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Abstract: Noise effects of the use of land-based wind energy

Deliberations concerning the planning and approval of wind turbines often revolve around the issue of noise. A wide range of questions are raised that concern both noise generation and noise reduction as well as the impact of noise on the health and quality of life of the population.

The present publication, 'Noise effects of the use of land-based wind energy', contains the results of a research project that investigated the impact of wind turbine noise. The focus of the research was on a particular sound characteristic of wind turbines known as 'amplitude-modulated noise'. A frequently discussed thesis is that this particular sound characteristic, describable for example as a 'whoosh' sound, leads to increased awareness of noise and annoyance among residents. A key aim of the research was to investigate the frequency, duration and intensity of amplitude modulations caused by wind turbines, and to determine whether these are audible and measurable in the surrounding vicinity.

Hence, in addition to measurements, the people who live in the vicinity of wind turbines were interviewed as well. The work to address this question was divided into five priority tasks:

- Long-term sonic measurements in the emission and immission area over a period of at least two and up to six weeks, conducted in five study areas distributed throughout Germany.
- Infrasound measurements in connection with amplitude modulation.
- Analysis of the measurements using a method for the detection of amplitude modulation that was developed within the scope of this project.
- Surveys of noise annoyance on the part of surrounding area residents in all five study areas.
- Listening tests were also carried out in three of the study areas.

The findings gleaned were as follows:

- The median modulation depth on the immission side falls between 1.5 and 2.5 dB.
- Only in one of the five study areas was it possible to identify a relationship of capacity dependency between the wind turbine and the frequency/modulation depth; this relationship was more pronounced in crosswind situations.
- Infrasound caused by wind turbines was detected in all of the study areas. The levels were always below the auditory threshold defined pursuant to DIN 45680 (Beuth 1997).
- In the listening test, the level of annoyance grew as the modulation depth increased. The results also showed that even the mere perceptibility of an amplitude modulation increases the level of annoyance reported by test subjects.

On average, across all study areas and noise levels, participants in the annoyance survey found that the annoyance due to wind turbine noise was relatively low. Once the noise rating level at a residential building exceeds a value of approx. 35 dB(A), however, there is a sharp rise in the percentage of respondents who report that they feel annoyed or highly annoyed. Sound characteristics such as 'whooshing', 'rushing' and non-acoustic factors (attitude towards wind turbines and visual impact) are factors that have a considerable influence on the annoyance due to wind turbine noise. Self-reported noise annoyance correspond with the frequency of occurrence of identified, stable amplitude modulations.

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List of abbreviations

%A, %HA	Percentage Annoyed, Percentage Highly Annoyed
A-weighting	Frequency weighting with A-filter
AM	Amplitude modulation
ANOVA	Analysis of variance
BImSchG	Bundes-Immissionsschutzgesetz [German Federal Emission Control Act]
dB	Decibel(s)
DIN	Deutsches Institut für Normung e.V. [German Institute for Standardisation]
E	Emission
FFT	Fast Fourier Transform
G-weighting	Frequency weighting with G-filter for low-frequency noise (ISO 7196 (Beuth 1995))
GW	Headwind
Hz	Hertz
I	Immission
L	Level
L_{01} – L_{99}	Percentile level, level value that is exceeded X % of the time
L_{Aeq}, L_{Geq}, L_{Zeq}	Energetically averaged frequency-weighted sound pressure level; A, G or Z describe the respective frequency weighting
$L_{HP,05}$-$L_{HP,95}$	Difference between the percentile frequencies of 5 and 95 of the high-pass-filtered signal when considering a single AM.
L_{AFT5eq}	Averaging level of the A-weighted maximum cyclical noise level (cycle 5 seconds)
L_{den}	L_{den} = day-evening-night level Rating level for a 24-hour day, composed of the level for the daytime L_{day}, a level value for the evening $L_{evening}$ with a supplement of 5 dB, and the night level L_{night} with a supplement of 10 dB.
L_r	Rating level typically shown separately as $L_{r,Tag}$ [$L_{r,day}$] for the daytime hours from 6:00 a.m. to 10:00 p.m., and as $L_{r,Nacht}$ [$L_{r,night}$] for the night hours from 10:00 p.m. to 6:00 a.m. Calculations of wind turbine noise assumed constant operation over a 24-hour period. Accordingly, in this study, particularly in the Section on the survey of residents (Section 5), the designation L_r was chosen and references a total level calculated over 24 hours for use in assessing wind turbine noise.
ΔL_{AM}	Modulation depth of amplitude modulation
m	Meter(s)
MW	Mitwind [tailwind]; if shown after a number = Megawatt(s)
NHN	Normalhöhennull [elevation above sea level]
QW	Crosswind

