capacity within the model. For future operations the following assumptions were made:

- Mining. The 2010 electricity consumption and use of thermal energy for future operations (connected with capacity expansion) is 20% lower than the 1995 figures.
- Refining. The tube reactor with fluidised bed had the lowest energy requirements of all refining technologies in 1995. It is assumed that this technology will be used for new refineries. For

Table 2
World average (a) total operating costs and (b) capital costs for mining, refining and smelting in 1995 (USD^{1995}/t_{Output})[a]

	Mining	Refining	Smelting
(a) Total operating costs	15	150	1350
Components (in %)			
Main raw material	–	34	33
Labour	43	13	10
Electricity	–	3	24
Other energy	11	22	–
Caustic soda	–	13	–
Other operating costs	46	15	33
(b) Capital costs			
Upgrading	n.a.	16–24	60–120
Brownfield expansion	n.a.	35	160
Greenfield expansion	6	70	400

[a] Own calculations based on [12,13] and others.

[5] It is assumed that old plants can, even without upgrading, reduce their energy requirements. They can cut their excess energy consumption *compared with the most efficient plant using the same technology* by 50% by 2010.

Table 3
Specific final energy consumption for mining, refining and smelting in 1995 (world averages or, for the single technologies, capacity-weighted world averages) and assumptions for future operations for 2010[a]

	Electricity consumption (MWh_{el}/t_{Output})	Thermal energy (GJ/t_{Output})
Mining		
All existing mines 1995	<0.1	0.2
Future operations	20% lower than 1995 figures	20% lower than 1995 figures
Refining		
All existing plants 1995:	0.25	13.6
Autoclaves low temperature/rotary kiln	0.24	14.2
Autoclaves low temperature/fluidised bed	0.23	10.3
Autoclaves high temperature/rotary kiln	0.33	17.8
Autoclaves high temperature/fluidised bed	0.24	13.1
Tube reactor/fluidised bed	0.26	8.0
Future operations 2010:		
Upgrading and brownfield expansion		
Autoclaves low temperature/fluidised bed	0.26	7.8
Autoclaves high temperature/fluidised bed	0.26	9.5
Tube reactor/fluidised bed	0.26	7.2
Greenfield expansion		
Tube reactor/fluidised bed	0.23	6.9
Smelting		
All existing plants in 1995:	15.5	–
Soderberg	16.6	–
CWPB	15.5	–
SWPB	14.6	–
PFPB	14.4	–
Future operations 2010:		
Upgrading and brownfield expansion		
PFPB	13.8	–
Greenfield expansion		
PFPB	13.3	–

[a] Different sources, among others [12,13].

upgrading and brownfield expansion it is assumed, according to existing experience, that technology for digestion will not change, whereas the fluidised bed will in all cases be used for calcination.

- Smelting. The most modern plants with PFPB technology require about 13.3 MWh_{el}/t_{Al}. The upgrading of existing plants, brownfield and greenfield expansion takes place using PFPB technology in the GlobAl model. For upgrading and brownfield expansion it is assumed that up to 2010 an electricity demand of 13.8 MWh_{el}/t_{Al} is achievable compared to 13.3 MWh_{el}/t_{Al} for new plants.

3.5. Regional CO_2 emission factors of electricity production

The regional CO_2 emission factors of electricity production depend on the mix of energy carriers, their specific CO_2 emissions in electricity production and the distribution losses in the regions [23–27]. Electricity produced from hydropower and nuclear fuels is assessed as CO_2-free in the model.

The attribution of the primary energy carriers to electricity production can either be obtained from the regional mix of energy carriers or from the contract mix. The regional energy carrier mix is based on the average shares of the energy carriers in electricity production within a region.[6] The contract mix reflects the mix of energy carriers resulting for electricity consumption according to the contracts of the respective production stage with utilities or for the consumers' own production of electricity from the power generating units used.[7] While the regional mix provides a statistical attribution of production stage to power generating units, the contract mix, on the other hand, permits a more causal attribution. The higher the electricity demand, for example, of a smelting plant, the more electricity has to be supplied by the contractual generating units. Thus, the resulting additional CO_2 emissions are causally linked with the smelting plant demanding additional electricity.

The regional mix is used for the production stages of mining, alumina production, for the transport processes, the production of the preliminary products of caustic soda and anodes because no data are available on the contract mix. The calculation of the CO_2 emissions from electrolysis is based in different scenarios both on the regional and the contract mix.

Worldwide, in total electricity production, the contract mix is characterized by obtaining a larger share of electricity from hydropower. This share was about 60% in 1995, which is not surprising because low-price electricity from hydropower is the deciding factor responsible for siting electrolysis. At about 30% in 1995, the share of electricity from hydropower is clearly lower in the regional mix. In contrast, fossil fuels in electricity supply covered only 37% of the contract mix and 56% of the regional mix in 1995. There are also clear differences in the particular regions. Canada, Brazil or the Rest of Western Europe (Iceland, Norway, Switzerland) had large shares of electricity from hydropower for the contract and regional mix in 1995. In the USA, Germany, India and China, on the other hand, electricity from coal dominated in both cases. It can be assumed that there will not be a significant change in the mix of energy carriers in the contract mix and that any change will also remain comparatively small in the regional mix until 2010. In the developed regions of the USA, Canada, Germany and the Rest of the European Union, slight proportional increases are assumed for gas, primarily at the expense of nuclear energy. In contrast, in China and the Rest of Asia the share of nuclear energy in electricity production increases slightly according to the figures available along with a strong total increase in electricity production. Significant extensions of hydropower are expected for the Rest of Latin

[6] Regions which only consist of one country and those comprising several countries are put on the same level in this respect. The electricity mix of a region is determined via the shares of the states under consideration in the region's total electricity production. In some regions, not all the countries belonging to a region are considered. With the exception of the Rest of Eastern Europe, the major countries with a share of at least 90% are covered with respect to regional electricity production. In the Rest of Eastern Europe, only slightly more than 60% of the regional electricity production is covered due to insufficient data.

[7] If there is more than one smelting plant in a region, weighting is effected via the production capacities of the respective smelting plants.

Table 4
Lower heating value and CO_2 emission factors of fossil reference fuels

Fuels	Lower heating value (MJ/kg_{fuel})	CO_2 emission factor (kg_{CO2}/kg_{fuel})
Natural gas	42.3	2.13
Oil	40.5	3.08
Coal	30.0	2.83

America and Africa. Coal becomes less significant as an energy carrier for electricity production in almost all regions.

The specific CO_2 emissions of electricity production from fossil fuels depend on the emission factors of the fuels, their lower heating values, the power plant efficiencies and the distribution losses between power plant and final consumer. Table 4 shows the lower heating values for region-independent reference fuels taken as a calculation basis and the emission factors resulting from their composition.

The efficiencies of fossil-fired power plants clearly differed for the single regions in 1995. The efficiency of gas-fired power plants was about one third higher for Germany or Canada than for the Former Soviet Union and the Rest of Eastern Europe. In the case of electricity from coal, the efficiency was comparatively low for the Former Soviet Union and the Rest of Eastern Europe, China and India also had low values.

In the projection of the CO_2 emission factors of electricity from fossil energy carriers in the year 2010, it is assumed that the upgrading and replacement of old and the additional construction of new power plants takes place using the same modern technology worldwide. Table 5 specifies the assumed efficiencies for fossil-fired power plants.

On the basis of this assumption, a clear decline in the specific CO_2 emissions of electricity production from fossil energy carriers is expected especially in those regions where power plant capacity is extended for the respective energy carriers. Consequently, improvements, primarily for gas, are obtained in the USA, in Canada, Germany and the Rest of the European Union. Moreover, concerning the specific emissions, the less developed regions approach the level of the developed regions due to the greater additional construction of modern power plants.

Table 6 shows the regional CO_2 emission factors for electricity production for the years 1995 and 2010. The lower values of the contract mix are explained by the higher share of electricity from hydropower in total electricity production.

Table 5
Assumed efficiencies of modern fossil-fired power plants

Natural gas	53%
Oil	48%
Coal	43%

Table 6
Regional CO_2 emission factors for electricity production in 1995 and 2010

	Contract mix 1995 (t_{CO2}/MWh_{el})	2010 (t_{CO2}/MWh_{el})	Regional mix 1995 (t_{CO2}/MWh_{el})	2010 (t_{CO2}/MWh_{el})
USA	0.55	0.49	0.61	0.54
Canada	0.00	0.00	0.19	0.18
Brazil	0.00	0.00	0.05	0.03
Rest of Latin America	0.00	0.00	0.48	0.31
Germany	0.70	0.61	0.67	0.58
Rest of EU	0.35	0.32	0.38	0.32
Rest of Western Europe	0.00	0.00	0.00	0.01
Former Soviet Union	0.24	0.21	0.64	0.50
Rest of Eastern Europe	0.59	0.50	1.10	0.91
Africa	0.66	0.57	0.71	0.55
Near/Middle East	0.29	0.20	0.68	0.50
India	1.06	0.83	0.98	0.71
China	1.06	0.72	1.06	0.66
Rest of Asia	0.00	0.22	0.42	0.34
Australia	0.76	0.68	0.82	0.75
World [a]	(0.40)	(0.33)	(0.56)	(0.45)

[a] Weighting factors are the regional electricity consumption for smelting in 1995.

4. Scenario results for final energy consumption

4.1. Electricity consumption

For the production of 19.7 million tonnes of primary aluminium about 320 TWh_{el} were required in 1995 in the overall material flow. This was 2.4% of the global electricity production of 13,263 TWh_{el} gross [28] estimated for 1995. Specifically, about 16.0 MWh_{el}/t_{Al} were consumed worldwide in 1995. By far the largest part, amounting to 15.5 MWh_{el}/t_{Al} (approx. 95%), is used for the electrolysis process (Table 7).

The absolute electricity consumption in the worldwide primary aluminium flow increases in each of the three scenarios, although degressively measured against production. In the base scenario, production rises by about 37% from 1995 to 2010, electricity demand by roughly 23% to about 390 TWh_{el}. In the low demand scenario, production increases by 26% in the same period and electricity demand by roughly 13% compared to 47% and about 30% in the high demand scenario. The world average specific electricity demand in electrolysis decreases from 15.5 MWh_{el}/t_{Al} to 13.8 MWh_{el}/t_{Al} and 13.9 MWh_{el}/t_{Al} in all three scenarios. This is due to the more extensive use of modern PFPB technology, both in upgraded or expanded and in new facilities. Applying PFBP technology in global primary aluminium production increases from about 40% in 1995 to about 90% in 2010. The Soderberg technology, still used for the production of about 30% of primary aluminium in 1995, will largely disappear. Existing plants with Soderberg technology will be upgraded with PFPB technology to a large extent according to the scenario calculations. The comparatively high electricity consumption makes upgrading economically attractive. Nevertheless, Soderberg plants will only be closed down in a few regions due to very high elec-

Table 7
Specific final energy consumption in the global flow of primary aluminium in 1995 and changes until 2010 (for the base scenario)[a]

	Electricity		Natural gas		Oil		Coal		Diesel	
	1995 (MWh/t_{Al})	Changes until 2010 (%)	1995 (GJ/t_{Al})	Changes until 2010 (%)	1995 (GJ/t_{Al})	Changes until 2010 (%)	1995 (GJ/t_{Al})	Changes until 2010 (%)	1995 (GJ/t_{Al})	Changes until 2010 (%)
Processes	16.0	−10.5	10.7	−25.4	10.7	−36.4	5.7	−35.4	1.0	−21.9
Mining	<0.1	−14.1	0.0	0.0	0.0	0.0	0.0	0.0	1.0	−21.9
Refining	0.5	−15.1	10.7	−25.4	10.7	−36.4	5.7	−35.4	0.0	0.0
Smelting	15.5	−10.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transport	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.3	0.0
Material inputs	0.2	0.0	0.3	20.3	0.8	35.0	0.0	0.0	0.0	0.0
Caustic soda prod.	0.1	−15.9	0.1	−15.9	0.1	−15.9	0.0	0.0	0.0	0.0
Anode production	<0.1	42.9	0.2	43.0	0.7	43.0	0.0	0.0	0.0	0.0
Total	16.2	−10.4	11.0	−24.3	13.0	−27.8	5.7	−35.4	1.3	−16.5

[a] Model calculations.

tricity prices, like the Rest of Eastern Europe and China according to the base scenario. Apart from the Soderberg technology, also the CWPB and SWPB technologies will lose ground.

4.2. Thermal energy consumption

In 1995 about 240,000 TJ gas, 280,000 TJ oil, 125,000 TJ coal and roughly 30,000 TJ diesel were consumed in the flow of primary aluminium to produce thermal energy. Gas, oil and coal are mainly needed for alumina production. Basically, the energy carriers are used for heating the caustic soda for digestion and covering the heat requirements of the calcining kilns. Diesel is mainly used for mining, especially for supplying heavy equipment (e.g. heavy-duty trucks, excavators, scrapers). The primary energy demand for thermal energy is clearly less than 25% of the primary energy demand for electricity production in the flow of primary aluminium. According to the base scenario, absolute consumption is expected to stagnate for the remaining final energy carriers until 2010. Slightly increasing consumption results for gas, slightly decreasing consumption for oil and coal. For the high demand scenario, consumption grows degressively whereas it decreases for the low demand scenario. Table 7 shows the specific final energy consumption in 1995 and 2010 for the base scenario. The specific values for low and high demand scenarios are very similar. The significant aspect is the stronger decline for oil and especially coal compared to gas. Countries also using coal as an energy carrier for alumina production (especially India and China) achieve higher efficiency gains starting from a low level. Increases in final energy consumption can be observed only in anode production, which can be put down to the change from Soderberg to PFPB technology using prebaked anodes.

5. Scenario results for CO_2 emissions

5.1. Total CO_2 emissions and shares of the different process steps

Worldwide energy-related CO_2 emissions were estimated to amount to approx. 23,125 million tonnes in 1995 [28] with a share of the primary aluminium flow of about 1%. According to the contract mix, approx. 217 million tonnes of CO_2 emissions were to be allocated to the flow of primary aluminium in 1995, compared to approx. 267 million tonnes according to the regional mix. Thus, almost 11 t and roughly 13 t of CO_2, respectively, were released per tonne of primary aluminium on a worldwide average.

Most of the CO_2 emissions resulting from the flow of primary aluminium are caused by electricity production for electrolysis, amounting to 58% for the contract mix and 66% for the regional mix. The second largest contribution of 23 and 19%, respectively, involves the provision and use of fossil energy carriers for alumina production. Process-related emissions from electrolysis follow with 16 and 13%, respectively. Energy-related emissions from mining as well as preliminary material chains are of very little significance (Fig. 3).

CO_2 emissions hardly undergo any change according to the calculations for the base scenario for the contract mix and the regional mix from 1995 to 2010. In the low demand scenario, the CO_2 emissions decrease whereas they increase slightly in the high demand scenario. The specific

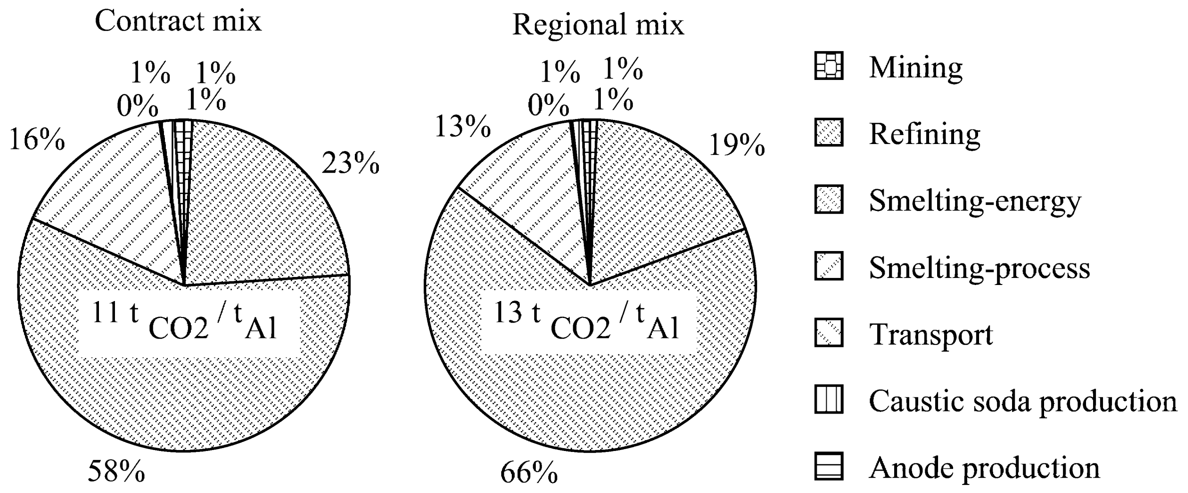

Fig. 3. Specific CO_2 emissions in the flow of primary aluminium in 1995.

CO_2 emissions clearly decrease in each scenario, i.e. by 25% to about 8 t_{CO2}/t_{Al} consistently for the contract mix and by 28% to about 9.5 t_{CO2}/t_{Al} consistently for the regional mix (Table 8).

5.2. Decrease of emissions in smelting—the reasons

The decrease in specific energy-related CO_2 emissions from electrolysis explains the decrease in total emissions of about 65 and 75%, respectively. Four variables are jointly responsible for the level of specific energy-related emissions from electrolysis: the specific final energy demand, the production geography, the mix of energy carriers for electricity production and the efficiency of fossil-fired power plants. It is possible to isolate their respective influence on the variation of the result by using two methods: in the first method, only one factor of influence is varied on the basis of the values in 1995, while the variation is based on the values for 2010 in the second method. The sum of the individual variations is normalised to 100% in both methods and the share of the individual parameter is isolated. Since in the first case the weighting of the unchanged

Table 8
CO_2 emissions in the flow of primary aluminium[a]

	1995 Reference year	Base scenario	2010 Low demand	High demand
World Wide (mt)				
Contract mix	217	222	210	243
Regional mix	267	261	239	284
Specific (t_{CO2}/t_{Al})				
Contract mix	10.7	8.0	7.9	8.2
Regional mix	13.2	9.5	9.3	9.6

[a] Model calculations.

quantities is effected relative to the values of 1995 and in the second case relative to those of 2010, the results differ for the two methods.

Irrespective of allocation method and selected mix of energy carriers, however, it is found that the decrease in specific energy-related emissions from electrolysis is in fact largely caused by the higher efficiency of fossil-fired power plants. This explains more than half of the decrease. The decline in specific electricity demand for electrolysis is responsible for about one third of the decrease in CO_2 emissions. The share of the changed production geography in the lower specific emissions ranges from 11 to 22%. The highest decrease is observed for the contract mix weighted in relation to the starting values. On the one hand, the contract mix provides a distinctive correlation between a large share of hydropower, free from CO_2, and the preferred region. On the other hand, the weighting in relation to starting values attributes higher specific CO_2 emissions from electricity production to the fossil-fired power plants, so that the shift to regions with a high contribution of hydropower is reflected by an increased reduction of emissions. Changes in the energy mix are of little consequence, as there is a slight decrease in emissions for the regional mix and a slight increase for the contract mix. For the regional mix, the shift from CO_2-free nuclear energy to gas in industrialised countries is overcompensated by the proportional losses of the highly unfavourable coal in terms of CO_2 emissions expected for almost all regions. Moreover, the shift to hydropower in Africa and the Rest of Latin America as well as to nuclear energy in India and China has certain effects. For the contract mix, the move away from hydropower to fossil energy carriers for the electricity supply of new smelting plants in India and the Rest of Asia is responsible for increasing emissions (Table 9).

5.3. *Decrease of emissions in smelting—the regional view*

The absolute energy-related CO_2 emissions from electrolysis in the regions differ as a function of their primary aluminium production and their regional specific CO_2 emissions. Fig. 4 gives a survey of the respective regional shares in the worldwide production of primary aluminium and in the worldwide energy-related CO_2 emissions from electrolysis for 1995 and, according to the base scenario, for 2010. The largest producers of primary aluminium in 1995 were the USA, the

Table 9
Reasons for and extent of change in the energy-related specific CO_2 emissions from smelting[a]

Change is caused by	Regional mix Values for 1995 as weights (%)	Values for 2010 as weights (%)	Contract mix Values for 1995 as weights (%)	Values for 2010 as weights (%)
Decrease of specific consumption of electricity	30	28	28	31
Change in production geography	16	11	22	15
Change in energy mix	3	5	−3	−7
Higher efficiencies of fossil-fired power plants	51	56	53	61

[a] Model calculations.

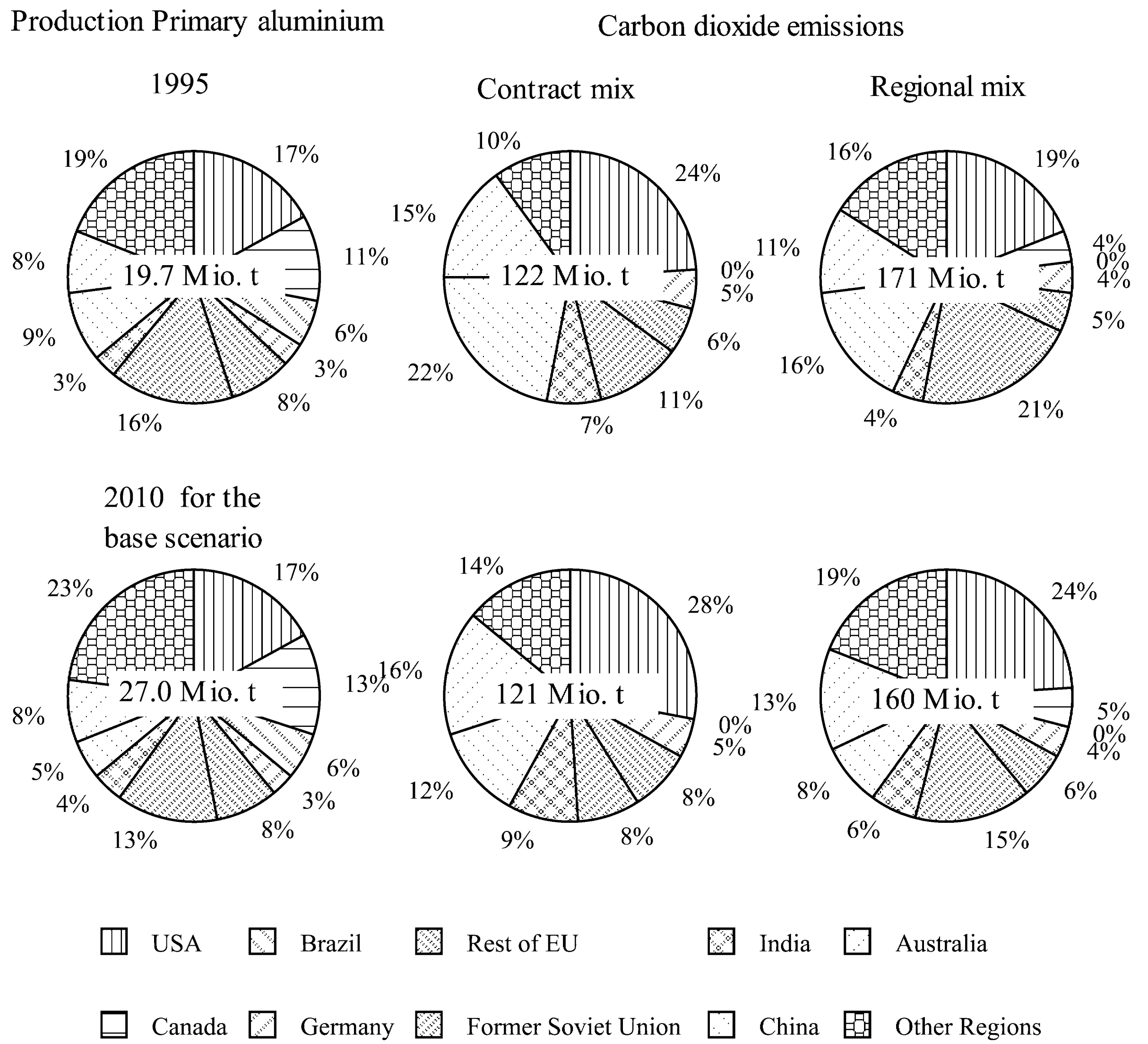

Fig. 4. Production of primary aluminium in the regions and corresponding CO_2 emissions of energy use in 1995 and for the base scenario in 2010.

Former Soviet Union and Canada. CO_2 emissions mostly occurred in the USA followed by China and Australia according to the contract mix, the Former Soviet Union ranks above the USA and China according to the regional mix. The contract mix does not provide any energy-related emissions for Canada and Brazil due to the fact that they obtain 100% of their electricity from hydropower. For the regional mix, too, low absolute CO_2 emissions were to be observed due to the major share of electricity from hydropower in comparison to the production share.

Regarding the base scenario, the USA will also produce the largest amount of primary aluminium in 2010, followed by the Former Soviet Union and Canada. The USA, and especially

Canada, show slightly growing production shares, whereas the Former Soviet Union exhibits a slight decline. Also in future the USA will be responsible for the highest energy-related CO_2 emissions from electrolysis. Australia and China follow for the contract mix, the Former Soviet Union and Australia for the regional mix. The relative position of the countries to each other is also maintained for the scenarios of low and high demand.

Table 10 gives a survey of the regional specific energy-related CO_2 emissions from electrolysis for the year 1995 and, according to the base scenario, for 2010. The figures are comparable for the scenarios of low and high demand. The differences in the regions mainly result from final energy demand and from the CO_2 emission factor of the total electricity supply, for which the respective mix of energy carriers and the efficiencies of the fossil power plants are decisive. In regions such as China, India or Germany, where electricity supply is primarily based on fossil energy carriers, the CO_2 emission factor of total electricity supply and the specific energy-related CO_2 emissions from electrolysis are high. The specific energy-related CO_2 emissions decrease in all regions except the Rest of Asia where hydropower was exclusively used in 1995 for the contract mix. The use of gas for the electricity supply of new plants leads there to increasing specific emissions.

Even though the specific energy-related CO_2 emissions from electrolysis decrease in nearly every region, not all regions make the same contribution to the reduction of worldwide specific emissions. In order to isolate the significance of the decrease in specific emissions in a region from the worldwide specific emissions, it is, first of all, necessary to weight the region's specific emissions for 1995 and 2010 with the respective production shares. The changes in weighted specific emissions obtained for the regions will then be normalised to the total change in worldwide specific emissions.

Much more than half of the reduction of worldwide specific energy-related CO_2 emissions from electrolysis is due to the reduction of specific emissions in only three regions for the contract mix: China, USA and the Former Soviet Union. These three regions are also responsible for more than half of the reduction for the regional mix. The pronounced reduction in specific emissions for the Former Soviet Union alone as a relatively large producer accounts for almost one third of the total reduction (Table 11).

6. Summary

The scenario calculations indicate that the absolute worldwide CO_2 emissions from the flow of primary aluminium will stagnate or decline in the case of growth rates below 2% per year for the worldwide demand for primary aluminium. The specific emissions will clearly decline irrespective of the demand development. This is largely due to the lower energy-related emissions from electrolysis. Their decline is caused by the higher efficiencies of fossil-fired power plants, electricity savings due to the increased use of modern PFPB technology and shifting of primary aluminium production to regions with a high share of electricity from (CO_2-free) hydropower.

The scenario calculations are only valid to a limited extent against the background of the underlying assumptions. Since the decline in worldwide specific energy-related CO_2 emissions from electrolysis is largely accounted by the Former Soviet Union, China and the USA according to the model calculations, it is important that the expectations of a modernisation of the primary

Table 10
Specific energy-related CO_2 emissions for electrolysis in the regions in 1995 and for the base scenario in 2010[a]

	Contract mix 1995 (t_{CO2}/t_{Al})	2010 (t_{CO2}/t_{Al})	Change (%)	Regional mix 1995 (t_{CO2}/t_{Al})	2010 (t_{CO2}/t_{Al})	Change (%)
USA	8.5	6.9	−19	9.5	7.6	−20
Canada	0.0	0.0	0	2.8	2.5	−11
Brazil	0.0	0.0	0	0.7	0.4	−47
Rest of Latin America	0.0	0.0	0	7.3	4.3	−41
Germany	10.7	8.5	−21	10.3	8.1	−21
Rest of EU	4.6	4.5	−3	5.4	4.5	−17
Rest of Western Europe	0.0	0.0	0	0.1	0.1	83
Former Soviet Union	4.4	2.8	−36	11.6	6.9	−40
Rest of Eastern Europe	9.0	7.2	−20	16.7	13.1	−22
Africa	9.6	8.0	−17	10.3	7.8	−25
Near/Middle East	4.4	2.8	−36	10.3	7.0	−32
India	16.2	11.4	−29	15.0	9.9	−34
China	15.9	10.0	−37	15.9	9.1	−43
Rest of Asia	0.0	3.0		6.3	4.7	−26
Australia	11.2	9.4	−16	12.1	10.4	−14
World	6.2	4.5	−28	8.7	5.9	−32

[a] Model calculations.

Table 11
Contributions of the single regions to the decline of worldwide specific energy-related CO_2 emissions from electrolysis[a]

	Contract mix		Regional mix	
	Weighting factors are the production shares of			
	1995 (%)	2010 (%)	1995 (%)	2010 (%)
USA	19	22	13	15
Canada	0	0	1	2
Brazil	0	0	1	1
Rest of Latin America	0	0	5	6
Germany	5	5	3	3
Rest of EU	1	1	3	3
Rest of Western Europe	0	0	0	0
Former Soviet Union	17	16	29	27
Rest of Eastern Europe	2	2	2	2
Africa	3	6	3	5
Near/Middle East	5	5	6	6
India	8	13	5	8
China	34	25	23	16
Rest of Asia	−2	−6	1	2
Australia	10	11	5	6

[a] Model calculations.

aluminium smelting plants and especially of the fossil power generating units will be realised precisely in these regions.

Acknowledgements

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MODEL-BASED ANALYSIS OF ENERGY USE AND GHG EMISSIONS OF GLOBAL ALUMINIUM INDUSTRY*

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ABSTRACT

The Collaborative Research Center 525 „ A Resource-Orientated Analysis of the Metallic Raw Materials Flows“ aims to develop operative recommendations for a resource-sensitive utilisation of metallic raw materials. The objects of research are the primary production processes of metallic raw materials, secondary production processes (recycling) and disposal. The survey will take particular account of economic and environmental factors alongside technical considerations.

For this purpose, among other models a computer-based partial equilibrium model of the global aluminium industry is developed to demonstrate the cause-and-effect relations behind the resource flows. The model simulates a competitive global market for primary aluminium and intermediate products. Allocations depend on demand, resource endowments, technologies, and instruments of economic policy. The model contributes to give an explanation of empirical observations on global level with regard to production structures, industry relocation, technological progress and environmental impacts. Besides investment, production and international trade, the global model as well assesses future developments of emissions for all main processes and regions.

At present, the model describes the global aluminium industry from bauxite mining to primary aluminium smelting. Assuming different growth rates of primary aluminium demand, its impacts to the investment and production allocation of the global aluminium industry, as well as energy use and correspondig emissions of carbon dioxide (CO_2) and emissions of perfluorinated hydrocarbons (CF_4, C_2F_6) are demonstrated.

KEYWORDS

Global aluminium industry, energy use, GHG, CO_2, CF_4, C_2F_6, partial equilibrium model

* Source: Proceedings 3rd Biennial Conf. of the European Society for Ecological Economics, Vienna, 2000

1. Introduction

Industry in general is seen as an important factor contributing to environmental stress. Within the industry, certain areas of industrial production place the largest burden on resource use and emission production. Besides the production of paper, petroleum products, stone, cement, clay, glass, chemicals and other primary metals, primary aluminium production is regarded to be amongst the main industrial contributers to environmental stress (Jänicke et al. 1997). In particular, it is regarded to be highly problematic because of its high energy requirements and related greenhouse gas emissions (carbon dioxide and perfluorinated hydrocarbons). On global average, electricity demand per tonne primary aluminium is around 16 MWh.

From an economic viewpoint, there are three important characteristics describing international aluminium industry. First, mining activities, alumina production and aluminium smelting require huge long-term investments of capital. Second, economic deposits of bauxite and access to cheap hydro-based electricity (in large quantities) are geographically limited. Third, technological barriers to new entrants will remain high for the foreseeable future (Ericsson 1996). Additionally, primary aluminium production is a prime example for an industry being incumbered with sunk costs. Altogether, these factors constitute a frame for geographical allocation of international aluminium industry and for modelling the international primary aluminium industry.

A number of studies are dealing with the subject of material and energy flows initiated by the aluminium industry (Tab. 1). They differ with respect to the modelling approach as well as their geographical reference. Representative approaches to model material and energy flows comprise process chain analysis (PCA), life cycle assessment (LCA), material flow/ substance flow analysis (MFA/SFA), and partial equilibrium analysis (PEA) (Definitions of LCA, MFA/SFA and PEA according to Bouman et al. 2000).

PCA and LCA both are tools to assess the environmental consequences of a product. They differ in how much process steps are regarded. Whereas PCA may concentrate on aspects of production of intermediates, for example primary aluminium, LCA follows a product from cradle to grave. It focuses on the function of a product, not on the product itself, e.g. the function of an aluminium window frame. Necessarily, it includes the use phase of a product. For LCA ISO-series 14040 proposes a standardised procedure.

MFA/SFA modeling is based on economic input-output analysis, a standard economic tool describing mutual deliveries between sectors in terms of money or in terms of volumes of goods. Partial equilibrium models describe the outcome of a market or a set of markets by depicting the behavioral relations that underlie the outcome. The results of PEA depend heavily on the assumption that all actors on a market behave as to maximise their pay-offs, equating marginal benefits and marginal costs, and the assumption that all markets are cleared. Therefore, PEA allows to cover important economic characteristics of the aluminium industry in a flexible manner.

Only a few studies are based on a scenario approach to show the range of plausible developments of the global aluminium and its initiated material and energy flows.

		National	Regional	Global
Techno-sphere	Process chain analysis (PCA)	UN 1995; Ayres et al. 1996; TERI 1996; Sheffield 1997; Phylipsen et al. 1998; Das et al. 1998[b]; Corradini et al. 1999	EAA 1997	Adelhardt 1997
	Life cycle assessment (LCA)[a]	Schäper et al. 1996 Zapp 2000[b]	Aluminium Association 1998	
Econo-mic sphere	Material flow and substance flow analysis (MFA/SFA)	Ferrer et al. 2000[b, c]		Duchin et al. 1994[b, c]
	Partial equilibrium analysis (PEA)	Sutherland et al. 1997[b]	Gielen 1998[b]	Brown et al. 1983[b, c] Nichols et al. 1992[b, c] Manne et al. 1994[b, c]

[a]: Though not all studies mentioned here may be classified as pure LCA-based studies, they follow to some extent the standardised procedure proposed by the ISO-series 14.040 or show strong similarities.
[b]: Scenario approach
[c]: Duchin and Ferrer concentrate on the evaluation of economic impacts of technical or structural change. Brown, Nichols and Manne study aspects of production and investment geography. The model concepts allow an extension to the assessment of energy flows.

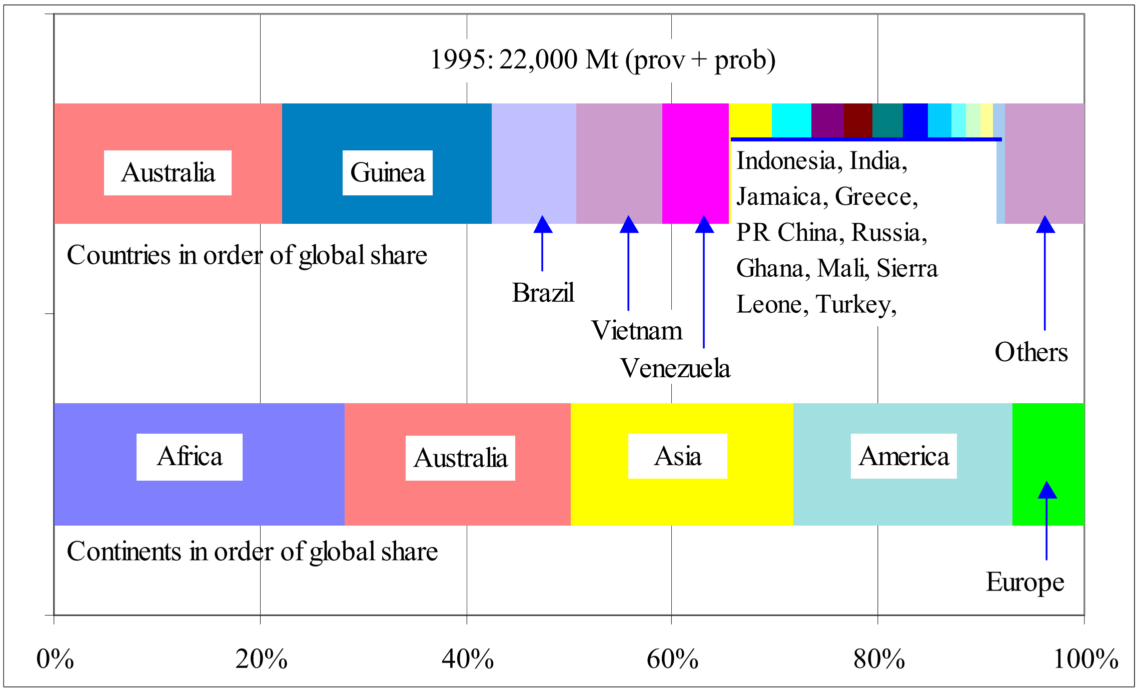
Tab. 1: Selected studies on energy flows associated with the production of aluminium

This paper aims to quantify the material and energy flows of present and future primary aluminium industry on a global and regional scale. The calculations are based on a PEA modelling approach. The paper concentrates on energy use and greenhouse gas emissions, e.g. CO_2 and perfluorinated hydrocarbons (CF_4, C_2F_6). In a first chapter, we present an overview on important factors, constituting the supply of the resource bauxite and the production of alumina and aluminium. After that, we present a computer-based model of the international primary aluminium industry. In the third chapter, calculations for the status quo (1995) and scenario-based calculations for 2010 are presented.

2. Bauxite reserves and global production capacity

The production of aluminium is divided into bauxite mining, production of alumina, and production of primary and secondary aluminium. Mining of bauxite is tied to regions with natural deposits, whereas the production of primary aluminium is related to regions with sufficient and cheap electricity. The geographical distribution of production at each value-adding stage is the result of weighing up the competitive advantages and disadvantages of competing locations. Further basic aspects comprise geopolitical stability (especial for mining activities), environmental policy, infrastructure, and level of training of employees.

Bauxite reserves, production and demand figures are statistically fairly well covered. Fig. 1 shows regional shares of bauxite reserves for 1995. Except Europe (7%), the other continents have high shares of bauxite reserves in the range of 21% to 28% of global reserves. From a countries perspective Australia, Guinea, Brazil, Vietnam and Venezuela own 66% of global reserves. Including Indonesia, India, Jamaica, Greece and China, 10 countries possess 82% of global bauxite reserves.

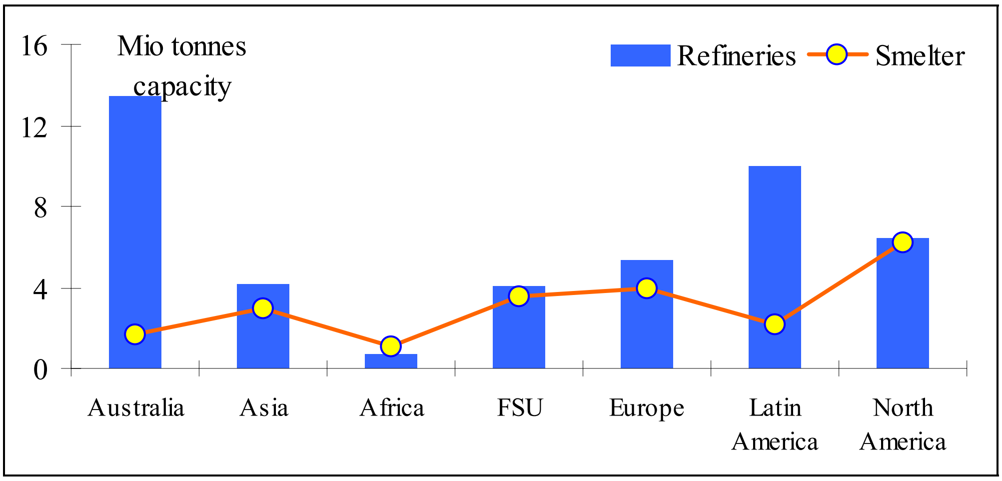


Source: Metals Statistics; SFB 525 – SP1

Fig. 1: Bauxite reserves and its regional shares, 1995

Global refinery capacity was 44 million tonne in 1995, mainly concentrating on Australia, Latin-America and North-America. The biggest shares of capacities are due to Australia (31 %) and Latin-America (23%) (Fig. 2), both regions having large amounts of bauxite deposits. North-America, with a minor share of bauxite deposits of 1%, has 15% of global refinery capacities. Other regions have 31% of global capacities.

Global smelting capacity was 22 million tonne in 1995, mainly concentrating on highly industrialized countries. As an energy-intensive industry, the aluminium industry is mainly located in those countries, which have large amounts of cheap electricity available. On the one hand the energy source may be hydro electricity. On the other hand it may be nuclear or coal-



Source: Information system SFB 525 based on CRU data

Fig. 2: Regional shares of global refinery and smelter capacity, 1995

based electricity, being relatively cheap for the aluminium industry due to special contracts. The biggest shares of capacities are due to US (18%), Western Europe (16%), Former Soviet Union (16%), and Canada (11%). Other regions have 39% of global capacities.

3. Modelling aspects

3.1 Model concept

To quantify production and to explain investment geography of the international aluminium industry model-based approaches were developed (Brown et al. 1983; Nichols et al. 1992). Manne et al. 1994 used an extended version of Brown's model to calculate the impact of a carbon tax on the location of aluminium smelting.

The model of the global aluminium industry (GlobAl) is a partial equilibrium model, which permits an integrated analysis of the technical, geographical, ecological and economic dimension of the material flow of primary aluminium (Schwarz 1999; Schwarz et al. 2000). It is computer-based and uses linear programming technique. The demand for primary aluminium is assumed to be given and not price-elastic. The model is static. All the model parameters and all the variables (production and transport quantities, investment) refer to the year 2010. The reference year 1995 influences the model results only indirectly. The assessment of model parameters for the year 2010 is based on figures for 1995 or a period including 1995.

The implemented mathematical algorithm calculates a long-term market equilibrium with perfect competition (Takayama et al., 1971). It is therefore implicitely assumed that the producers of bauxite, alumina and primary aluminium maximize their profits decentrally. They accept the market price as given and adjust their production quantities according to their marginal costs.