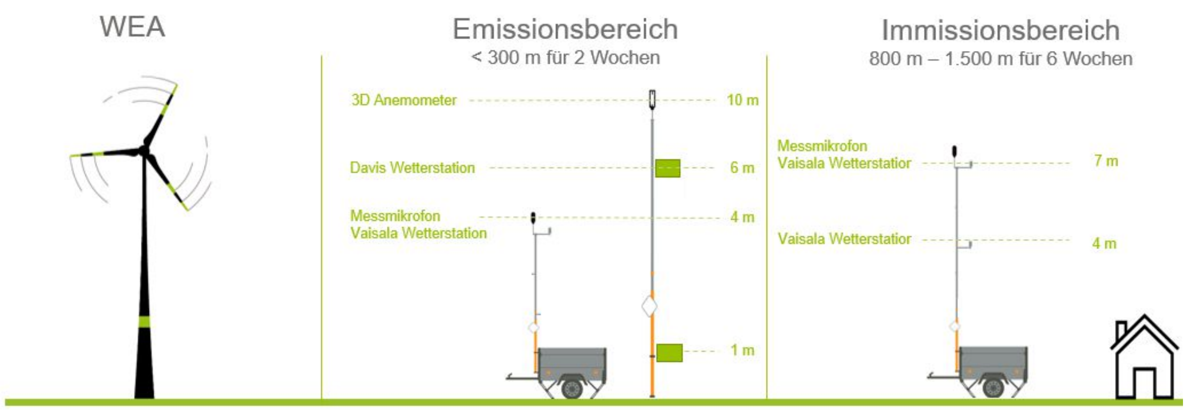
s	Second(s)
SD	Standard deviation
UBA	Umweltbundesamt [German Environment Agency]
SA	Study Area
UK	United Kingdom
Upm	Umdrehung pro Minute [revolution(s) per minute, rpm]
WEA	Windenergieanlage [wind turbine]
Wg	Windgeschwindigkeit [wind speed]
Z-weighting	Z stands for ‘zero’ indicates that no frequency weighting has been carried out

Summary

Deliberations concerning the planning and approval of wind turbines often revolve around the issue of noise. A wide range of questions are raised that concern both noise generation and noise reduction as well as the impact of noise on the health and quality of life of the population. The amplitude and frequency composition of the noise generated by wind turbines is subject to considerable spatial and temporal fluctuation. The noise varies due to factors specific to location, weather and wind and is a function of the type, rotational speed, and operating mode of the wind turbines themselves. Investigations focus specifically on the noise induced by wind turbines and often referred to as a 'whooshing' sound. The present research project refers to this 'whooshing noise' as amplitude-modulated noise induced by wind turbines. When this project began, it was unclear whether and how often amplitude modulations (AM) could be detected at all from distances of greater than 1000 m from the wind turbines. The aim was therefore to investigate the extent to which amplitude modulations are caused in wind turbines, whether these are audible and measurable in the immission area, and what influence they have on nearby residents' awareness of noise.