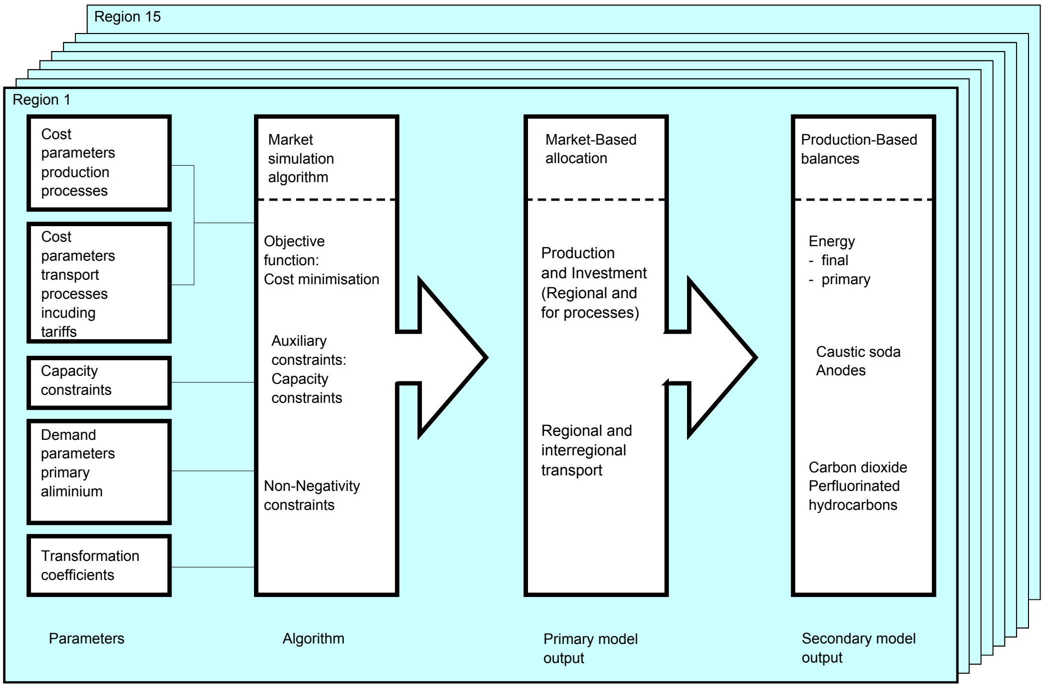


Fig. 3: Concept of the model of the global primary aluminium industry

3.2 Material and energy flows and production processes

The model of the global aluminium industry considers the global flow of primary aluminium. The manufacture of primary aluminium in the remaining process chain, reusage through recycling and, if necessary, waste disposal is additionally part of the total flow of aluminium.

Technical transformations within the material flow are reflected in processes which are characterised by inputs and outputs (Fig. 4). Assuming to use processes to capacity its technical transformations are strictly linear.

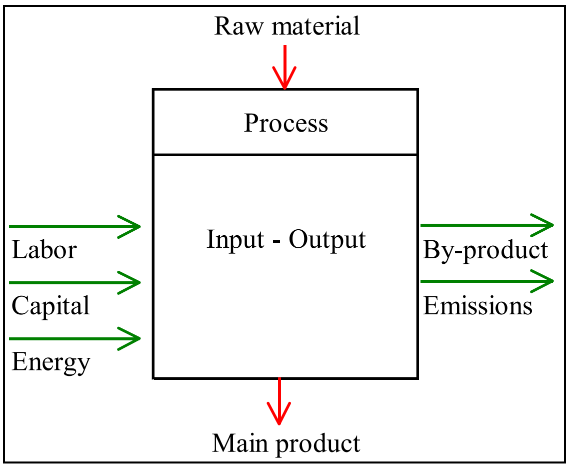


Fig. 4: Main inputs and outputs of a simplified process

The inputs comprise raw materials, labor, capital and energy as main inputs. The outputs are the product (main output) and by-products. Additional information is given for costs and value added, as well as for emissions. Emissions are divided into energy-related and others. Due regional or global impacts, a division of energy-related emissions into greenhouse gases and other (locally or regional active) emissions is useful.

Three process steps are constituting production of primary aluminium: mining, refining and smelting (Fig. 5). Transport processes complete the process chain. Additionally, the supply of final energy carriers for processes, e.g. diesel, electricity and gas, is integrated.

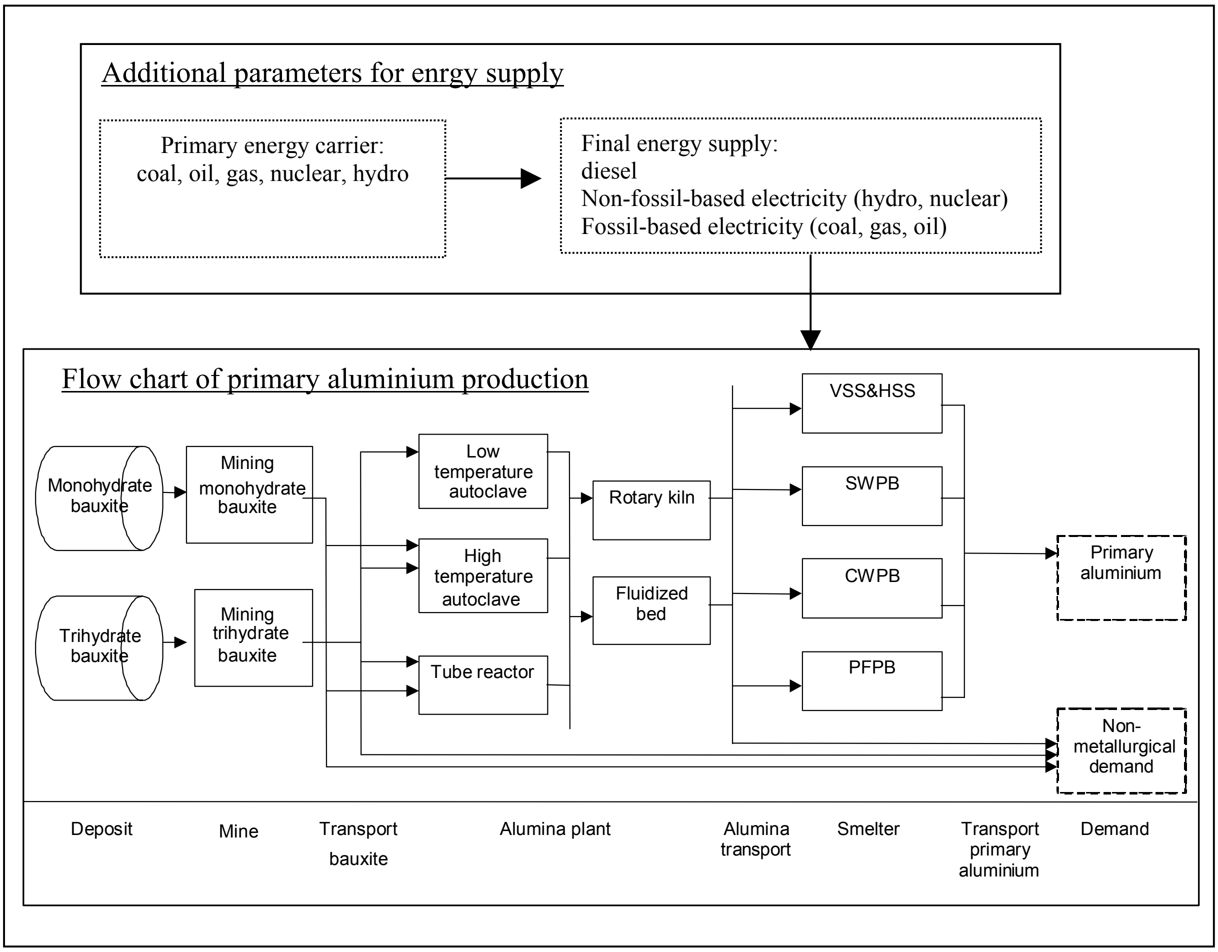


Fig. 5: Simplified model structure

The chemical and mineralogical heterogeneity of bauxite is reflected in 18 bauxite types. The different technical options for the three process steps are integrated into a few technologies. Six technologies are distinguished for refining and four technologies for smelting. The model considers three transportation steps: mine to refinery, refinery to smelter and smelter to final demand. Means of transport are truck, rail, conveyor belt, inland and overseas ship.

The model separates four kinds of investment strategies for ming, refining and smelting: old plants, upgrading, brownfield expansion and greenfield expansion. Upgrading of old plants means that the technical parameters of the plants are improved by changing components. Outmoded technologies are usually replaced by modern technology. Within the model, upgrading is not connected with capacity expansion. It is the brownfield expansion which leads to the capacity expansion of existing plants. Greenfield expansion means that new plants are built. The reason for considering the different investment strategies is, on the one hand, that old plants and new plants do not have the same technical parameters even if they use the same technology. Usually the new plant will be superior. On the other hand, new plants as well as brownfield expansion and upgrading cause investment costs, whereas the (former) investment costs of old plants are not relevant from the model's perspective ('sunk costs').

The model considers 15 world regions (Fig. 2).

3.3 Energy use and greenhouse gas emissions

Besides labor, other operational costs (including aluminium fluoride and cryolite), caustic soda, anodes, the main output from the preceeding value-adding step (bauxite, alumina) and energy carriers (diesel, thermal energy, electricity) are important inputs for the processes. The most important energy carrier is electricity used for electrolysis. Final energy used in the processes, e.g. diesel for transportation, natural gas for thermal energy, causes process-induced greenhouse gas emissions (CO_2, CF_4, C_2F_6) as well as other energy-related emissions (SO_2, CO).

Additionally, the conversion process of primary energy carriers to final energy carriers has to be considered to quantify energy-related emissions initiated by the aluminium industry. The mix of primary energy carriers for electricity production and the efficiencies of different conversion processes determine to a large extent the amount of specific emissions, especially for carbon dioxide. Across the world, both factors differ widely. The model takes into account the specific conditions for the 15 global regions. Therefore, region-specific CO_2-factors for electricity supply vary considerably.

Due to special electricity supply contracts between utilities and smelters the model differentiates between contract mix and regional mix of electrical power supply. The contract mix considers the energy carriers for electricity production used after existing contracts for smelting or self-generated electricity. The regional mix on the other hand reflects the average shares of the energy carriers for regional production of electricity. The contract mix is characterized by high efficiencies of power supply and a high share of fossil-free produced electricity (hydro, nuclear), whereas the regional mix shows lower efficiencies and a higher share of fossil-fuel based power plants.

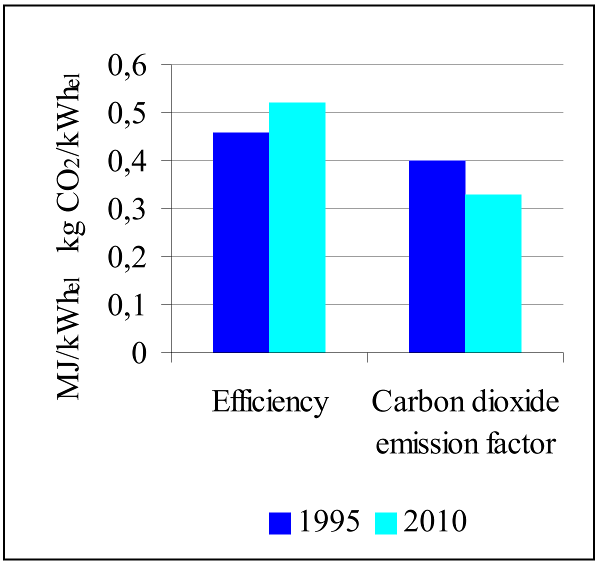


Fig. 6: Efficiency of electricity supply and CO_2-factors for contract mix

As a consequence, CO_2-factors based on the contract mix are lower (Fig. 6, for a detailed discussion of energy supply and technology-specific energy requirements cp. Schwarz 1999). Until today it is not fully discussed under what circumstances to choose contract mix or regional mix for primary energy calculations and greenhouse gas balances is appropriate. Besides technical aspects of energy conversion and contracts economic aspects become more important. The ongoing liberalisation of electricity markets and the effects of increasing electricity trade and transportation have to be considered more intensively.

3.4 Costs

Technical parameters and input prices together determine the specific costs. Because of the great regional differences in technical parameters and input prices the operating costs vary remarkably between the regions. On the world average, the specific operating costs are 15 $\$_{1995}$ for mining, 150 $\$_{1995}$ for refining bauxite and 1350 $\$_{1995}$ for smelting alumina (Fig. 7). Labor is the dominant single cost for mining. Bauxite costs are dominant for refining and thermal energy is responsible for more than 20 % of the costs. For smelting, alumina cost were dominant. Nevertheless, electricity costs which were responsible for 24% of operating costs are more important for the location of the smelters. The reason for this is that the variation of prices for electricity is much greater than for alumina. This is not surprising because hydropower has a natural competitive advantage and long-distance trading of electricity is only economic to a limited extent.

The operating costs vary considerably across the world. For Germany average operative costs of smelters are 1500 $\$_{1995}$, for the rest of European Union 1400 $\$_{1995}$, and for the rest of Western Europe 1380 $\$_{1995}$. In Germany operative costs range from 1400 $\$_{1995}$ to 1660 $\$_{1995}$ (own calculations based on CRU).

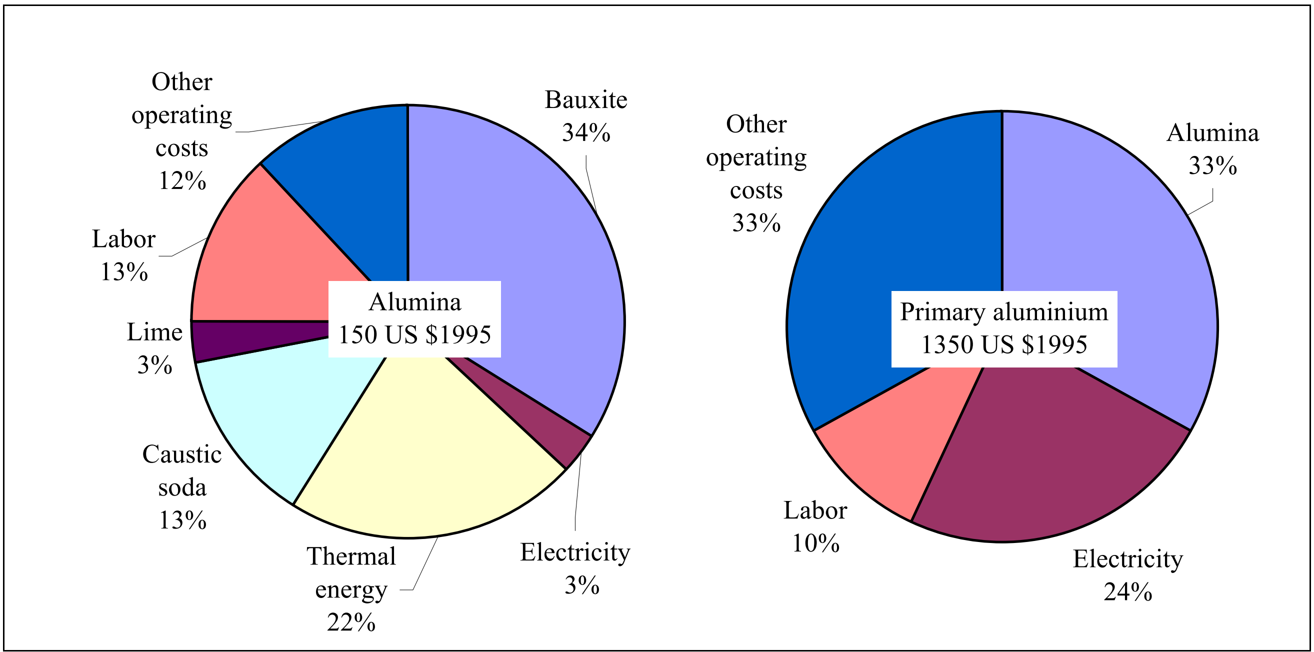


Fig. 7: World average operating costs per tonne of output for refining and smelting

4. Scenario approach and model calculations

4.1. Assumptions

To go beyond calculating the status quo (1995) we use a scenario approach for future projections (2010) of the global aluminium supply and initiated material and energy flows and resulting greenhouse gas emissions. The projection of the model parameters is based on two assumptions: globalisation and worldwide deregulation. Therefore, we implicitely assume a convergence of regional prices to an average price for tradable goods. Additionally, we assume the markets to become more effective and to initiate the same technical parameters worldwide for upgrading, brownfield and greenfield expansion.

As a critical model parameter, future demand of primary aluminium has great influence on model results because the implemented material balance equations lead to an equalization of supply and demand. Projections of the future global demand for primary aluminium are difficult. The reason is that the growth rates of the demand for primary aluminium are dependent on the future development of the world economy. Competition with other raw materials and the recycling quota additionally influence demand. Therefore, future demand for primary aluminium is varied to reflect a range of possible developments.

In 1995, demand for primary alminium was 19.7 million tonnes. Adapting the World Bank outlook for metals (World Bank 1994) three cases for future projection are distinguished:

- The base case assumes a moderate growth rate of primary aluminium of 1.9% per year from 1995 to 2010. This is the growth rate which was valid for the period from 1980 to 1995.
- The low-demand case assumes a growth rate of 1.4% per year.
- The high-demand case assumes a growth rate of 2.4%.

With respect to primary energy and CO_2 calculations the use of contract mix or regional mix is another critical model parameter. Although the appropriateness of the use of contract mix or regional mix is not yet extensively discussed, we concentrate in the following on contract mix.

4.2. Status quo and scenario calculations

For further presentation we concentrate on the base case.

Final energy

According to the calculations for the base scenario the production of primary aluminium will expand from 19.7 to 27.0 million tonnes. In 1995 about 320 MWh of electricity was used for the production of primary aluminium. This is about 2.4% of the total world electricity production. Smelting itself was responsible for about 95% of the electricity consumption in the flow of primary aluminium. The consumption of electricity will increase underproportinately by 23% to 393 million MWh until 2010. Specific electricity consumption will decrease from 16.2 MWh per tonne of metal in 1995 to 14.5 MWh in 2010. The reason for this is especially the superseding of Söderberg technology by modern PFPB technology.

The picture is similar for other final energy consumption carriers. The consumption of natural gas will increase until 2010, but only underproportinately. Specific consumption will decrease. For oil and coal even the absolute figures will decline marginally. The reason for this is the technology progress in alumina production.

Primary energy

The worldwide consumption of primary energy in 1995 was assessed at about 343,000 PJ (BMWi 1998). Model-based calculations show the share initiated by the flow of primary aluminium to be about 1% or 3,300 PJ (Fig. 8).

The expansion of demand for primary aluminium has a great influence on the absolute figures. In the base case absolute primary energy consumption will increase to 3,500 PJ. Varying the growth rates of demand, calculation show a decrease of absolute primary energy consumption (low-demand case) or a considerable increase (high demand case).

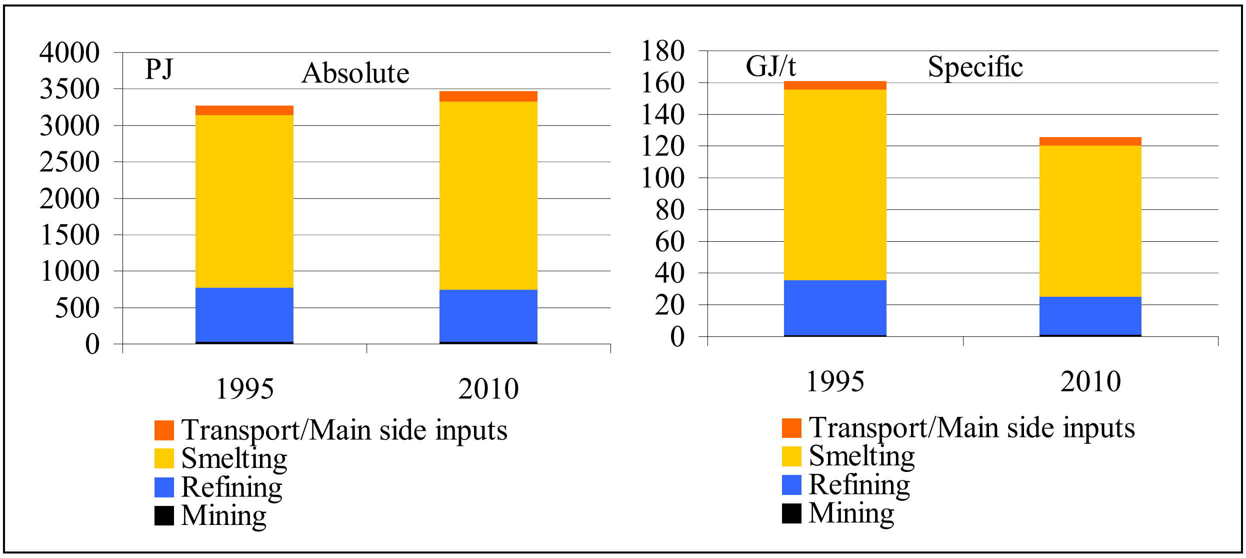


Fig. 8: Absolute and specific total primary energy use for processes (base case)

For the base case, as in the other cases, smelting and refining processes initiate 95 % of total primary energy consumption, with smelting accounting for more than two thirds of it. Therefore, reductions of specific energy consumption for this process dominate total reduction of specific energy consumption. In the case of smelting the reduction is considerable. The average specific consumption of electricity for smelting will decrease from 15.5 MWh per tonne Metal in 1995 to 13.9 MWh per tonne in 2010. The reason for this is Söderberg technology being superseded by modern PFPB technology. There will also be a decline in specific consumption for other energy carriers.

The specific primary energy consumption of the material flow will decrease remarkably especially because of the reduced consumption for smelting. There are three reasons for this (Fig. 9). In the first place, the higher efficiency of electricity generated from fossil fuels leads to a reduced consumption of primary energy. Except own electricity production, this is a matter of the electricity supplying sector. Secondly, modern PFPB plants use less electricity than the Söderberg plants they replace. And thirdly, the production of primary aluminium is being shifted to regions where the production of electricity is mainly based on hydropower. The shift itself is economically determined. There is a strongly marked correlation between the share of hydropower for electricity production in one region and the regional tariffs for electricity for electrolysis.