For this purpose, long-term sonic measurements were carried out in the immission area (> 800 m) for at least six weeks and in the emission area (< 300 m) for two weeks. The noise-specific influences of wind turbines were investigated on the basis of these long-term sonic measurements. To help evaluate the measurements obtained, an algorithm was developed to locate and quantify amplitude modulation in the measurement signal. To assess the human impact of the noise, controlled listening tests were carried out in the study areas, and people living in the vicinity of wind turbines were surveyed with regard to their noise awareness and any feelings of annoyance.

Figure 1: Schematic representation of the measurement set-up

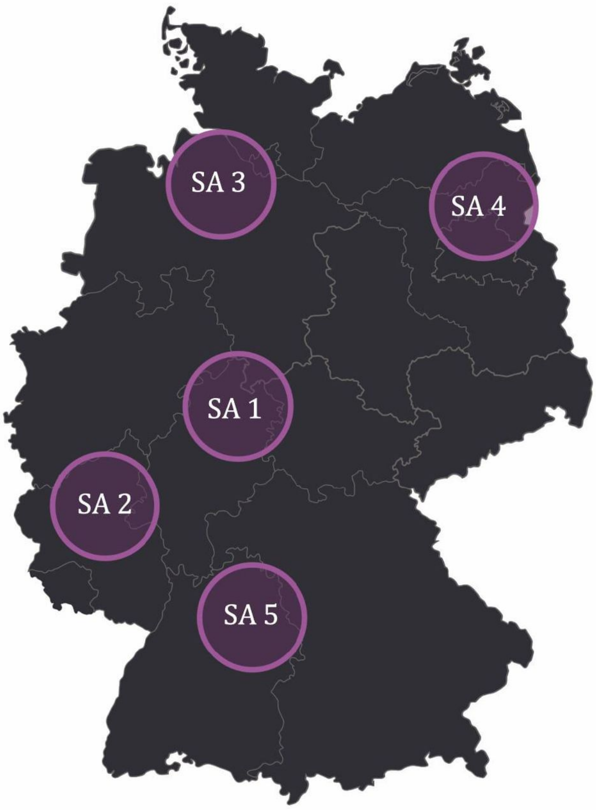


Source: own presentation, deBAKOM GmbH

WEA = Wind turbine; Emissionsbereich < 300 m für 2 Wochen = Emission area < 300 m for 2 weeks; 3D Anemometer = 3D anemometer; Davis Wetterstation = Davis weather station; Messmikrofon Vaisala Wetterstation = Measuring microphone Vaisala weather station; Immissionsbereich 800m-1.00m für 6 Wochen = Immission area 800 m - 1500 m for 6 weeks; Messmikrofon Vaisala Wetterstation = Measuring microphone Vaisala weather station, Vaisala Wetterstation = Vaisala weather station

The study areas were distributed throughout Germany as shown in Figure 2.

Figure 2: Location of the study areas in Germany



Source: own presentation, deBAKOM GmbH

The wind farms in the study areas featured different constellations. They varied in terms of:

- The number of wind turbines (1 to 21 wind turbines)
- Wind turbine type (four manufacturers with a total of six different models)
- Wind turbine height (hub heights of approx. 100 m to approx. 140 m)
- Wind turbine power output (2 MW to 3 MW)
- Rotor diameter (approx. 80 m to approx. 135 m)
- Topographical location (flat to hilly landscape)
- The distance of the measurements taken in the immission area (approx. 800 m to 1500 m)
- Measurement period (spring to winter)