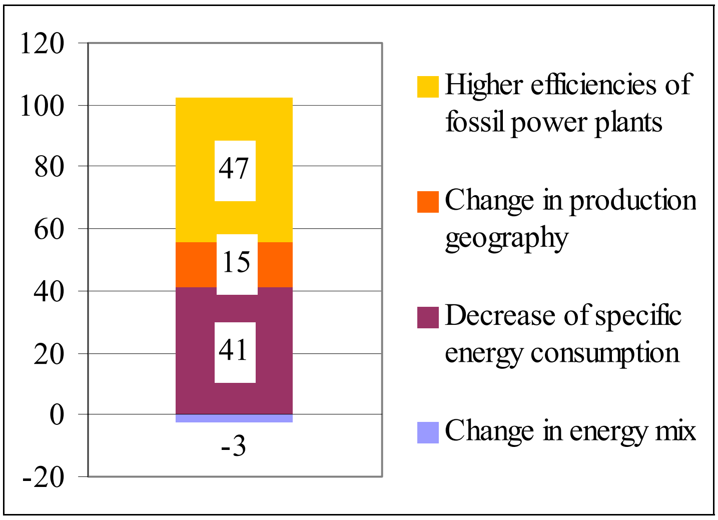


Fig. 9: Decomposition of total reduction of specific primary energy in % (base case)

Greenhouse gases

For CO_2 emissions the model calculations show a similar picture. In absolute terms, it will increase from 217 million tonnes in 1995 to 222 million tonnes in 2010. The specific emission will decrease considerably by 25 % from 10.7 t/t in 1995 to 8.0 t/t in 2010 (Fig. 10). Again, the development is mainly influenced by smelting (65 % of reduction of specific carbon dioxide emission). Analogous to the decline in the consumption of primary energy for smelting, the reduction in the specific emission of carbon dioxide for smelting is in the first place due to the higher efficiency of the fossil-fuelled power plants, in the second place to the decrease of electricity consumption for smelting, and in the third place to the changes in production geography. The change in energy mix is again only of minor influence.

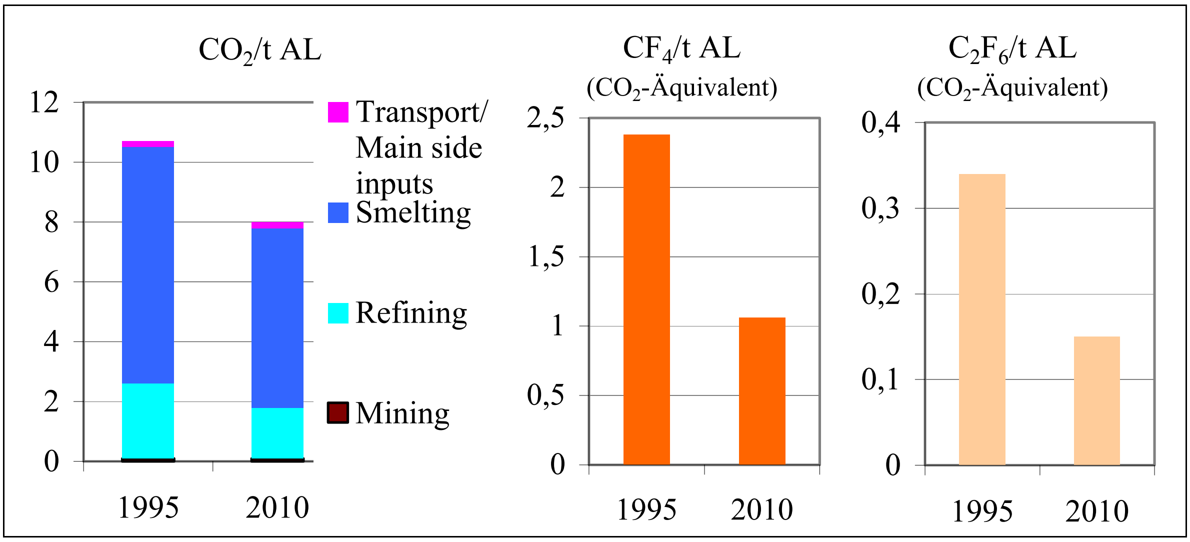


Fig. 10: Specific greenhouse gas emissions

For perfluorinated hydrocarbons (CF_4, C_2F_6) the situation differs. The emissions of perfluorinated hydrocarbons are due to the anode effects of the electrolysis. Calculated by their global warming potential (CF_4 6500 and C_2F_6 9200 tons CO_2-equivalents per emitted ton, cp. Schwarz et al. 1996), they will decrease from 53 million tonnes in 1995 to 33 million tonnes in 2010. In specific terms, they will decrease from 2.7 t/t to 1.2 t/t. Again, the reason is Söderberg technology being superseded by modern PFPB technology. Therefore, the anode effects will be reduced considerably.

5. Summary

The model of the global aluminium industry (GlobAl) is a partial equilibrium model which permits an integrated analysis of the material flow and the belonging energy consumption and GHG emissions. It simulates a long-run market equilibrium for primary aluminium and intermediate products. 1995 is the base year whereas 2010 is the future horizon of scenario calculations. The critical parameter "global demand for primary aluminium" is varied.

The most important energy carrier is electricity used for electrolysis. Other final energy carriers comprise diesel for transportation and natural gas for thermal energy.

Assuming an increase of primary aluminium demand from 19.7 million tonnes in 1995 to 27.0 million tonnes in 2010 electricity consumption will increase underproportinately by 23% to 393 million MWh. Therefore, specific electricity consumption will decrease from 16.2 MWh per tonne of metal to 14.5 MWh per tonne of metal. The main reason is the superseding of Söderberg technology by modern PFPB technology for electrolysis.

Further calcultations show that the absolute worldwide electricity consumption in the material flow of primary energy will already increase with a growth rate of demand of 1% per year or more. Therefore an increase of electricity consumption for primary aluminium production is very likely.

For primary energy consumption the situation is different. For the base case the calculations show an increase from 3,300 PJ to 3,500 PJ. A further analysis shows that the absolute worldwide consumption will increase considerably when the expansion of demand for primary aluminium is higher than 2% per year. The reduction of the specific primary energy consumption is much higher than the reduction of electricity consumption. The specific primary energy consumption of the material flow will decrease remarkably especially because of the reduction of primary energy consumption for electricity production for electrolysis. Reasons are the higher efficiency of electricity generated from fossil fuels, the growing use of modern PFPB technology with less electricity requirements and the shifting of primary aluminium production to regions where the production of electricity is mainly based on hydropower. The situation for CO_2 emissions is similar. Specific emissions for smelting are reduced remarkably for the same reasons. A decline in absolute perfluorinated hydrocarbon emissions is to be expected. The specific emissions will decline sharply because of the much smaller anode effects of modern PFPB plants.

Acknowledgment

The paper was produced within the framework of Special Research Program (SFB) 525 „Resource-orientated analysis of metallic raw material flows". Thanks are due to the German Research Council (DFG) for financial support. Thanks to all colleagues of SFB 525 for helpful discussions. Special thanks to Mr. Briem from the Chair of Rector Safety and Reactor Technology, Aachen University, for providing figures for power plant efficiencies and CO_2 emission factors.

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ANALYSE DES ALUMINIUMSTOFFSTROMS - POTENZIALE ZUR REDUKTION DES RESSOURCENBEDARFS UND DER UMWELTINANSPRUCHNAHME -*

(ANALYSIS OF ALUMINIUM FLOWS -POTENTIALS TO REDUCE RESOURCE USE AND ENVIRONMENTAL IMPACTS)

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ABSTRACT

The production, processing and use of aluminium initiates direct and indirect material and energy flows. Resulting resource depletion and environmental effects justify efforts to reduce the flows.

For this paper resources comprise bauxite and energy. Environmental effects are reported by production of red mud and emissions of greenhouse gases.

Methodologically, the analysis is carried out using computer-based models. In particular, a process chain approach and (an economic) partial equilibrium model are used to reduce the complexity to its main elements, taking into account its technical, economic and ecological aspects. The process chain approach makes it possible to analyse detailed technical systems whereas the economic model links aluminium flows to market mechanisms. The models are applied to set up balances of present material and energy flows. Using scenario techniques, trends and plausible developments are demonstrated. Its effects on material and energy flows are analysed.

The paper focuses on the quantification of potentials to reduce resource use and environmental impacts, taking into account the pros and cons of the approaches. Therefore, the process chain model is used to analyse the German packaging sector, whereas the economic model considers the global flow of primary aluminium.

KEYWORDS

Systems analysis, material flow of aluminium, process chain analysis, partial equilibirium model

* Source: Stein, G. (Hrsg.) 2003: Umweltschutz im Gleichschritt? Systemanalyse und Technikfolgenforschung in Deutschland. Heidelberg et al.: Springer Verlag, S. 305-320.

1 Einleitung

Die Analyse von Metallstoffströmen, insbesondere des Aluminiumstoffstroms, nimmt in der Diskussion zum Stoffstrommanagement breiten Raum ein. Ursache hierfür sind nicht wie bei einigen anderen Metallen durch Aluminium ausgelöste human- und ökotoxikologische Effekte, sondern die durch Herstellung und Nutzung des Werkstoffs ausgelösten direkten und induzierten Stoffströme. Darunter fallen z.B. Bauxit, Energie und Wasser.

In einer Reihe von Studien wurden für das Management von Aluminiumstoffströmen methodische Grundlagen entwickelt und Analysen erstellt.[1] Die Studien konzentrieren sich i.d.R. auf ausgewählte Aspekte des Stoffstroms und unterscheiden sich hinsichtlich der räumlichen Systemgrenzen. Insbesondere bleiben Aspekte des technischen Recyclings von Aluminium und des globalen Marktes für Aluminium nur ungenügend berücksichtigt.

Der vorliegende Beitrag konzentriert sich auf die Quantifizierung von Potenzialen zur Reduktion des Ressourcenbedarfs und der Umweltinanspruchnahme.[2] Die Potenziale werden hinsichtlich ihrer technischen und ökonomischen Ausprägung differenziert. Ressourcen umfassen natürliche nicht erneuerbare Ressourcen wie z.B. Bauxit, Kohle, Erdöl und Erdgas, aber auch erneuerbare wie z.B. Wasserkraft. Die Umweltinanspruchnahme konzentriert sich auf die Emission der Klimagase CO_2 und perfluorierte Kohlenwasserstoffe (CF_4, C_2F_6) sowie auf die Ausbringung von Rotschlamm. Nach einer Einordnung des Aluminiumstoffstroms werden je ein methodischer Ansatz zur Modellierung technischer Prozessketten bzw. des globalen Marktes für Primäraluminium erläutert. Anschließend werden auf der Basis der Modelle zwei Szenarien vorgestellt, die für das Zieljahr 2010 Potenziale zur Reduktion des Ressourcenbedarfs und der Umweltinanspruchnahme vor dem Hintergrund des technischen Recyclings bzw. des globalen Marktes für Primäraluminium quantifizieren.

1.1 Der globale Aluminiumstoffstrom

Die Produktion von Aluminium ist durch die Wertschöpfungsstufen der Bauxitförderung, der Tonerdeherstellung und der Herstellung von primärem und rezykliertem Aluminium gekennzeichnet. Die Förderung von Bauxit ist an Regionen mit natürlichen Lagerstätten gebunden. Die Standortwahl für die Produktionsstufen der gesamten Kette ist das Ergebnis der vergleichenden Abwägung von Wettbewerbsvor- und –nachteilen konkurrierender Standorte. Zu berücksichtigende Wettbewerbselemente umfassen z. B. Bauxitverfügbarkeit, Energiequellen für die

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[1] Vgl. z.B. Adelhardt/Mori (1997), European Aluminium Association (1996), Ayres (1996), Jänicke (1992), United Nations Industrial Development Organisation (1995) und Phylipsen et al. (1998).

[2] Der vorliegende Beitrag fasst Arbeiten im Rahmen des SFB 525 „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“ zusammen. Der DFG sei für die finanzielle Unterstützung gedankt.

Elektrizitätserzeugung, niedrige und variable Energiepreise, Subventionen, Zölle, Steuern, Löhne, Umweltpolitik (speziell Ausmaß der Internalisierung von externen Effekten), aber auch Infrastruktur und Ausbildungsstand der Arbeitskräfte.[3]

Daten zu Produktion und Nachfragen sind statistisch relativ gut erfasst. Abbildung 1 gibt dazu einen Überblick und zeigt die geographischen Anteile an Bauxitreserven, an Produktion auf den einzelnen Stufen der Wertschöpfungskette und an Nachfrage nach Aluminium. Darüber hinaus weist Abbildung 1 auf die globale Verflechtung und das hohe Maß an internationaler Arbeitsteilung bei der Produktion von Aluminium hin. Indiz dafür sind die unterschiedlichen Anteile einzelner Regionen an der Produktion auf den Wertschöpfungsstufen und am Konsum.

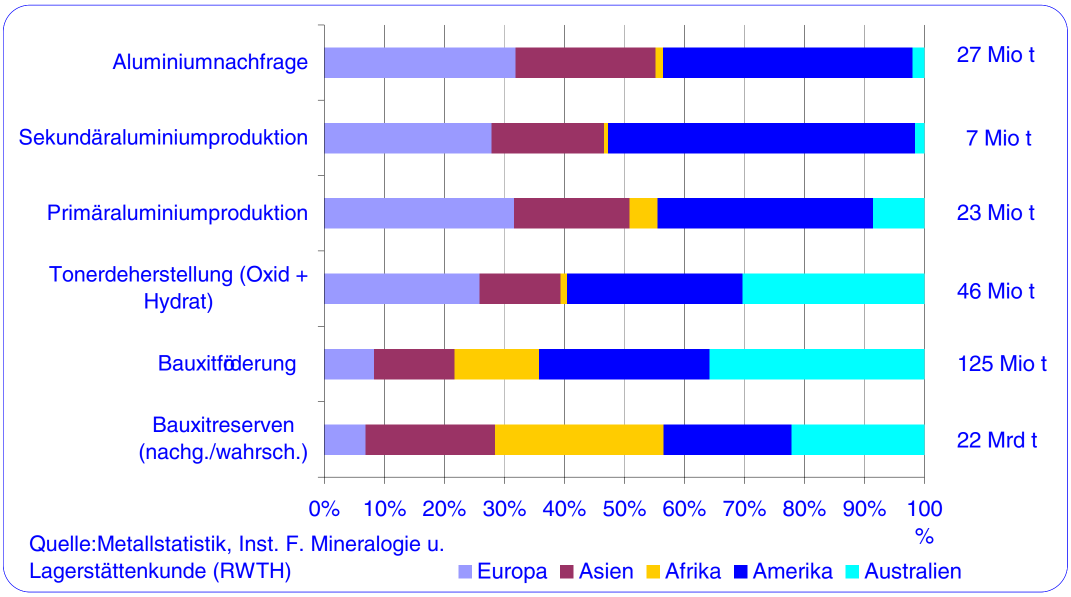

Abb. 1: Mengen und regionale Verteilung von Bauxitreserven, Produktion von und Nachfrage nach Aluminium, 1998

Produktion von Aluminium und Nutzung von aluminiumbasierten Gütern setzen direkte und induzierte Stoff- und Energieströme in Gang. Hinsichtlich der Umweltwirkungen ist zwischen lokalen, regionalen und globalen Wirkungen zu unterscheiden. Lokale Wirkung zeigt z.B. der Flächenbedarf für die Bauxitförderung oder die Emission von Rotschlamm und die Ausbringung von Abwässern. Regionale Wirkung kann die Inanspruchnahme von Primärenergieträgern zeigen. Treibhausgase (perfluorierte Kohlenwasserstoffe und Kohlendioxid) dagegen wirken global.

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[3] Kuckshinrichs/Poganietz (2002).

1.2 *Systemanalyse im Sonderforschungsbereich 525*

Der Sonderforschungsbereich (SFB) 525[4] *„Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe“* hat sich das Ziel gesetzt, Handlungsoptionen für eine ressourcenschonende Bereitstellung und Verarbeitung metallischer Rohstoffe im Spannungsfeld technischer Entwicklungen sowie ökonomischer, ökologischer und gesellschaftlicher Zielsetzungen aufzuzeigen. Ein wichtiger Aspekt ist hierbei die Abbildung der fachübergreifenden Wirkungszusammenhänge im Rahmen einer Systemanalyse zur Durchführung einer ressourcenorientierten Gesamtbetrachtung.

Der Betrachtungsraum des SFB 525 reicht von der Lagerstättenbildung über Gewinnung, Aufbereitung und Verhüttung primärer Rohstoffe bis zur Verarbeitung und Nutzung. Die zur Bereitstellung sekundärer Rohstoffe durchgeführten Prozesse des Recyclings, die sich an die Nutzungsphase anschließen, werden gleichermaßen betrachtet und als integrierter Bestandteil der Rohstoffversorgung mit bilanziert. In die Untersuchungen einbezogen werden die Transportvorgänge, die Prozesse der Energiebereitstellung sowie die Prozesse zur Verwertung oder Entsorgung der im Zusammenhang mit der Prozesskette stehenden wichtigsten Abfallströme. Diese Vorgehensweise ermöglicht es, den Einfluss des Aluminiumstoffstroms auf die Umwelt sowie wirtschaftliche und soziale Aspekte zu analysieren.

2 Modellierung des Aluminiumstoffstroms

Für die Analyse von Material-, Energie- und Produktflüssen sind eine Reihe methodischer Ansätze entwickelt worden. Zu den Methoden, die sich an physischen Flüssen und technischen Systemen ausrichten, zählen die Prozesskettenanalyse und die Lebenszyklusanalyse. Diesen Ansätzen mangelt es jedoch meist an einer Integration von ökonomischen Mechanismen. Zu den Methoden, die sich an ökonomischen Systemen ausrichten, zählen die Input-Output-Analyse, Gleichgewichts- sowie makroökonomische Modelle. Nachteilig ist, dass ihnen oftmals eine hinreichend detaillierte Abbildung von Transformationsprozessen und Material-, Energie- und Produktflüssen fehlt.[5] Für die Modellierung des Aluminiumstoffstroms werden vorhandene Ansätze weiterentwickelt und deren jeweilige Vorzüge genutzt.

Im Rahmen der Systemanalyse sind dazu ein Prozesskettenmodell (ProkAl) und ein Modell der globalen Aluminiumwirtschaft (GlobAl) entwickelt worden.[6] Beide Ansätze sind prozessbasiert und tragen mit unterschiedlicher Ausrichtung und Aussagefähigkeit zur ressourcenorientierten Gesamtbetrachtung bei (Tab. 1).

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4 http://sfb525.rwth-aachen.de/sfb525.

5 Bouman et al. (2000).

6 Robach et al. (2001), Zapp et al. (2001), Schwarz (2000), Poganietz (2001).

	GlobAl	ProkAl
Konzeption	• Partielles Gleichgewichtsmodell (Simulation eines Aluminiummarktes bei vollständiger Konkurrenz) • Optimierungskalkül (Kriterium: Kostenminimierung) • Vollständiges Mengengerüst	• Prozesskettenmodell zur Simulation einer technischen Vernetzung • Vollständiges Mengengerüst
Transformation und Flüsse	Aggregiert	Detailliert
Ökonomische Mechanismen	• Kostenminimierung • Allokation von Produktionsfaktoren und Standorten[a] • Wettbewerb von Standorten und Prozessen	
Betrachtungsraum 1. räumlich	Global	Regional / länderspezifisch
2. Wertschöpfungsstufen	Bauxitförderung, Tonerdeproduktion, Primäraluminiumherstellung	Bauxitförderung bis Halbzeugfertigung bzw. Formguss inkl. Aufbereitung und Verhüttung sekundärer Rohstoffe
Modellparameter	• Nachfrage • Prozessparameter • Kostenparameter • Zölle	• Prozessparameter • Allokationsparameter (hier Inputverhältnis von Primär- zu Sekundärmaterial)[a]
Modellvariablen	Regional / Wertschöpfungsstufen: • Einsatz Produktionsfaktoren • Investition • Produktion	Auf Wertschöpfungsstufen: • Produktion
Bilanzierung 1. technisch	• Bedarf Haupteingangsmaterial • Andere Inputs: Energie, Kalk, Natronlauge, Anoden	• Bedarf Haupteingangsmaterial • Andere Inputs: Energie, Kalk, Natronlauge, Petrolkoks, Pech, Kathodenmaterial, Aluminiumfluorid (AlF_3),...
2. ökologisch	Umweltbelastungen • Emissionen: CO_2, perfluorierte Kohlenwasserstoffe (CF_4, C_2F_6)	Umweltbelastungen • Emissionen: CO_2, perfluorierte Kohlenwasserstoffe (CF_4, C_2F_6), HF,... Rotschlamm Abwasser • Flächennutzung
3. sozial	Direkter Beschäftigungseffekt	

a: Der Begriff *Allokation* wird in der ökonomischen Theorie und in der Lebenszyklusanalyse unterschiedlich verwendet. Während er in der Ökonomie das Ergebnis von (modellierten) Marktprozessen kennzeichnet, bezeichnet er in der Lebenszyklusanalyse eine Modellannahme.

Tab. 1: Charakterisierung der Modellansätze

Während beim Prozesskettenmodell die Vernetzung detaillierter technischer Prozesse im Vordergrund steht, ist GlobAl als partielles Gleichgewichtsmodell durch eine ökonomische Ausrichtung geprägt. Beide Ansätze zeigen den Stoff- und Energiefluss entlang der Bereitstellungskette und verwenden das Konzept der Prozessbeschreibung durch In- und Outputs.

GlobAl beschreibt die Aluminiumkette von der Bauxitförderung bis zur Herstellung von Primäraluminium in ihrer globalen Dimension. ProkAl führt die Hauptkette weiter bis zum Halbzeug bzw. Formguss und zur Aufbereitung sekundärer Rohstoffe. ProkAl ist als standortunabhängiges Modell mit hoher Prozessdetaillierung konzipiert. Es konzentriert sich auf die Bilanzierung technischer und ökologischer Aspekte, während GlobAl die Bilanzierung um den sozialen Aspekt der (direkten) Beschäftigungseffekte erweitert. Tabelle 1 vergleicht die wesentlichen Modellcharakteristika.

Mit Hilfe der beiden Modelle werden die Umweltbelastungen in Form einer Sachbilanz quantifiziert.

3 Potenziale zur Reduktion des Ressourcenbedarfs und der Umweltinanspruchnahme

Das Prozesskettenmodell und das Modell der globalen Aluminiumwirtschaft bilden das Grundgerüst der systemanalytischen Arbeiten. Neben der Bilanzierung der Ausgangslage werden die Modelle eingesetzt, um künftige Entwicklungen einzugrenzen und um den Rahmen für Handlungsoptionen zu erarbeiten. Für die Ableitung plausibler Entwicklungen werden dazu explorative Szenarien entwickelt.

Gegenwärtig existieren zwei Szenarien, die in unterschiedlichen Systemgrenzen Analysen zum Ressourcenbedarf und zur Umweltinanspruchnahme zulassen:

- Aluminium im deutschen Verpackungssektor ⇒ Prozesskettenmodell
- Regionalisierte Weltnachfrage nach Primäraluminium ⇒ Modell der globalen Aluminiumwirtschaft

3.1 Aluminium im deutschen Verpackungssektor

Ziel der Ausarbeitung mit dem Prozesskettenmodell ist die Analyse der Auswirkungen technischen Fortschritts auf Stoff- und Energieflüsse für den Einsatz von Aluminium im deutschen Verpackungssektor.[7] Dazu gilt es, die Prozesskette eines Basisjahres durch den Austausch von

[7] Die Ausführungen zu diesem Szenario basieren auf Rombach et al. (2001) und Zapp et al. (2001).

einzelnen Modulen[8] zu ändern. Mit dieser Vorgehensweise können z.B. alte oder gegenwärtig verfügbare Techniken durch neueste verfügbare Techniken[9] ersetzt und die Auswirkungen des Technikeinsatzes hinsichtlich Ressourcen- und Umweltinanspruchnahme analysiert werden.

3.1.1 Systemgrenzen

Als Basis- und Zieljahr wurden 1997 bzw. 2010 gewählt. Das geografische System umfasst Deutschland und seine direkten und indirekten Vorlieferanten für Bauxit, Tonerde und Aluminium. Das technische System umfasst die Prozesskette vom Bauxit über das Primäraluminium bis zur Herstellung von Bändern, Folien und Dosendeckeln und das Recycling von Leichtverpackungsmaterial über den DSD (Abb. 2).

Die Analyse ist auf folgenden Fallrechnungen aufgebaut:

- Der Referenzfall (1997) umfasst das inländische Angebot für Deutschland für das Basisjahr 1997, bestehend aus der inländischen Produktion plus den Nettoimporten von primärem und rezykliertem Aluminium und deren Vorprodukten;

- Für das Jahr 2010 wird das technische Potenzial auf der Annahme ermittelt, dass für jeden Prozess ausschließlich neueste verfügbare Technologie (NT) eingesetzt wird. Im Vergleich zum Referenzfall werden daher die installierten Kapazitäten vollständig ausgetauscht;

- Im dritten Fall (2010) wird nur ein unter ökonomischen Gesichtspunkten bis 2010 plausibler Ersatz von Kapazitäten durch neueste Technik angenommen. Damit ist hier das im Vergleich zum technischen geringere ökonomische Potenzial eingeführt.

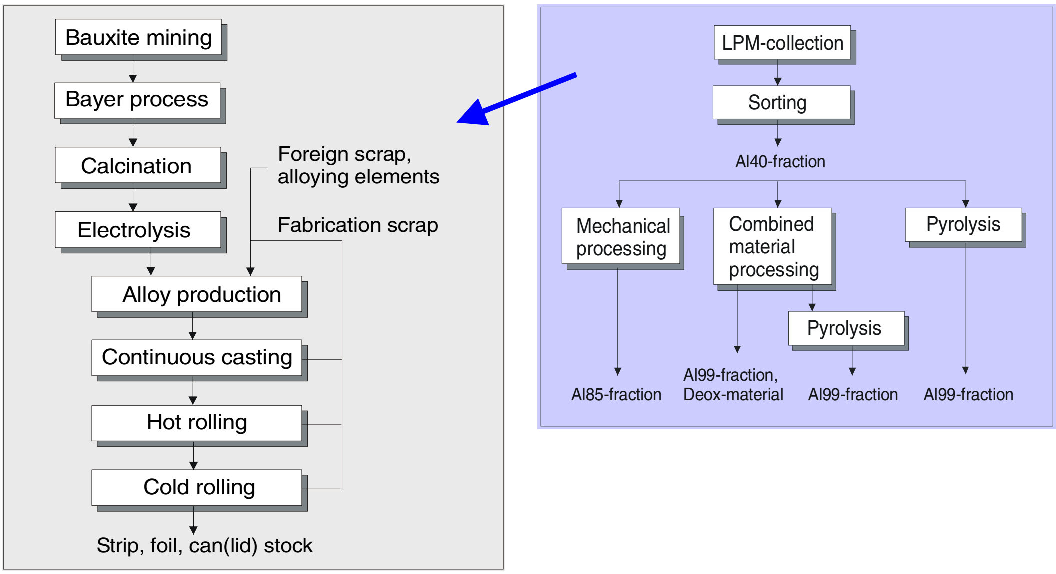

Abb. 2: Herstellung und Recycling von Verpackungsmaterial

[8] Ein Modul ist ein Element einer technischen Prozesskette.

[9] Zu besten verfügbaren Techniken vgl. IPPC (2000).

Die Differenzanalyse resultiert in der Quantifizierung des technischen Potenzials und des ökonomischen Potenzials des technischen Fortschritts in der Prozesskette Aluminium für Verpackungen in Deutschland und den Wirkungen hinsichtlich Ressourcenbedarf und Umweltinanspruchnahme.

3.1.2 Annahmen

Für das Szenario wurden eine Reihe von Annahmen zu fallunabhängigen strukturellen Aspekten und fallabhängigen technischen Aspekten des betrachteten Systems getroffen. Folgende Annahmen zu strukturellen Aspekten sind von Bedeutung:

- Für Produktion und Recycling wurden konstante Mengen angenommen, sodass kein Effekt über Kapazitätszuwachs eintritt;

- Die Struktur der Quellen von Bauxit, Tonerde und Primäraluminium bleibt unverändert (Abb. 3);

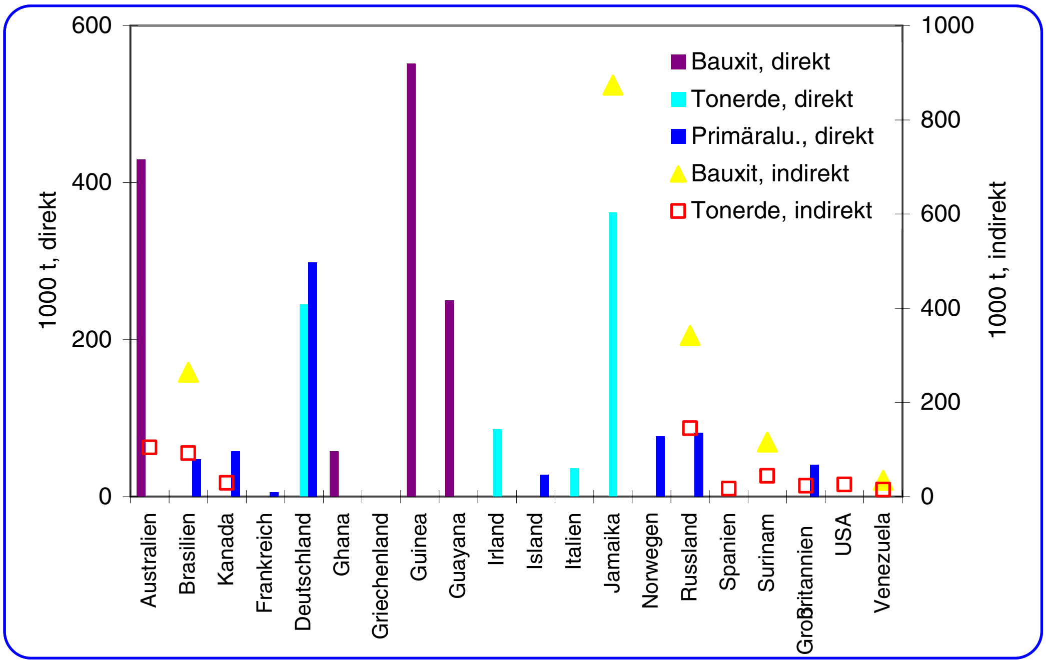

Abb. 3: Direkte und indirekte Quellen von Primäraluminium und den Vorstoffen für die Herstellung von Verpackungsmaterial in Deutschland

- Der Anteil von Sekundärrohstoffen für die Herstellung von Legierungen bleibt konstant;

- Das Angebot an Energie für die verschiedenen Prozesse basiert auf dem regionalen Energiemix. Nur für die Elektrizitätsversorgung der Elektrolysen wurde der Vertragsmix (Mix Grundlaststrom) der Stromanbieter angenommen.

Fallabhängige Annahmen zu technischen Aspekten konkretisieren für jeden Prozess technischen Fortschritt (Tab. 2).[10] Die Annahmen können je einer der drei folgenden Gruppen zugeordnet werden. Die erste Gruppe reflektiert Annahmen zu den dargestellten Prozessen selbst. Darüber hinaus sind Annahmen aufgestellt, die zu einer Verbesserung der Material- und Ressourceneffizienz führen, oder die Veränderungen im vorgelagerten Elektrizitätssektor charakterisieren.

<table>
<tr><th></th><th>1997</th><th>NT</th><th>2010</th></tr>
<tr><td>Bergbau</td><td>Liefermix 1997</td><td>Bauxitqualität unverändert</td><td>Schließung einiger Minen</td></tr>
<tr><td>Tonerdeproduktion</td><td rowspan="3">Prozessmix 1997 der Lieferländer</td><td>Nur Rohrreaktor und Wirbelschichtkalzination</td><td>10% Energieeinsparung, 1% höheres Ausbringen</td></tr>
<tr><td>Elektrolyse</td><td>Nur neueste PFPB-Technologie</td><td>Modernisierung, Ausweitung nur durch NT</td></tr>
<tr><td>Legierungsherstellung</td><td>Nur moderne Öfen mit Sauerstoffbrennern oder Wärmerückgewinnung</td><td rowspan="3">Erhöhter Anteil neuester Technologie</td></tr>
<tr><td>Strangguss</td><td rowspan="3">Prozessmix 1997</td><td>Max. Barrengewicht = Min. Fabrikationsschrott</td></tr>
<tr><td>Warm/Kaltwalzen</td><td>Niedrigerer Energie- und Materialaufwand</td></tr>
<tr><td>LPM-Recycling</td><td>Nur voll automatisierte Sortierung und Pyrolyse</td><td>10% voll automatisierte Sortierung, mechanische Aufbereitung entfällt</td></tr>
<tr><td>Energieversorgung</td><td>Energieträgermix 1997</td><td>1997 Energieträgermix, neueste Umwandlungstechnologie</td><td>Technischer Fortschritt und veränderter Energieträgermix 2010</td></tr>
</table>

Tab. 2: Wichtige fallspezifische Annahmen

3.1.3 Ergebnisse

Für die wichtigsten Inputs und Outputs sind in Abbildung 4 die Analyseergebnisse der Fallbetrachtungen wiedergegeben. Wie erwartet ist das technische jeweils größer als das ökonomische Potenzial. Im Einzelnen sind die Ergebnisse sehr verschieden, zeigen aber eine Reduktion des Ressourcenbedarfs und der Umweltinanspruchnahme:

- Das technische (ökonomische) Potenzial zur Bauxiteinsparung beträgt 13,1% (5,1%) und ist zurückzuführen auf einen erhöhten Aufschluss und eine Reduktion des Inputs an Primäraluminium. Die Ressourceneffizienz mit Blick auf Bauxit gemessen als kg Verpackungsmaterial pro kg Bauxitinput steigt somit bei einmaligem Durchlauf des kombinierten Primär- und Sekundärkreislaufs entsprechend;

[10] Zapp et al. (2001).

- Die Rotschlammproduktion sinkt um 21% (8,6%). Wesentlicher Einfluss entspringt der Verbesserung der Ressourceneffizienz beim Bauxit und dem Einsatz fortschrittlicher Prozesse zur Tonerdeherstellung;

- Der Metallgehalt, der aus den genutzten Leichtverpackungen durch Recycling wieder zurückgewonnen und somit dem Aluminiumsystem wieder zugeführt werden kann, steigt um 26,6% (4,7%). Dieses rezyklierte Material ersetzt an anderer Stelle Primäraluminium und reduziert den Gesamtressourcenbedarf;

- Der Bedarf an Primärenergie sinkt um 25,9% (15,7%). Wichtigste Ursache des Rückgangs ist hier verbesserte Prozesstechnologie. Daneben spielen auch Verbesserung der Materialeffizienz, Einsatz effizienterer Energietechniken und strukturelle Änderungen der Energieversorgung eine Rolle;

- Die energiebedingten CO_2-Emissionen und die prozessbedingten CO_2-, CF_4- und C_2F_6-Emissionen sinken. Auf der Basis der Global Warming Potentials sinken diese Treibhausgasemissionen um ca. 45% (21%). Der größte Anteil des Rückgangs ist dem CO_2 zuzurechnen. CF_4 und C_2F_6 tragen aber trotz geringer eigener Mengen beinah zur Hälfte zur Reduktion bei. Die perfluorierten Kohlenwasserstoffe haben ein hohes Global Warming Potential[11] und zeigen hohe Reduktionspotenziale.

Insgesamt erweist sich hier der dominante Einfluss des Elektrolyseprozesses, der mit etwa 74% den größten Beitrag des technischen Potenzials zur Einsparung von Treibhausgasen ausmacht. Die Emissionen perfluorierter Kohlenwasserstoffe sind aus-

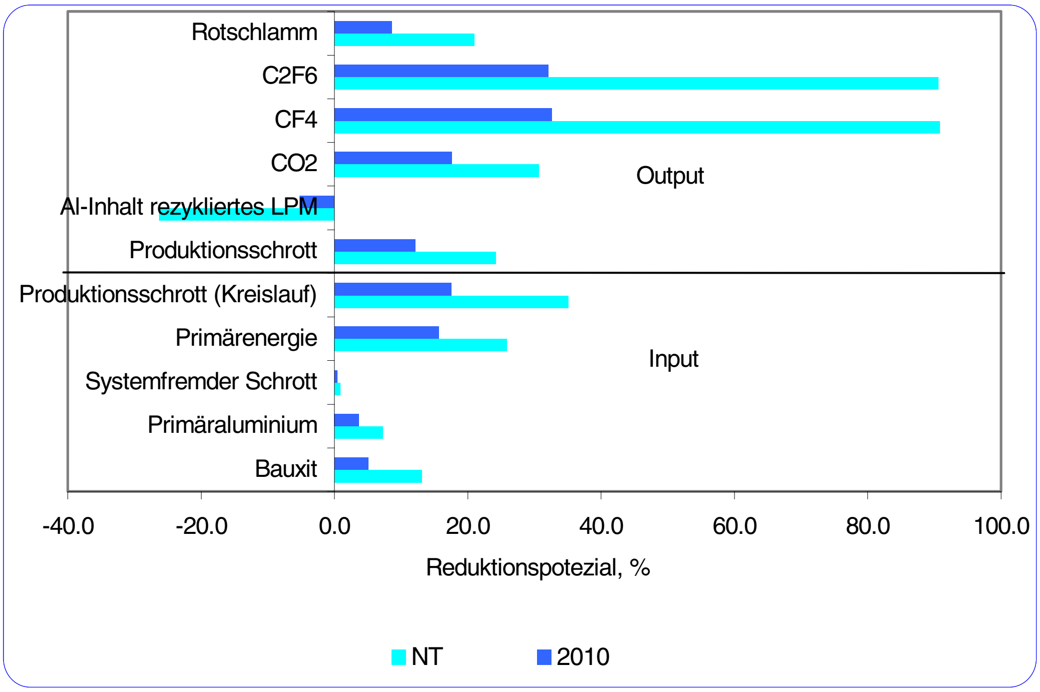

Abb. 4: Reduktionspotenziale bei spezifischen Inputs und Outputs pro Tonne Verpackungsmaterial

schließlich der Elektrolyse zuzurechnen. Darüber hinaus trägt die Elektrolyse durch eine Reduktion des Elektrizitätsbedarfs von 10% (4,5%), gekoppelt mit einer Verbesserung der Elektrizitätsbereitstellung zum Einsparpotenzial bei.

3.2 *Regionalisierte Weltnachfrage nach Primäraluminium*

Ziel der Untersuchung mit dem Modell der globalen Aluminiumwirtschaft ist es, Nachfrageänderungen nach Primäraluminium hinsichtlich der globalen Auswirkungen auf Produktion und Handel der nachgefragten Güter sowie auf den Energiebedarf und die stoffstrombedingten Treibhausgasemissionen zu analysieren.[12] Dazu gilt es zunächst, die Nachfrage nach Primäraluminium regional differenziert zu bestimmen. Weiterhin ist die Prozesskette eines Basisjahres hinsichtlich des Einsatzes fortschrittlicher Techniken für das Zieljahr zu öffnen.

3.2.1 Systemgrenzen

Als Basis- und Zieljahr wurden die Jahre 1995 und 2010 gewählt. Das räumliche System umfasst die ganze Welt, aufgeteilt in 15 Regionen (Abb. 5).

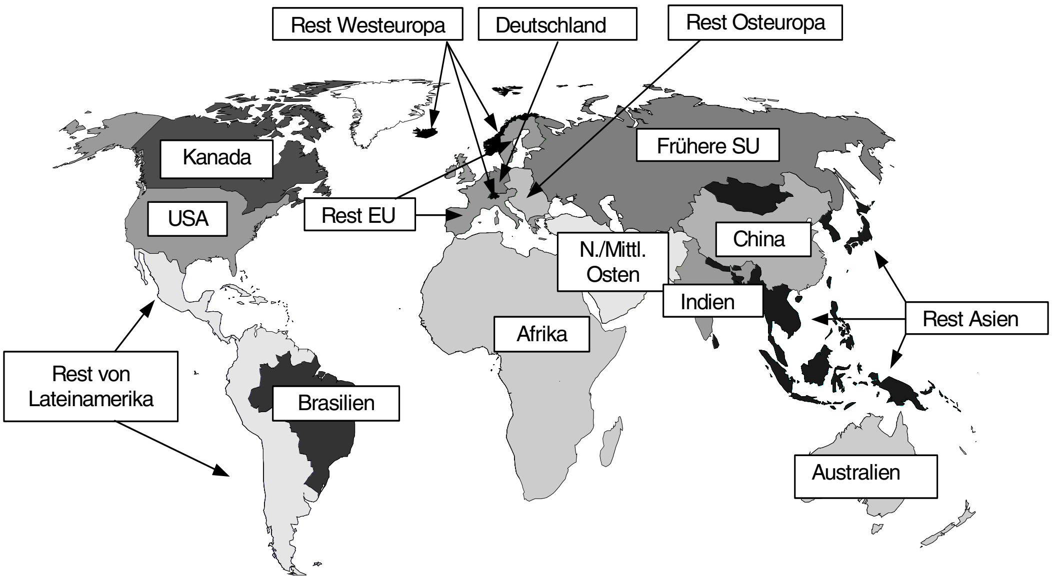

Abb. 5: Räumliche Systemgrenze und Regionen

Als wichtige Parameter für die Entwicklung der Nachfrage nach Primäraluminium gelten neben der Höhe des Bruttoinlandsprodukts die Aluminiumintensität des Bruttoinlandsprodukts und die Primäraluminiumintensität der gesamten Aluminiumnachfrage. Auf der Basis vorsich-

[11] CO_2-Äquivalente: 6300 kg CO_2/kg CF_4; 12500 kg CO_2/kg C_2F_6.

tiger, regional differenzierter Schätzungen dieser Parameter wurde eine Nachfrageprojektion für das Jahr 2010 erstellt. Die Analyse ist auf folgende Fallbetrachtungen aufgebaut:

- Der Referenzfall (Fall 1) entspricht einer moderaten Zunahme der globalen Nachfrage nach Primäraluminium in Höhe von 2,2%/Jahr bis 2010, wobei die Wachstumsraten zwischen den Regionen erheblich divergieren: Für China und Indien wurde eine jährliche Zunahme um 5,5%/Jahr berechnet; für Australien eine Wachstumsrate von 0,6%/Jahr;

- Fall 2 geht von der Annahme höheren wirtschaftlichen Wachstums und in der Folge höherer Nachfrage nach Primäraluminium (2,9%/Jahr) aus. Die regionalen Wachstumsraten reichen von 1,0%/Jahr (Rest von EU und Deutschland) bis 7,4%/Jahr (China);

- Fall 3 basiert auf Fall 2, nimmt aber bzgl. Innovation und struktureller Änderungen in Richtung des Einsatzes von rezykliertem Material eine stärkere Dynamik an. In der Folge ergibt sich die insgesamt niedrigste Nachfrage nach Primäraluminium (1,4%/Jahr). In diesem Fall wird die Nachfrage in einigen Regionen kontinuierlich fallen, wobei mit einer Rate von 0,5%/Jahr die Staaten der EU den höchsten Rückgang erfahren werden. Die höchste Wachstumsrate wurde mit 5,9%/Jahr wiederum für China ermittelt.

3.2.2 Annahmen

Bis auf die Nachfrage nach Primäraluminium sind die Annahmen zu den Parametern fallunabhängig definiert und betreffen technische Prozesse, relative Preise für bestimmte Inputgüter sowie Transportkosten und Politikparameter.

Mit dem Ansatz ist technischer Fortschritt modelliert. Auf der Basis von learning-by-doing-Effekten wird angenommen, dass bis 2010

- im Bauxitbergbau der spezifische Bedarf an Produktionsfaktoren um 20% sinkt;

- für Tonerde- und Primäraluminiumherstellung eine Annäherung an die jeweils weltweit beste Anlage in den einzelnen Regionen erfolgt. Hierbei wird angenommen, dass sich die Divergenz zur besten Anlage um 50% reduziert.

Bei der Tonerde- und Primäraluminiumherstellung ergibt sich technischer Fortschritt auch bei der Installierung von neuen Anlagen bzw. bei der Modernisierung von Altanlagen. Die modernisierten und neuen Anlagen weisen bezüglich aller Inputfaktoren im Vergleich zur besten Technologie im Jahr 1995 einen geringeren Einsatzbedarf aus. Es wird weiterhin angenommen, daß sich bezüglich der technischen Parameter weltweit ein einheitlicher Standard durchsetzen wird.