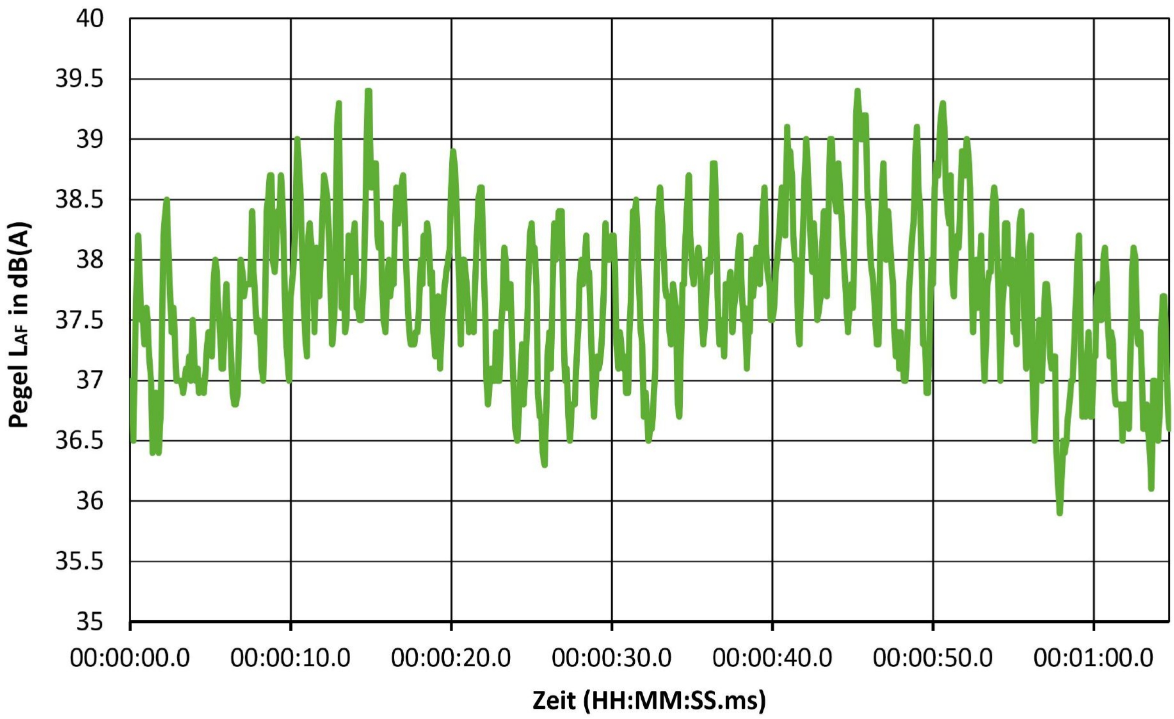
The measurements were evaluated using a method for the detection of amplitude modulation that was developed within the scope of this project. Surveys of surrounding area residents' annoyance levels were also conducted in all five study areas. Listening tests using previously recorded sample noises were also carried out at three study locations.

Amplitude modulation measurement and assessment

The term 'amplitude modulation' refers to the noise generated by wind turbines and usually perceived as a 'whooshing' sound. This sound is produced by a periodic rise and fall in the sound pressure level.

Wind turbine noise is also subject to other temporally irregular fluctuations that are perceptible to humans. These can be generated, for example, by propagation processes, wind or interference; the technical literature sometimes refers to this noise as amplitude-modulated noise. These fluctuations are typically not directly related to rotational frequency, and residents do not describe them as 'whooshing'. In this study, the term 'amplitude modulation' is used to describe fluctuations in volume level in connection with the rotational frequency; this is shown by way of example in Figure 3 as a rapid swelling and fading in volume level in 1.2-s cycles.

Figure 3: Sample fluctuation in volume levels due to amplitude modulation



Source: own presentation, Dr. Kühner GmbH

Pegel LAF in dB(A) = Level LAF in dB(A)