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[12] Die Ausführungen zu dem Szenario basieren auf Schwarz (2000) und Poganietz (2001).

Das Modell ist realwirtschaftlich ausgerichtet, so dass keine Preisniveauänderungen erfasst werden können. Es wird aber angenommen, dass die regionalen Preise der Inputgüter, mit Ausnahme von Bauxit und Tonerde, deren Preise durch das Modell bestimmt werden, gegen den jeweiligen Weltmarktpreis konvergieren. Die Konvergenzraten variieren zwischen 0,95 und 0,5. Ein Wert von 0,95 sagt aus, dass die Divergenz eines Inputfaktorpreises einer Region vom Weltdurchschnitt sich um 5% verringert.[13]

Die Transportkosten sinken in dem betrachteten Zeitraum um linear 10%, die Zollsätze für Bauxit, Tonerde und Primäraluminium um 20%.

3.2.3 Ergebnisse

Die wichtigsten Analyseergebnisse der Fallbetrachtungen sind in Abbildung 6 wiedergegeben.

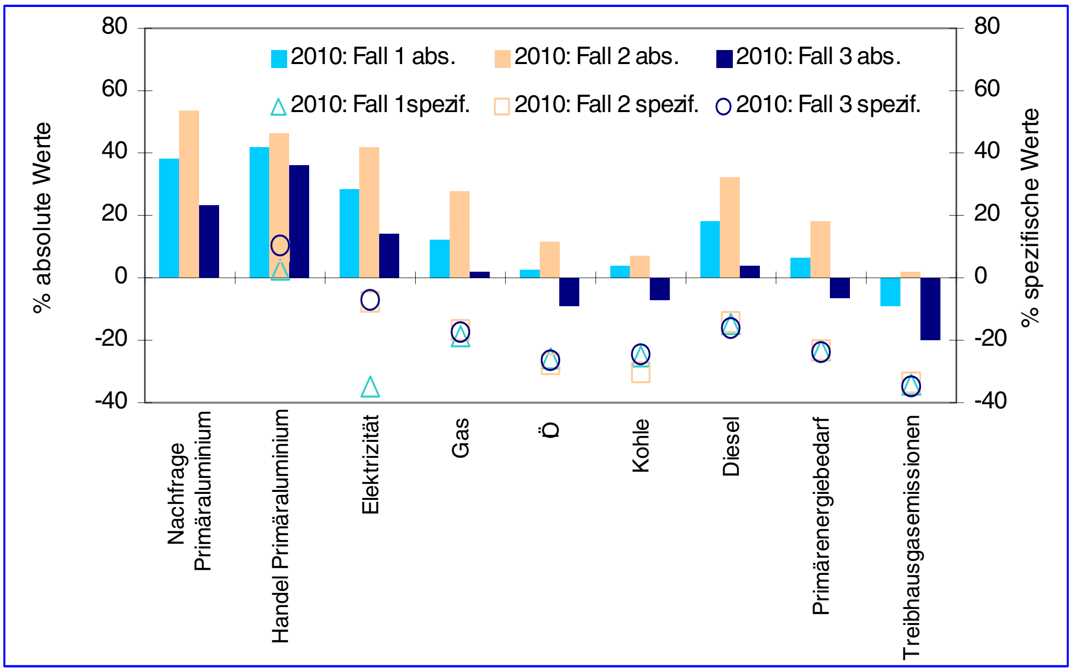

Abb. 6: Absolute und spezifische In- und Outputs in den drei Fällen

Wie erwartet sind die Inputs und Outputs im Fall hoher Nachfrage (Fall 2) immer höher als in den beiden anderen Fällen. Im einzelnen sind die Ergebnisse jedoch sehr verschieden. Insbesondere ist hier die Divergenz zwischen absoluten und spezifischen Veränderungen hervorzuheben:

- Die Nachfrage und damit auch die Produktion von Primäraluminium und damit der vorgelagerten Produkte Tonerde und Bauxit wächst von 1995 bis 2010 zwischen 23% (Fall 3) und 54% (Fall 2);

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13 Vgl. detailliert Poganietz (2001), S. 23/24.

- Der internationale Handel von Primäraluminium intensiviert sich und nimmt zwischen 36% (Fall 3) und 66% (Fall 2) zu. Der für Produktionswachstum notwendige Kapazitätsausbau findet zunächst in typischen Exportregionen (z.B. Kanada, Rest von Westeuropa (Norwegen, Island)) statt. Zusätzlich werden dann Kapazitäten in typischen Importregionen (z.B. USA) aufgebaut. Eine abgeschwächte Entwicklung kann man für den Tonerde- und Bauxithandel erwarten. Im Fall einer niedrigen Nachfrage nach Primäraluminium (Fall 3) wird das Handelsvolumen für Bauxit sogar um 12% sinken;

- Der spezifische Bedarf an den Endenergieträgern Elektrizität, Gas, Öl, Kohle und Diesel sinkt. Aufgrund des Produktionszuwachses werden aber die spezifischen Einsparungen im allgemeinen überkompensiert. Lediglich bei niedriger Nachfrage (Fall 3) sinkt auch der Bedarf an Öl und Kohle;

- Der Bedarf an Primärenergie steigt im Vergleich zur Produktion unterproportional und sinkt für den Fall niedriger Nachfrage (Fall 3). Der spezifische Bedarf an Primärenergieträgern sinkt um ca. 23%. Diese Entwicklung ist im wesentlichen auf die Verbesserung der Endenergieeffizienz der Elektrolysen und der fossil befeuerten Kraftwerke für die Elektrizitätserzeugung zurückzuführen. Die zwei Effekte erklären ca. 90% der Reduktion des spezifischen Primärenergiebedarfs. Die restlichen 10% resultieren im wesentlichen aus der Veränderung der Produktionsgeografie;

- Gemessen in CO_2-Äquivalenten, basierend auf dem 100 jährigen Global Warming Potential, fallen im Basisjahr CO_2 und perfluorierte Kohlenwasserstoffe (PFCs: CF_4, C_2F_6) grob im Verhältnis 2:1 an. Mit Ausnahme von Fall 2 werden die Emissionen von Treibhausgasen absolut um 9% (Fall 1) und 20% (Fall 3) sinken. Im Fall 2 kommt es zu einem leichten Anstieg (2%). Die Reduktion der spezifischen Treibhausgase beträgt im Durchschnitt aller Fälle sogar 34%. Diese Entwicklung wird wesentlich durch den Rückgang an spezifischen PFC-Emissionen bestimmt, die, je nach Fall, zwischen 69% und 73% fallen werden. Dahingegen sinken die spezifischen CO_2-Emissionen für sich nur um ca. 27%.

  Energie- und prozessinduzierte Treibhausgasemissionen fallen grob im Verhältnis 2:1 an. Die Verbesserung der energieinduzierten spezifischen Emissionen (CO_2) ist mehrheitlich auf die Verbesserung der Wirkungsgrade der Elektrizitätserzeugung zurückzuführen. Der Einfluss des technischen Fortschritts bei den Elektrolysen spielt eine geringere Rolle.

  Der Rückgang prozessinduzierter spezifischer Emissionen (CO_2, CF_4, C_2F_6), die nur bei der Elektrolyse anfallen, ist im wesentlichen auf den Rückgang der PFC-Emissionen CF_4 und C_2F_6 zurückzuführen. Dieses ist wesentlich Folge des verstärkten Einsatzes von neuester Technologie im Jahr 2010. Aufgrund der erhöhten Gesamtnachfrage nach Primäraluminium und den veränderten regionalen relativen Inputpreisen kommt es im Betrachtungszeitraum zu einer umfangreichen kapazitätserweiternden Modernisierung von Altanlagen sowie Installation von Neuanlagen. Für diese Anlagen werden annahmegemäß jeweils die neuesten Technologien eingesetzt.

  Auch wenn der Rückgang an spezifischen Emissionen von CO_2 relativ zu den PFC-gasen gering ist, so wird die potenziell maximal mögliche Verminderung an prozessinduzierten Kohlendioxidgasen nahezu ausgeschöpft. Hierbei wird die maximal mögliche Reduktion von Treibhausgasen dann erreicht, wenn weltweit alle Schmelzhütten die neueste Technologie, die sog. PFPB-Technologie, einsetzen. Bei den PFC-Gasen besteht noch ein erhebliches Verminderungspotenzial. Im Jahr 2010 wird nur etwa ein Drittel des Potenzials ausgenutzt.[14]

4 Resümee

Der vorliegende Beitrag fasst ausgewählte Arbeiten des SFB 525 „Ressourcenorientierte Gesamtbetrachtung von Stoffströmen metallischer Rohstoffe" zusammen und konzentriert sich auf die Quantifizierung von Potenzialen zur Reduktion des Ressourcenbedarfs und der Umweltinanspruchnahme innerhalb des Aluminiumstoffstroms. Die Potenziale werden nach ihrer technischen und ökonomischen Ausprägung differenziert. Im Rahmen der ausgewählten Untersuchungen umfassen Ressourcen natürliche nicht erneuerbare Ressourcen wie z.B. Bauxit, Kohle, Erdöl und Erdgas, aber auch erneuerbare wie z.B. Wasserkraft. Die Umweltinanspruchnahme konzentriert sich beispielhaft auf die Emission der Klimagase Kohlendioxid und perfluorierte Kohlenwasserstoffe (CF_4, C_2F_6) sowie auf die Ausbringung von Rotschlamm.

Im Rahmen der Systemanalyse werden mit dem Prozesskettenmodell ProkAl und dem Modell der globalen Aluminiumwirtschaft GlobAl je ein mittelfristiges Szenario (Zieljahr 2010) analysiert.

Ziel der Ausarbeitung mit dem Prozesskettenmodell ist die Analyse der Auswirkungen technischen Fortschritts auf spezifische Stoff- und Energieflüsse für den Einsatz von Aluminium im deutschen Verpackungssektor. Die Ergebnisse zeigen, dass das technische Potenzial zur Reduktion des spezifischen Ressourcenbedarfs und der spezifischen Umweltinanspruchnahme bis 2010 erheblich ist. Insbesondere sind hiervon der Bauxitbedarf, die Rotschlammproduktion, der Metallgehalt aus Recycling von Leichtverpackungen, der Bedarf an Primärenergie und die energie- und prozessbedingten Emissionen der Klimagase CO_2 und perfluorierte Kohlenwasserstoffe (CF_4, C_2F_6) betroffen. Gleichzeitig weisen die Ergebnisse darauf hin, dass das wirtschaftliche Potenzial in allen Fällen erheblich kleiner ist.

Ziel der Untersuchung mit dem Modell der globalen Aluminiumwirtschaft ist es, Nachfrageänderungen nach Primäraluminium hinsichtlich der globalen Auswirkungen auf Produktion und Handel der nachgefragten Güter sowie auf den Energiebedarf und die stoffstrombedingten Treibhausgasemissionen zu analysieren. Die Ergebnisse zeigen, dass wie erwartet der Ressourcenbedarf und die Umweltinanspruchnahme im Fall hoher Nachfrage nach Primäraluminium höher sind als bei niedriger Nachfrage. Der Anteil international gehandelten Primäraluminiums steigt. Der spezifische Bedarf an Elektrizität, Gas, Öl, Kohle, Diesel und der Einsatz von Primär-

[14] Vgl. Poganietz (2001), S.56.

energieträgern sowie die Treibhausgasemissionen sinken. Allerdings werden diese Rückgänge aufgrund des Produktionszuwachses im allgemeinen überkompensiert.

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GLOBALIZATION: AN ENCUMBRANCE FOR THE ENVIRONMENT? THE CASE OF PRIMARY ALUMINUM*

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ABSTRACT

Objective of the paper is to analyze the development of selected greenhouse gas (GHG) emissions by the process chain of primary aluminum until 2010 as international trade intensifies. The analysis bases on a partial equilibrium model (PEM), using scenario technique. Contrasting other commonly used approaches, PEM allows modeling not only economic relations between economic agents, like MFA or SFA, but also the driving forces underlying economic decisions, like profit maximizing. LCA focuses on environmental consequences of a product as they are determined by used technology. Actually, GHG emissions are heavily influenced by economic decisions. The used PEM permits an integrated analysis of the technical, geographical, ecological, and economic dimension of the material flow of primary aluminum inclusive its auxiliary chains. To simulate the impacts of increasing globalization on GHG emissions a scenario with any trade barriers is compared with a scenario with slight trade liberalization, using 1995 data as a reference point. In a "globalizing" world, emissions of CO_2 will fall, as CF_4 and C_2F_6 emissions will not be affected. CO_2 emissions induced by the increasing trade are outmatched by the slow down of emissions induced by smelters. A world with no trade barrier promotes the installment of smelters in regions using mainly energy carrier with low or no CO_2 emissions.

KEYWORDS

Globalization, material flow, partial equilibrium model, primary aluminum, greenhouse gases

* Source: Proceedings 5th International Conference on EcoBalance: Pratical tools and thoughtful principles for sustainability, Tsukuba, Japan

INTRODUCTION

The proposal of the government of the UK to abolish EU-tariffs on primary aluminum was not enthusiastically agreed by the European aluminum industry. The abolishment of tariffs should intensify the competition within the EU, possibly crowding out some of the European producer. Considering the environmental impact of such a trade policy the consequences on global greenhouse gas (GHG) emissions are at a first glance not obvious, as the shift of production sites to foreign countries will lead to conflicting effects.

Objective of the paper is to analyze the impact of trade liberalization on the emissions of selected GHG by the process chain of primary aluminum. The analysis bases on a process-based partial equilibrium model (PEM). That means, in a PEM the material flow of primary aluminum is integrated. Contrasting other commonly used approaches, PEM considers not only economic interdependencies between economic agents, like MFA or SFA, but also the driving forces of underlying economic decisions, like profit maximizing. MFA/SFA modeling grounds on economic input-output analysis, a standard economic tool describing mutual deliveries between sectors in terms of money or in terms of volumes of goods.

Partial equilibrium models describe the outcome of markets by depicting the behavioral relations that underlie the outcome. The results of PEM depend heavily on the assumptions regarding the behavior of all actors in the markets, i.e. in the used model, that all actors behave as to maximize their pay-offs, always leading to a balancing of supply of and demand for a product. Therefore, PEM allows covering important economic characteristics of an industry in a flexible manner, considering in the used model-setting explicitly technical characteristics of the material flow of primary aluminum. The used PEM permits an integrated analysis of the technical, geographical, ecological, and economic dimension of the material flow of primary aluminum inclusive its auxiliary chains.

Process chain analysis (PCA) and LCA both are tools to assess environmental consequences of a product. They differ in how much process steps are regarded. Whereas PCA may concentrate on aspects of production of intermediates, e.g. primary aluminum, LCA follows a product from cradle to grave. It focuses on the function of a product, not on the product itself, e.g. the function of an aluminum window frame. Necessarily, it includes the use phase of a product [1, 2]. However, both approaches cannot deal with a changed economic environment, like the abolishment of tariffs.

To simulate the impacts of increasing globalization on GHG emissions a scenario with any trade barriers is compared with a scenario with slight trade liberalization, using 1995 data as a reference point. In a "globalizing" world, global emissions of carbon dioxide (CO_2) by the material flow of primary aluminum will fall, as perfluorinated hydrocarbons (CF_4 and C_2F_6) emissions will not be affected. CO_2 emissions induced by the increasing trade are outmatched by the slow down of emissions induced by smelters.

MODEL, SYSTEM BOUNDARIES AND SCENARIOS

The study is made by using the model GlobAl, a partial equilibrium world aluminum trade model. The version used is a slightly revised variant of the model developed by Schwarz [3] (cf. Poganietz [4]). The model depicts the process chain of primary aluminum: mining of bauxite, transforming of bauxite to alumina, smelting of alumina to primary aluminum, demanding primary aluminum. On each process step, the different used technologies are modeled explicitly. Transport is considered, connecting the 15 regions, in which the model world is divided. The model balances the emissions of selected greenhouse gases, i.e. carbon dioxide and perfluorinated hydrocarbons, of all stakeholders involved in the production process. The model is static and depicts the development between 1995 and 2010 in one period.

In the following, two scenarios are compared. In scenario 1 (in the following base run), slight trade liberalization is considered. Tariffs of each good – bauxite, alumina, and primary aluminum – and in each region are lowered by 20%. In scenario 2 (in the following free trade run), all tariffs in each region and of each good are abolished.

The two scenarios are computed on base of two cases, which differ regarding estimated demand for primary aluminum [4]:

- Case 1: On base of projections regarding the development of income in each region, final aluminum intensity of the entire output of an economy as well as of primary aluminum intensity of final aluminum products for each region demand for primary aluminum in each region was calculated. Following estimated data world demand for primary aluminum will increase in the period under study by 2.9% p.a. However, regional growth rates range in this case from 1.0% p.a. (EU) to 7.4% (China).
- Case 2: Because of increasing innovation rate and structural change in aluminum production a lower final aluminum intensity of the entire output of an economy and of primary aluminum compared to the one in case 1 has been

predicted. As a consequence, world demand for primary aluminum is below the one in the other case. The annual growth rate corresponds to 1.4% p.a. In some regions, demand for primary aluminum will decrease. The highest cut back will occur in the EU (0.5% p.a.). The highest increase in demand is once again in China: + 5.9% p.a.

The assumptions regarding technologies, technological progress, prices, and costs are in both scenarios and all cases the same.

Technological progress is revealed in the model by two ways. On base of learning-by-doing in mining the specific demand for labor and energy declines in the whole period from 1995 to 2010 by 20%. In case of alumina and primary aluminum processing a converging process of plants run inefficiently compared to global average to efficient plants is assumed. Plants not producing at the efficient edge can fill the gap to plants using the same technology efficiently regarding energy and labor by 50%. Additionally, in alumina and aluminum processing technological progress is revealed by installing plants with newest technology and by modernizing old plants. It is assumed that all new and modernized plants have a lower specific demand for labor and energy compared to 1995 standard. Furthermore, all new and modernized plants are identical regarding technical parameters irrespective of the location of that plant.

Regional prices of input goods converge between 5 and 50%. Transport tariffs decline between 1995 and 2010 by 10%.

RESULTS

The development of GHG emissions depends heavily on the performance of the industry in the regions and thus, on trade and, in a further step, on energy demand. To get an idea about the overall development in the base run regarding trade, energy, and GHG emissions the relevant data are shown in Fig. 1. The main results of the free trade scenario compared to the base run are presented in Fig. 2-5.

Rising demand for primary aluminum leads to an increase in production, trade of primary aluminum, and energy use. The latter is not true for all energy carriers and in all cases. Nevertheless, due to a fall in specific energy demand the growth in energy demand of either energy carrier falls short to the rise in output. Greenhouse gas emissions contrast the development of production of primary aluminum. Total GHG emissions denominated in CO_2-equivalents decline in case 2. In case 1, a small increase in emissions can be stated (Fig. 1).

Most of these trends in the base run are affected by a total abolishment of all trade barriers [5]. Due to the setting of the model, trade liberalization has no effect on the world demand for primary aluminum and alumina and a negligible effect on world demand for bauxite. Irrespective of that, regional demand for alumina and bauxite will change as abolishing tariffs leads to a re-allocation of production sites on each process level, i.e. geographic mix of production sites changes. Because of economic batch sizes, i.e. temporarily existence of capacity constraints, not all regions are affected by the shift of sites (Fig. 2).

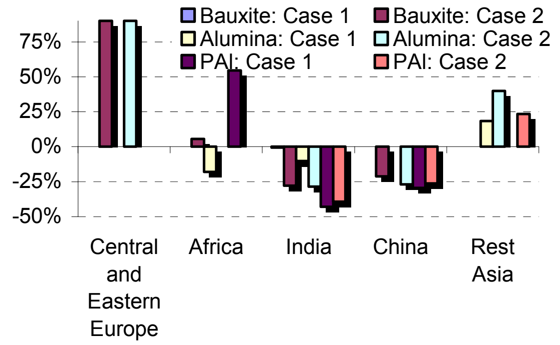

Fig. 2 Change of output in selected regions, compared to the base run

The new dispersion of sites pushes up the trade volume of all goods, compared to the base run. The only exception is trade of bauxite in case 2 (Fig. 3). The increased demand for

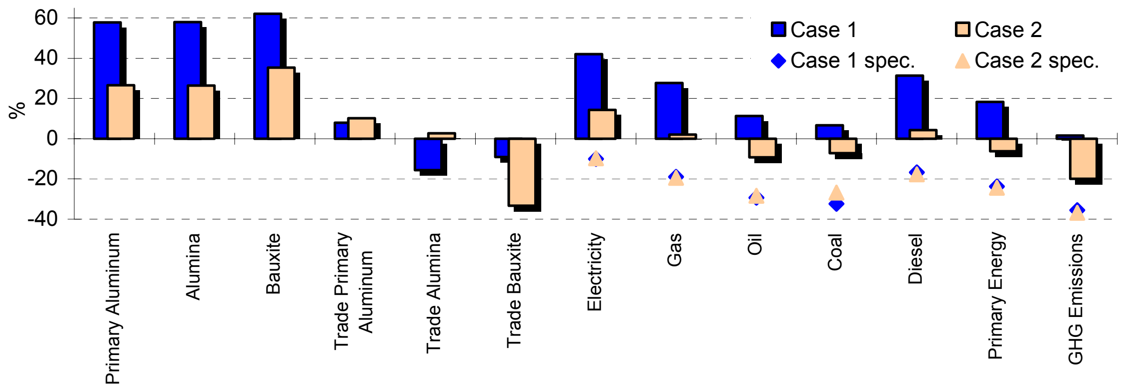

Fig. 1 Inputs and outputs of base run compared to 1995

bauxite in case 2, induced by rising primary aluminum demand, can be matched by those regions, which produce alumina cheap, compared to world average. Consequently, intra-regional trade is promoted by trade liberalization in expense to inter-regional trade. However, demand increase in case 1 exceeds the mining capacities of alumina producing regions.

The effects of trade liberalization on energy demand follow no clear-cut trend, neither regarding energy carrier nor analyzed case. Abolishing trade barriers lead either to an increase (e.g. diesel), to a decrease (e.g. coal) or have nearly no effects (electricity or gas; Fig. 4). The trend of energy demand depends on the favored energy carrier in the involved regions, the amount of additional transport services as trade increases, and the (worldwide) divergence of technical level of the used technologies.

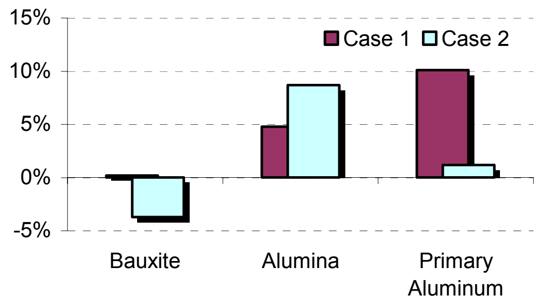

Fig. 3 Change of trade volume, compared to the base run

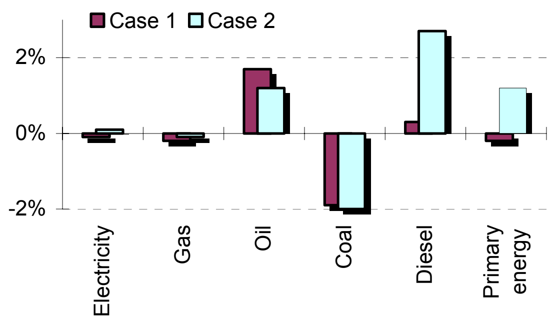

Fig. 4 Change of energy demand, compared to the base run

In case 1 trade liberalization reduces primary energy demand, compared to the base run, but the overall effect is rather small. Only in case 2 free trade induces an increase in primary energy demand. However, the effect is not very significant: + 1.2%, compared to the base run (Fig. 4).

In the base run total GHG emissions, measured in CO_2-equivalents of the 100-year direct GWP, will decline in case 2. In case 1, a slight increase of emissions can be expected (Fig. 1). Abolishing all trade barriers will lead in all cases to emission levels below the one in the base run (Fig. 5). Moreover, free trade would lead to an emission level below the one in the reference year 1995.

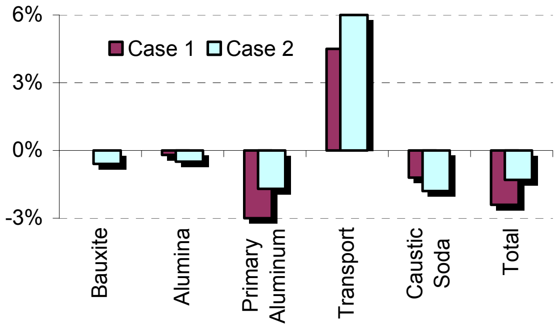

Fig. 5 Change of GHG emissions, compared to the base run

In the model, trade liberalization influences GHG emissions mainly through two channels: via transport and via dispersion of new smelting plants. Free trade barriers has no significant impact on the emissions of bauxite mining and alumina processing, as well as on the auxiliary chains, never exceeding the base run data by more than 1.5%.

Furthermore, only energy-induced emissions, i.e. in the model only carbon dioxide emissions, are affected. Process-induced emissions will not change, as all new and modernized smelting plants are run by newest technology, irrespective of the location of the plant.

Opening an economy leads to an intensified international trade and thus, to more transport services. A consequence of that development is an increasing use of (primary) energy resulting in growing carbon dioxide emissions. Since no technical progress regarding emissions in the transport sector is modeled, the edging up of (primary) energy demand as well as carbon dioxide emissions is not counteracted by falling specific (primary) energy use or specific carbon dioxide emissions.

The increase in carbon dioxide emissions by transport sector is outmatched by a fall in carbon dioxide emissions induced by smelters. Free trade forces the dispersion of new smelting plants with newest technology to regions with rather low power generation costs. Accidentally, energy carrier with low generation costs are those with low or none carbon dioxide emissions, like hydropower. Consequently, carbon dioxide emissions of smelting plants will decrease in the free trade scenario compared to the base run.

SUMMARY

The paper focuses on the impact of trade liberalization on global GHG emissions. Since all new and modernized smelting plants are run by newest technology, irrespective of the location of the plant, the re-allocation of production sites have no effect on process-induced emissions. Only energy-induced emissions are affected by abolishing of tariffs. Free trade reduces the global emissions of carbon dioxide. The increase of transport-induced emissions is outmatched by the fall of emissions caused by power generation serving the electricity need of smelters. A world with no trade barrier promotes the installment of smelters in regions using mainly energy carrier with low or no CO_2 emissions.

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INCREASING WORLD DEMAND FOR PRIMARY ALUMINIUM
IN THE CURRENT DECADE:
AN ENCUMBRANCE FOR ENVIRONMENT?
– A PARTIAL EQUILIBRIUM ANALYSIS –*

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ABSTRACT

Aluminium is in the manufacturing industry a very popular light metal. The prevalence of aluminium is due to its mineralogical and chemical characteristics. But, primary aluminium processing is by its nature energy and resource intensive and thus, potentially, high polluting. Primary aluminium is the main intermediate good for aluminium alloys and products. Furthermore, for the current decade an increase in demand for primary aluminium can be expected. Thus, growing stress on environment by aluminium processing seems to be likely.

Objective of this paper is to discuss whether increasing demand for primary aluminium in the current decade is companioned by rising emissions of greenhouse gases. Using simulation technique three cases are considered. These differ in the calculated demand level for primary aluminium in 2010. The study is made by using a partial equilibrium world aluminium trade model.

KEYWORDS

Aluminium, greenhouse gas, partial equilibirium model, material flow, environmental impact, scenario

* Source: Workshop ConAccount in Stockholm, Schweden, 25.04.-27.04.2001: Economic Growth, Material Flows and Environmental Pressure, http://www.account2001.scb.se/prog.asp.

1 Introduction

Aluminium is in the manufacturing industry a very popular light metal. The prevalence of aluminium is due to its mineralogical and chemical characteristics [Ullmann's Encyclopaedia 1985]. But, primary aluminium processing is by its nature energy and resource intensive and thus, potentially, high polluting. Primary aluminium is the main intermediate good for aluminium alloys and products. Furthermore, for the current decade an increase in demand for primary aluminium can be expected. Thus, growing stress on environment by aluminium processing seems to be likely.

Objective of this paper is to discuss whether increasing demand for primary aluminium in the current decade is companioned by rising emissions of greenhouse gases (GHG). Using simulation technique three cases are considered. These differ in the calculated demand level for primary aluminium in 2010. The study is made by using a partial equilibrium world aluminium trade model. The original version of the model was developed by Schwarz [2000, *cf.* Schwarz *et al.* 2000] and bases on works of Brown *et al.* (1983), Nichols *et al.* (1992) and Manne *et al.* (1994).

The paper is organised as follows: In section 2 a short overview over processing of primary aluminium is given. Section 3 outlines main features of the model. Section 4 deals with the effects of rising demand of primary aluminium on GHG emissions. In section 5 main findings are presented.

2 Processing of primary aluminium

Aluminium is the third most abundant element on the Earth's surface. Only oxygen and silicon are more common. The Earth's crust to a depth of 16 kilometres contains 8% aluminium. Aluminium has a strong tendency to combine with other common elements and so rarely occurs in nature in the metallic form.

For processing primary aluminium aluminium oxide is used, which is enclosed in bauxite. To be used economically, bauxite should contain at least 40% aluminium oxide. Mined bauxite is processed to alumina in two steps. In a first step crushed bauxite is digested by caustic soda and thermal energy, getting after several mechanical and chemical processes aluminium hydro oxide. This is calcinated to aluminium oxide.

To produce primary aluminium, the aluminium and oxygen in alumina must be separated by electricity in the reduction process. This reduction takes place in carbon-lined cells, through which direct electric current is passed. The bottom of each cell acts as a cathode. Carbon is used in the cell to serve as an anode. Inside the cell, alumina is dissolved in a bath of molten electrolyte, composed mainly of cryolite. The electric current passing from the anode to the cathode separates oxygen from alumina, which reacts with the carbon anode to form carbon dioxide, while the aluminium metal settles to the bottom of the cell to be siphoned off [Gagnier and Berthoud 1999].

3 The model GlobAl

GlobAl belongs to the group of partial equilibrium world trade models and is linear by its nature. The model gives a simplified picture of the process chain of primary aluminium.[1] The entire material flow, considered in the model, consists of the three processing steps – bauxite mining, alumina refining, and primary aluminium smelting – as well as the production of

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[1] A detailed description of the model version used for this study can be found in Poganietz (2001).

caustic soda, baking of anodes, and transportation. Caustic soda is used to digest aluminium oxide, anodes in electrolysis.

Technologies shaped in the model follow in a stylised way the used one in reality. For mining only one technology is modelled, which is not altered until 2010. But, due to technical progress, requirement of all input goods decreases between 1995 and 2010 by 20%. Alumina is refined in the model by six types of processing: three types of digestion – autoclaves with high or low temperature, tube reactor – are combined with two types of calcination – rotary kiln process, fluidised bed process. Four technologies are distinguished for smelting: Söderberg (VSS&HSS), side-worked pre-baked (SWPB), centre-worked pre-baked (CWPB) and point-feeder pre-baked (PFPB) technology. Point feeding is the most modern technology. In contrast to the others the voltage in the cell of a point-feeder plant is permanently checked. Hence, energy use by PFPB smelters should be smaller, compared to other technologies. Technical progress in refining alumina and smelting primary aluminium is revealed by installing new equipment, which generates higher energy efficiency. Additionally, learning-by-doing technical progress is implemented in the model. But, it is realised only in old production plants, which are not producing at the efficient margin.

Demand and production of all goods are separated geographically. Hence, the world is divided in 15 regions.

The model calculates on the base of minimising the total costs of production, investing and transport the production of the different goods in each region as well as trade flows between regions. Irrespective of this, since in all markets perfect competition is assumed the model is demand driven. Demand for primary aluminium is exogenous given. Demand for alumina and bauxite is derived from the demand of primary aluminium and alumina, respectively. The assumption of perfect competition secures that bauxite, alumina, and primary aluminium, which is produced in a region, is disbursed domestically and abroad completely. The chosen objective function implies profit maximising economic agents. The model is static and depicts the development between 1995 and 2010 in one period.

To assess the impact of primary aluminium processing on climate change, the model balances the emissions of GHG. In this model emissions of carbon dioxide (CO_2) and the perfluorinated hydrocarbons (PFCs) tetrafluormethan (CF_4) and hexafluorethan (C_2F_6), are considered.

The data in the base year refer to 1995 [*cf.* Schwarz 2000]. Prices of various input factors – i.e. labour, electricity, thermal energy carrier, caustic soda, lime – converge between regions, leaving the world price of each input good constant. Relative world prices of input factors are constant throughout the period. Nevertheless, relative prices in the regions as well as between the regions will change. Transport tariffs will decrease by 10% [*cf.* Schwarz 2000].

Tariffs for bauxite, alumina and primary aluminium differ regarding traded good and region. In general higher processed goods are taxed higher than lower processed and regions with higher income levied a lower tariff rate than regions with lower income.

4 Scenario: Cases and results

The model is used to analyse the effects of changed demand for primary aluminium on GHG emissions. Emissions occur during processing, either as final energy is used or due to the so-called anode effects. The former are called energy-induced emissions, which are in this model only of carbon dioxide type. Emissions induced during the anode effects are defined as process-induced one. Anode effects occur during smelting. If separated alumina concentration of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, the so-called anode effect. Anode effects cause carbon from the anode and fluorine from the molten cryolite bath to combine, producing significant quantities of perfluorinated hydrocarbons [Gagnier and Berthoud 1999]. Additionally, carbon is reacting with the dissolved oxygen to carbon dioxide [Ullmann's Encyclopaedia 1985].

Emissions emitted during generating electricity as well as during anode baking, caustic soda production and transport are assigned to the material flow of primary aluminium. These emissions are appointed to energy-induced emissions.

To assess the impact of growing demand on GHG emissions three cases are analysed, using scenario technique. The cases differ in the calculated demand for primary aluminium in the regions in 2010 [*cf.* Poganietz 2001]:

- Case 1 (or base case): On base of projections regarding the development of income in each region, final aluminium intensity of the entire output of an economy as well as of primary aluminium intensity of final aluminium products for each region demand for primary aluminium in each region was calculated,
- Case 2: In this case a higher income growth than in case 1 was predicted, leading to a higher demand for primary aluminium, compared to case 1,
- Case 3: In this case development of income as in case 2 was assumed. But, because of increasing innovation rate and structural change in aluminium production a lower final aluminium intensity of the entire output of an economy and of primary aluminium compared to the one in case 1 and 2 has been predicted. Consequently, the world demand for primary aluminium is below the one in the other cases.

Considering above sketched assumptions world demand for primary aluminium in 2010 is estimated. On base of the estimation demand for alumina and bauxite is derived by the model. The figures are shown in table 1.[2]

Because of the nature of the model rising demand leads to an upsurge of production to the same level. Rising production requires increasing energy use. However, mainly due to technical progress specific energy consumption of all considered energy carriers, i.e. electricity, gas, oil, coal, and diesel, will fall on all production steps in all cases. Consequently, increase in energy demand will be below the growth of output of each good [*cf.* Poganietz 2001]. For some energy carriers in some cases absolute energy use will even drop [*cf.* table 2].

Table 1: World demand of bauxite, alumina, and primary aluminium, in million tonnes

	1995	2010		
		Case 1	Case 2	Case 3
Bauxite	115.57	167.25	183.02	152.82
Alumina	42.99	60.93	67.73	54.39
Aluminium	20.22	27.94	31.08	24.95

Notes: Demand for primary aluminium in 2010 is calculated along the assumptions, sketched in the text. Demand for alumina and bauxite is derived by the model.
Source: Own calculations.

[2] Schwarz *et al.* (2001) differ in their assumptions regarding the annual growth rate of primary aluminium. Consequently, calculated demand for each good and carbon dioxide emissions are different to the one presented in this paper. Additionally, in this paper specific PFCs emissions by each technology follow Schlimbach *et al.* (2001). Hence, results in that respect in this paper diverge from the one presented in *inter alia* Schwarz *et al.* (2000) as well as Kuckshinrichs and Schwarz (2000).

Table 2: Absolute and specific use of energy carriers in the process chain

	Absolute use				Specific use[1]			
		Change against 1995				Change against 1995		
	1995	**Case 1**	**Case 2**	**Case 3**	**1995**	**Case 1**	**Case 2**	**Case 3**
Electricity	**TWh**				**MWh/t**			
Mining	0.48	9.7%	15.5%	5.0%	0.02	-22.6%	-26.8%	-17.1%
Refining	10.96	20.6%	35.5%	5.9%	0.56	-15.0%	-14.1%	-16.4%
Smelting	302.99	28.4%	42.4%	14.7%	15.38	-9.5%	-9.7%	-9.5%
Transporting	0.28	18.4%	44.3%	-4.3%	0.01	-16.5%	-8.6%	-24.4%
Caustic soda producing	2.27	31.2%	44.6%	18.2%	0.12	-7.5%	-8.4%	-6.7%
Sum	***316.98***	***28.0%***	***42.0%***	***14.4%***	***16.09***	***-9.8%***	***-10.0%***	***-9.7%***
Gas	**PJ**				**GJ/t**			
Refining	225.86	11.7%	27.2%	1.5%	11.47	-21.2%	-19.4%	-19.9%
Smelting[2]	5.76	28.6%	42.8%	14.9%	0.29	-9.3%	-9.4%	-9.3%
Caustic soda production	2.09	31.2%	44.6%	18.2%	0.11	-7.5%	-8.4%	-6.7%
Sum	***233.71***	***12.3%***	***27.7%***	***2.0%***	***11.86***	***-20.8%***	***-19.0%***	***-19.5%***
Oil	**PJ**				**GJ/t**			
Refining	229.86	-4.9%	1.5%	-16.1%	11.67	-32.9%	-35.6%	-33.7%
Smelting[2]	23.03	28.6%	42.8%	14.9%	1.17	-9.3%	-9.4%	-9.3%
Transporting	34.48	33.6%	53.5%	17.6%	1.75	-5.8%	-2.7%	-7.2%
Caustic soda production	2.09	31.2%	44.6%	18.2%	0.11	-7.5%	-8.4%	-6.7%
Sum	***289.45***	***2.6%***	***11.3%***	***-9.3%***	***14.69***	***-27.6%***	***-29.4%***	***-28.4%***
Coal	**PJ**				**GJ/t**			
Refining	***112.20***	***3.2%***	***6.7%***	***-7.1%***	***5.70***	***-27.2%***	***-32.4%***	***-26.7%***
Diesel	**PJ**				**GJ/t**			
Mining	21.82	16.4%	27.7%	6.0%	1.11	-17.9%	-19.0%	-16.3%
Transporting	6.17	22.4%	44.4%	-1.7%	0.31	-13.7%	-8.5%	-22.4%
Sum	***27.99***	***17.7%***	***31.4%***	***4.3%***	***1.42***	***-17.0%***	***-16.7%***	***-17.7%***

Notes: 1 Energy consumption per produced tonne primary aluminium.
2 Gas and oil are used during baking of anodes. Non-Söderberg technologies need anodes baked outside the electrolysis.

Source: Own calculations.

Energy consumption influences, namely energy-induced, emissions, but not solely. To get a full picture of sources and causes of GHG emissions assigned to the process chain demand for primary aluminium, efficiency of energy generation, regional energy carrier mix in power generation, and production geography should be taken into account.

Considering these factors in calculation in 1995 the entire material flow emitted 336m t CO_2, CF_4 and C_2F_6 gases, denominated in CO_2 equivalents. Carbon dioxide and perfluorinated hydrocarbons differ in their direct impact on climate change. To compare the effects of both types of gases the 100-year direct global warming potential was used in this paper, following the Kyoto Protocol. According to this measure one unit CF_4 equals 6,500 units CO_2; in case of C_2F_6 a relation of 9,200 units CO_2 per one unit C_2F_6 is used [Grubb *et al.* 1999].

About 79% of total emissions in CO_2 equivalents are carbon dioxide, the rest PFCs [*cf.* table 3]. According to the calculations in case 2 total emissions of greenhouse gases will increase slightly by 1.6%. In the other two cases a fall of them will be likely. Different demand levels cause a diverging development of emissions. Specific emissions decline rather uniform by 36.1% on average of all cases from 17.1 t in CO_2 equivalents in 1995. The drop is uneven distributed between the greenhouse gases. Specific carbon dioxide emissions go down by

27.2% on average of all cases, the one of PFCs by 70.9%. Due to the different variation of specific emissions total emissions of CO_2 will increase in case 1 and 2 and will drop in case 3 as PFCs emissions will fall in all cases, quite considerably [*cf.* table 3].

Table 3: Emissions and specific emissions of selected GHG

	Emissions				Specific emissions[1]			
	1995	Change against 1995			1995	Change against 1995		
		Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
	m t CO_2-e[2]				t/t CO_2-e[2]			
CO_2	267.24	3.9%	16.8%	-9.5%	13.565	-26.7%	-26.0%	-28.5%
PFCs	68.90	-59.0%	-57.3%	-60.6%	3.498	-71.1%	-72.9%	-68.9%
CF_4	60.36	-59.0%	-57.3%	-60.6%	3.064	-71.1%	-72.9%	-68.9%
C_2F_6	8.54	-59.0%	-57.3%	-60.6%	0.434	-71.1%	-72.9%	-68.9%
Total	***336.14***	***-9.0%***	***1.6%***	***-20.0%***	***17.063***	***-35.8%***	***-35.6%***	***-36.8%***
N.B.	**t**				**kg/t**			
CF_4	9,286.1	-66.6%	-65.3%	-68.2%	471.38	-71.1%	-72.9%	-68.9%
C_2F_6	928.6	-59.0%	-57.3%	-60.6%	47.14	-71.1%	-72.9%	-68.9%

Notes: 1 Emissions per produced tonne primary aluminium.
2 CO_2-e: CO_2 equivalents.
Source: Own calculations.

Main source of GHG emissions is electrolysis: In 1995 smelters induced 82% of all emissions, measured in CO_2 equivalents. In 2010 the share will decline to about 79% on average of all cases. The fall of PFCs emissions leads to a variation of GHG emissions induced by smelters, which are smaller than the changes induced by the entire material flow [*cf.* table 4].

Table 4: Emissions and specific emissions of selected GHG assigned to each process

	Emissions				Specific emissions[1]			
	1995	Change against 1995			1995	Change against 1995		
	m t CO_2-e[2]	Case 1	Case 2	Case 3	t/t CO_2-e[2]	Case 1	Case 2	Case 3
Mining	1.99	11.6%	22.0%	2.0%	0.10	-21.3%	-22.6%	-19.5%
Refining	53.49	1.9%	10.9%	-9.1%	2.72	-28.2%	-29.7%	-28.2%
Smelting	275.09	-12.0%	-1.2%	-22.8%	14.00	-37.9%	-37.4%	-39.1%
Transporting	3.84	30.4%	50.6%	13.2%	0.20	-8.1%	-4.6%	-10.6%
Caustic soda prod.	1.74	14.1%	25.4%	1.7%	0.09	-19.6%	-20.5%	-19.7%
Sum	***336.14***	***-9.0%***	***1.6%***	***-20.0%***	***17.01***	***-35.8%***	***-35.6%***	***-36.8%***

Notes: 1 Emissions per produced tonne primary aluminium.
2 CO_2-e: CO_2 equivalents.
Source: Own calculations.

The other important source of emissions in the material flow is refining. Its share was in 1995 about 16%. It will increase presumably to 18%, on average of all cases. Efficiency of emissions, i.e. the reciprocal of specific emissions, in refineries will not edge up to the same extent as in smelters [*cf.* table 4]. Other emission sources are negligible.

Gaseous emissions, measured in CO_2 equivalents, induced by smelters will decrease between 1.2% and 22.8% from 275m t in 1995. The amount of drop depends on assumed output growth, as specific emissions decline rather uniform by 38.1% on average of all cases [*cf.* table 5].

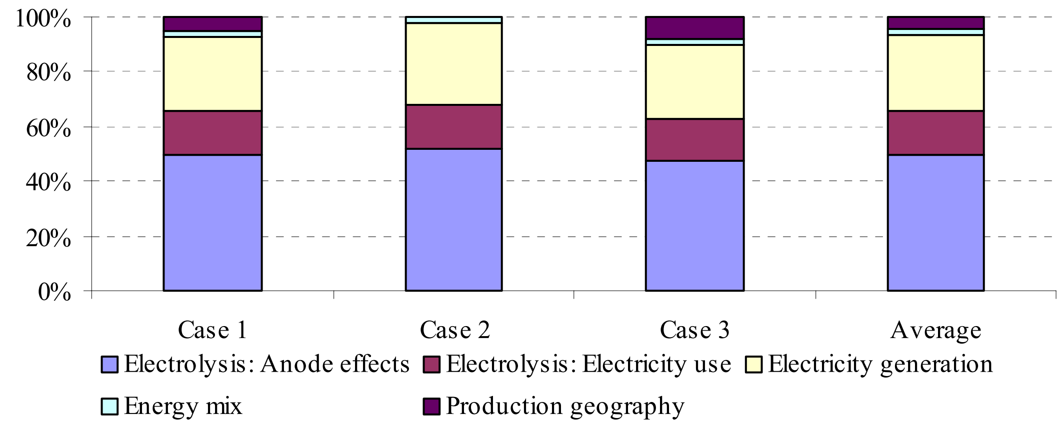
Table 5: Emissions and specific emissions of GHG by smelters

	Emissions				Specific emissions[1]			
	1995	Change against 1995			1995	Change against 1995		
	m t CO_2-e[2]	Case 1	Case 2	Case 3	t/t CO_2-e[2]	Case 1	Case 2	Case 3
Energy induced (CO_2)	172.76	-1.1%	12.7%	-15.1%	8.77	-30.2%	-28.6%	-32.9%
Process induced	102.34	-30.4%	-24.6%	-35.9%	5.19	-50.9%	-52.2%	-49.4%
CO_2	33.43	28.6%	42.8%	14.9%	1.70	-9.3%	-9.4%	-9.3%
PFCs	68.90	-59.0%	-57.3%	-60.6%	3.50	-71.1%	-72.9%	-68.9%
Sum	***275.09***	***-12.0%***	***-1.2%***	***-22.8%***	***13.96***	***-37.9%***	***-37.4%***	***-39.1%***

Notes: 1 Emissions per produced tonne aluminium.
2 CO_2-e: CO_2 equivalents.
Source: Own calculations.

The fall of specific GHG emissions is forced by technical progress by large. On average of all cases about 93.5% of decline can be explained by that [regarding method see Schwarz 2000]. On average of all cases nearly two-third of total decline is due to instalment of advanced smelting technology and, to a lesser degree, due to learning by doing technical progress, i.e. is influenced directly by decisions on the level of firms. Three-quarters of that are the consequence of an improved technology concerning anode effects; one quarter because of a higher efficiency in electricity use [figure 1].

Figure 1: Actual process induced emissions of selected GHG relative to the best achievable level, 2010



Source: Own calculations.

Because of changed relative prices and increasing demand for primary aluminium smelters will be widely modernised or new one will be installed. By assumption modernised and new smelters use PFPB technology. Consequently, in 2010 96.5% of produced aluminium will be processed in PFPB plants, compared to 45.5% in 1995. 70% of all smelters will be run by newest PFPB technology. This technology needs significantly less electricity than other technologies [CRU 1997]: In the model economy newest PFPB technology established in a new plant will demand in 2010 between nine and 24% less electricity per tonne primary aluminium than other technologies. Specific PFCs emissions by newest PFPB smelters reach between 4.2% and 16.7% of specific emissions of plants using older or other than PFPB technology [*cf.* Schlimbach *et al.* 2001]. In case of process-induced specific CO_2 emissions the respective range reach from 80% to 97.6% [*cf.* Poganietz 2001].

Higher efficiency in power generation partakes 28% on average of all cases at the decline of specific emissions. A changed mix of energy carrier explains 2% of fall of specific emissions, a changed production geography 4% [*cf.* Poganietz 2001].

Considering the sources of smelter's emissions, in 1995 62% were energy-induced. Energy-induced emissions are not solely determined by electrolysis, but also by – to name the other important factor – efficiency of generation of electricity. The overall efficiency of supply will presumably increase on world average by 11% from 44% in 1995. In view of all factors determining specific energy-induced emissions, these will fall on average by 30%. Thus, in case 1 and 3 overall energy-induced emissions will decline, as they will grow in case 2.

The comparable low emissions of PFCs gases by newest PFPB technology lead to a drastic reduction of process-induced emissions, in specific and in absolute terms. This will not be offset by the rather low improvement of reducing CO_2 emissions [*cf.* table 5].

The amount of reduction in specific PFCs emissions depends crucially on the assumption that during modernisation of older technology or instalment of new plants always the newest PFPB technology is established. Any deviation from that assumption will lead to a smaller decrease of specific PFCs emissions.

The widely instalment of newest PFPB technology in case of either investment leads to a nearly complete approach of actual process induced CO_2 emissions to the best achievable level. This is not true in case of perfluorinated hydrocarbons. The best achievable level is the one, which would be realised, if primary aluminium were produced solely in smelters run by newest PFPB technology. CO_2 emissions reach on average of all cases 98% of that value. PFCs emissions reach only a third of the best value [*cf.* table 6]. In 2010 about 30% of production will not be produced in smelters with newest technology.

Table 6: Actual process induced emissions of selected GHG relative to the best achievable level, 2010

	Case 1	Case 2	Case 3
CO_2	97.8%	97.9%	97.7%
PFCs	36.7%	39.2%	34.1%
Total	73.5%	75.5%	71.4%

Notes: Calculated on base of CO_2 equivalents.
The values indicate to which extent process-induced GHG emissions in 2010 will approach to the value, which is realised if all smelters use newest PFPB technology.

Source: Own calculations.

5 Concluding remarks

Objective of the paper was to analyse the impact of growing demand for primary aluminium on emissions of greenhouse gases in the current decade. Using simulation technique the study bases on a linear partial equilibrium world aluminium trade model.

Rising demand for primary aluminium induces increasing production of that good as well as of alumina and bauxite. This should lead to higher consumption of energy on all considered processing steps. But, mainly due to technical progress, declining specific energy consumption will lower the going up of energy demand.

Total emissions of GHG gases will fall in two of three cases. Only in case of high demand, the additional production of aluminium and thus the additional emissions are not offset by the drastic decline of specific emissions. But, the drop of specific emissions is mainly due to a decline of PFCs emissions. Carbon dioxide emissions surge up in case 1 and 2.

Looking at electrolysis as the dominant issuer of GHG gases, the drop of emissions is caused mainly by technical progress in smelting technology and, to a lesser degree, in energy generation. Technical progress in electrolysis affects in a tremendous way emissions of PFCs gases and, to a lesser degree, CO_2 emissions. Irrespective of this, process-induced emissions of CO_2

reach nearly the best achievable level, in contrast to PFCs emissions. A further adjustment of actual emissions of carbon dioxide to the optimal one is rather not possible. Two consequences emerge from these findings. Any further considerable reduction of carbon dioxide emissions can only be expected by the energy generation sector. However, a discussion of the opportunities of that sector is not in the scope of this paper.

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PERFLUORINATED HYDROCARBONS IN THE PRIMARY ALUMINUM PROCESSING
– TRENDS IN THE CURRENT DECADE –

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ABSTRACT

Aluminum is in the manufacturing industry a very popular light metal. But, processing of primary aluminum, the main intermediate for aluminum products and alloys, generates huge amounts of the perfluorinated hydrocarbons (PFCs) tetrafluormethan (CF_4) and hexafluorethan (C_2H_6). According to our calculations in 1995 primary aluminum industry issued worldwide 9300 t CF_4 and 930 t C_2H_6. PFCs are caused by the so-called anode effect during the electrolysis.

The objective of this paper is to analyze the development of PFC gaseous emissions in the current decade. The analysis bases on the model GlobAl, a partial equilibrium world aluminum trade model.

Estimating rising demand for primary aluminum, reaching in 2010 25m t, 28m t and 31m t, respectively, compared to 20m t in 1995, production of primary aluminum will follow. However, due to technical progress, emissions of PFC gases will be at least by 57% below the level of 1995. Irrespective of that, the emission level of PFCs in 2010 reaches just about 39%, at it best, of the technological feasible level using best available technology as a reference point. A promotion of installing best available technology is needed, if a further decline of PFC gas emissions is seen as desirable.

KEYWORDS

Perfluorinated hydrocarbons, partial equilibrium analysis, primary aluminum, material flow

* Source: van Ham, J., Baede, A.P.M., Guicherit, R., Williams-Jacobse, J.G.F.M. (ed.): Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects. Rotterdam: Millpress, S. 213-218

INTRODUCTION

Aluminum is in the manufacturing industry a very popular light metal. The prevalence of aluminum is due to its mineralogical and chemical characteristics. But, processing of primary aluminum, the main intermediate for aluminum products and alloys, generates huge amounts of the perfluorinated hydrocarbons (PFCs) tetrafluormethan (CF_4) and hexafluorethan (C_2H_6). According to our estimations the emissions by primary aluminum industry were in 1995 9300 t CF_4 and 930 t C_2H_6. The figures differ slightly from the one of Harnisch et al. (1999). About 60% of PFC emissions of anthropogenic origin were attributable to the primary aluminum industry (Harnisch et al. 1999). The so-called anode effect causes PFC gases during the electrolysis.

The objective of this paper is to analyze the development of PFC gaseous emissions in the current decade. Since the development of emissions depends heavily on the increase in demand for primary aluminum and on technical progress in electrolysis technology, both features are explicitly considered. The analysis is made by using the model GlobAl, a partial equilibrium world aluminum trade model. It depicts the material flow of global primary aluminum processing.

The paper is organized as follows: In the following section 2 the anode effect as the only source of PFC emissions of the primary aluminum processing is described. Furthermore, the connection between specific emissions and the used technology is presented. Section 3 gives a short overview over the model GlobAl. The then following section 4 describes the analyzed scenario and presents the main findings. In the final section concluding remarks are offered.

1 THE ANODE EFFECT

In the process chain of aluminum processing perfluorinated hydrocarbons occur exclusively during electrolysis in the so-called anode effect. To produce metal, aluminum oxide (alumina) is reduced in an electrolysis process. The reaction takes place in a carbon-lined cell through which electric current is passed. When the alumina concentration in a cell falls below the critical amount of 1 to 2% a gaseous layer (CF_4 and C_2F_6) establishes between the bottom side of the anode and the melt. Due to that the cell voltage jumps up to a ten fold of its normal value. The increase of the voltage leads to an increase of cell temperature and in turbulences of the bath. This effect was formerly used to clean the bath and indicated the alumina content in the electrolyte. It can be stopped by adding alumina while simultaneously moving the anodes.

Two reasons lead to the attempt to prevent this effect. One is the reduction of the increasing power demand and the second is the avoidance of the emitted PFC gases. This was reached by a better dosing of alumina using point feeder technology. The exact concentration of alumina cannot be determined directly. The monitoring of the cell voltage is used to draw conclusions of the concentration. In modern computer controlled cells using point feeder technology the voltage in the cell is permanently checked. As a consequence point feeder pre-baked (PFPB) technology reduces the anode effect to one in ten days while it were up to three effects in one day in earlier times. Hence, the amount of specific emissions of PFCs should be smaller at PFPB compared to the other technologies, i.e. vertical stud Söderberg (VSS), horizontal stud Söderberg (HSS), side-worked pre-baked (SWPB), and center-worked pre-baked (CWPB) technology. Specific emissions are defined as emissions per produced tone primary aluminum.

The amount of specific emissions of CF_4 and C_2F_6 is presented in table 1. Since different stages of development of each technology can be stated, old technology (OT), present technology (PT), and newest technology (NT) are distinguished.

Table 1. Specific PFC emissions caused by the different electrolysis technologies, in g/t primary aluminum.

	CF_4			C_2F_6		
	OT	PT	NT	OT	PT	NT
PFPB	500	300	50	50	30	5
CWPB	500	300	--	50	30	--
SWPB	--	1200	700	--	120	70
VSS	1100	550	--	110	55	--
HSS	400	70	--	40	7	--

Note: --: Technology does not exist.
Source: Schlimbach et al. (2001).

2 THE MODEL

GlobAl belongs to the group of partial equilibrium world trade models and is linear by its nature. The model gives a simplified picture of the process chain of primary aluminum (cf. Poganietz 2001). The entire material flow, considered in the model, consists of three processing steps – bauxite mining, alumina refining, and primary aluminum smelting – as well as the production of caustic soda, baking of anodes, transportation, and energy generation. Caustic soda is used to digest aluminum oxide; anodes are utilized in electrolysis.

Technologies shaped in the model follow in a stylized way the used one in reality. In case of smelting four technologies are distinguished: Söderberg as a combination of VSS and HSS technology, SWPB, CWPB, and PFPB technology. Point feeding is seen as the most advanced technology, as the specific energy demand is the lowest, compared to other technologies. Technical progress is revealed by installing new equipment, which generates higher energy efficiency. Additionally, learning-by-doing technical progress is implemented in the model. But, it is realized only in old production plants, which are not producing at the efficient margin.

Demand and production of all goods are separated geographically. Hence, the world is divided in 15 regions.

The model calculates on the base of minimizing the total costs of production, investing and transport the output of bauxite, alumina, and primary aluminum in each region as well as trade flows between regions. Irrespective of this, since in all markets perfect competition is assumed the model is demand driven. Demand for primary aluminum is exogenous given. Demand for alumina and bauxite is derived from the demand of primary aluminum. The assumption of perfect competition secures that bauxite, alumina, and primary aluminum produced in a region, is disbursed domestically and abroad completely. The chosen objective function, i.e. minimizing the total costs of production etc, implies that all enterprises maximize their profits. The model is static and depicts the development between 1995 and 2010 in one period.

To assess the impact of primary aluminum processing on climate change, the model balances the emissions of greenhouse gases. In this model emissions of carbon dioxide (CO_2), tetrafluormethan (CF_4), and hexafluorethan (C_2F_6) are considered.

The data in the base year refer to 1995 (cf. Schwarz 2000). Prices of various input factors – i.e. labor, electricity, thermal energy carrier, caustic soda, lime – converge between regions, leaving the world price of each input good constant. Relative world prices of input factors are constant throughout the period. Nevertheless, relative prices in the regions as well as between regions will change. Transport tariffs will decrease by 10%. Tariffs for bauxite, alumina and primary aluminum differ regarding traded good and region. In general higher processed goods are taxed higher than lower processed and regions with higher income levied a lower tariff rate than regions with lower income. Tariffs will decrease by 20%.

The version of the model used in this paper is a slightly revised variant of the model developed by Schwarz (1999, 2000). The model bases on works of Brown et al. (1983), Nichols et al. (1992) and Manne et al. (1994).

3 SCENARIO AND RESULTS

To assess the impact of growing demand on PFC emissions three cases were analyzed, using scenario technique. The cases differ in the calculated demand for primary aluminum in the regions in 2010 (cf. Poganietz 2001):

- Case 1 (or base case): To compute the regional demand for primary aluminum in 2010 projections were made regarding the development of income in each region, the development of the share of (final) aluminum at the output of an economy and the development of the share of primary aluminum at (final) aluminum at each region.
- Case 2: In this case a higher income growth than in case 1 was predicted, resulting in higher demand, compared to the base case.
- Case 3: In this case development of income as in case 2 was assumed. But, because of increasing innovation rate and structural change in aluminum production lower (final) aluminum intensity of the entire output of an economy and a lower share of primary aluminum at (final) aluminum compared to the one in cases 1 and 2 has been predicted. This leads to a lower demand, compared to cases 1 and 2.

Considering above sketched assumptions world demand for primary aluminum in 2010 has been calculated. The demand for primary aluminum will rise in case 1 to 27.9m t, in case 2 to 31.1m t, and in case 3 to 25.0m t. In 1995 demand for primary aluminum was 20.2m t.

Due to the assumption of perfect markets output will follow demand. Depending on chosen case the worldwide output will grow between 23.4 and 53.7% until 2010. But, emissions of PFCs will not succeed in either case. Not even that, the emission level will drop dramatically, at least by 57% (case 2); in case 3 the decline will be even 61% (Table 2). The uniform decline of CF_4 and C_2F_6 in each case results from the way that C_2F_6 is “measured”. Since no precise method to measure C_2F_6 was known Schlimbach et al. (2000) set specific C_2F_6-emissions to a tenth that of specific CF_4-emissions.

Table 2. Emissions of PFCs, in tones.

	1995	2010			Change against 1995		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
CF_4	9286.1	3807.2	3964.3	3657.9	-59.0%	-57.3%	-60.6%
C_2F_6	928.6	308.7	396.4	365.8	-59.0%	-57.3%	-60.6%

Source: Own calculations.

The fall in emissions results from a more drastic decline in specific emissions of both gases. The extent of the decline ranges from 69 (case 3) to 73% (case 2; Table 3). In contrast to total emissions the largest decrease is in the high demand case 2; the lowest in the low demand case 3.

Table 3. Specific emissions of PFCs, in g/t primary aluminum.

	1995	2010			Change against 1995		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
CF_4	471.4	136.3	127.6	146.6	-71.1%	-72.9%	-68.9%
C_2F_6	47.1	13.6	12.8	14.7	-71.1%	-72.9%	-68.9%

Source: Own calculations.

The fall in specific emissions is largely, but not solely, a consequence of technical progress. Technical progress is revealed by an increasing use of newest PFPB smelter technology worldwide (Table 4). According to our calculations the share of PFPB smelters will increase to 96% (case 3) at world output, at least, from 45.5% in 1995. In the same period the output share of PFPB smelters run by newest technology will triple.

Specific emissions by newest PFPB smelters technology reach between 4.2 and 16.7% of specific emissions of plants using older or other than PFPB technology (Schlimbach et al. 2001, cf. table 1). Since the share of PFPB NT is highest in the high demand case 2 the drop in specific emissions have to be highest in that case. The installment of new capacities is forced by increased demand for primary aluminum. Since 1995 production capacity will not match demand in 2010 new plants have to be built. It is assumed that new plants are run by newest PFPB technology. Due to this the increase in share of PFPB in case 2 has to be highest.

Table 4. Distribution of world output according to used technology, in percent.

	1995	2010		
		Case 1	Case 2	Case 3
Söderberg	27.8	0.0	0.0	0.0
CWPB	16.2	3.0	2.7	3.4
SWPB	10.5	0.5	0.5	0.5
PFPB	45.5	96.5	96.8	96.0
o/w NT*	26.6	70.2	73.4	68.6

Note: * Newest technology.
Source: Own calculations.

The impact of a changed geographic production mix on emissions is rather negligible. On average of all three cases just 3.4% of the decline in specific emissions is due to a variation of allocation of plants to regions. But the range varies between 8.5 (case 1) and – 4.4% (case 3; cf. Poganietz 2001). The shift in the geographic production mix is caused by changed relative prices, altering competitiveness of regions and thus the geographic dispersion of new plants.

The amount of decrease in specific emissions depends crucially on the assumption that during modernization of older technology or installment of new plants always the newest technology of PFPB is established. Any deviation from that assumption will lead to a smaller decrease of specific gaseous emissions.

Even though the drop in emissions is impressive further decline is possible, without implementing future technology. Future technology is the one which is currently under development but which is actually not used and which will presumably not be implemented until 2010. If in 2010 the worldwide output of primary aluminum would be solely produced at plants run by newest technology the emissions of CF_4 would be between 1250 and 1550 t. The emissions of C_2F_6 would range from 125 and 155 t (Table 5).

Table 5. Estimated emissions of PFCs if solely newest PFPB technology is used, in tones, 2010.

	2010		
	Case 1	Case 2	Case 3
CF_4	1397.0	1554.0	1247.5
C_2F_6	139.7	155.4	124.8

Source: Own calculations.

A comparison of these figures with the one presented in table 2 reveals that a further drastic decline in emissions until 2010 is achievable, from a technological point of view. Depending on the case the fall in emissions calculated for the three cases will range between 34 and 39% of the technical attainable cutback (Table 6). In 2010 at least a quarter of world output will not be produced in plants run by newest PFPB technology. These experience very high gaseous emissions, compared to newest PFPB technology (Table 1).

Table 6. Estimated emissions of PFCs relative to the best achievable level, 2010.

	2010		
	Case 1	Case 2	Case 3
CF_4	36.7%	39.2%	34.1%
C_2F_6	36.7%	39.2%	34.1%

Note: The values indicate to which extent PFC emissions in 2010 will approach to the value, which is realized if all smelters would use newest PFPB technology.
Source: Own calculations.

4 CONCLUDING REMARKS

The aim of the paper was to discuss trends in emissions of PFCs in primary aluminum processing in the current decade. The analysis based on a partial equilibrium world aluminum trade model considering technical progress.

Due to technical progress between 1995 and 2010 emissions should drop, at least by 57%. Even though the decline is impressive by the amount, a further reduction of emissions is possible by using best available technology. On average of all discussed cases the fall in emissions will equal about 37% of the amount that is currently technically feasible.

It is beyond the scope of this paper to discuss various possibilities to reach a further decline or discuss the problems of implementing such measures. However, it is worth noting, that any policy forcing installment of PFPB smelters run by newest technology beyond the one computed in each case would generate additional costs. The findings of the paper ground on cost minimizing considerations. The realized equilibrium in each case means that the total costs of producing, investing, and trading are minimized. A consequence of additional costs would be higher prices for primary aluminum compared to the one calculated in the above-discussed scenario.

However, the extent of the price increase depends not only on the emission target and thus the amount of new plants. But also whether measures to enforce new plants will lead to a re-allocation of existing plants away from current locations to regions with lower costs to install new plants.

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