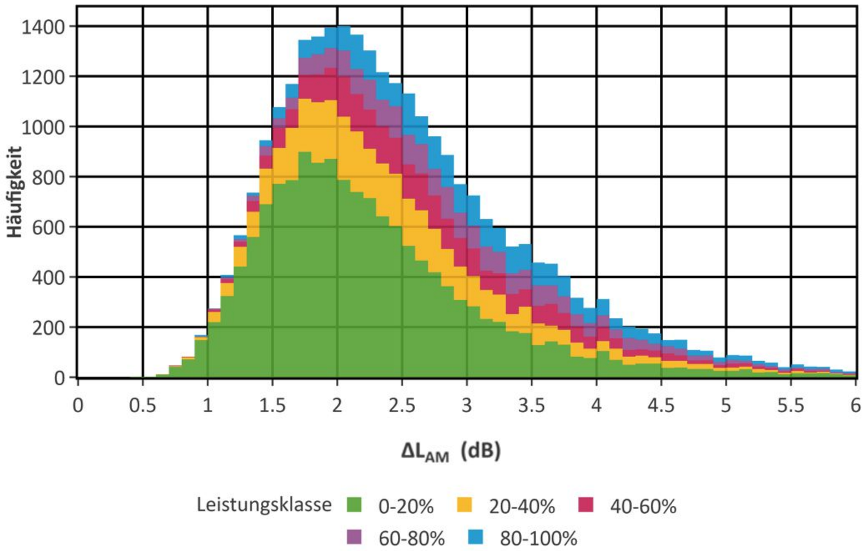
In order to investigate the measurement data within the scope of this study, an algorithm was created that determines the modulation depth ΔL_{AM} and the frequency of the amplitude modulation f_{AM} based on the audio data recorded for segments 10 seconds in length.

The measurement data obtained at the five locations were evaluated for the occurrence of amplitude modulation. The measurement locations were selected in such a way as to keep measurements as free as possible from extraneous noise. Nevertheless, amplitude-modulated noise was detectable, particularly during the night, as there was no other noise superimposed on the wind turbine noise at time of day.

An evaluation of measurement data in which there was no interfering extraneous or wind noise present showed that the median modulation depths, across all locations and across all turbine power ranges, were at approx. 1.5 dB to 2.5 dB (by way of example for a single location, see

Figure 4). A comparison of the various study areas shows that higher modulation depths occurred in Study Areas 1 and 2. These locations are wind farms with few wind turbines and relatively short distances between the wind turbines and the residential construction and/or the measuring position.

Figure 4: Frequency distribution of modulation depth ΔL_{AM} in Study Area 2, classified by turbine output



Source: own presentation, deBAKOM GmbH

Häufigkeit = Frequency; Leistungsklasse = Power class

To examine the meteorological dependence of amplitude modulation, the data records were classified based on turbine electrical output and wind direction. As this analysis shows, in cross-wind conditions, the modulation depth in immission area SA 2 increases slightly, by 1.2 dB, as the level of output increases. In tailwind conditions, on the other hand, the modulation depth increases by just 0.6 dB. Based on the data, this trend is discernible only for the wind farm with a single turbine in SA 2. Where the other study areas are concerned (SA 1 and SG 3 to 5), there is no discernible correlation between output and wind direction or modulation depth.

A comparison of the results generated under the AM method developed here against the maximum cyclical noise level method pursuant to the Technical Instructions on Protection Against Noise [Technische Anleitung zum Schutz gegen Lärm – TA Lärm (1998)] shows a relatively linear relationship between the two methods. The maximum cyclical noise level method, however, does not make a distinction between periodically modulated noise and other sound characteristics. If, for a particular period of time, it can be ensured that noise is essentially periodically amplitude-modulated noise, for the areas studied here, it turns out that the modulation depth can be estimated using the maximum cyclical noise level method.

Infrasound immission measurement and assessment

Airborne sound waves in a frequency range of less than 20 Hz are referred to as 'infrasound'. The physiology of the human ear does not permit perception of pitches with a frequency of less than 20 Hz. At sufficient levels of intensity, however, infrasound is nevertheless perceptible, for example as a pulsation or feeling of pressure. The perception threshold varies from one individual to the next. Hence, sensitive people may experience clear acoustic sensations, while others still cannot hear anything.

Because wind turbines are very large and have very low rotational speeds, they can generate infrasound. Whether and to what extent wind turbines cause infrasound immissions at distances of approx. 1000 m between the wind turbines and residential construction – distances which are quite common – should be investigated on the basis of long-duration measurements.

Since the main aim of the measurements was to study amplitude modulations, the measurement equipment and measurement concept were chosen and devised with this objective in mind. In an effort to generate robust results for infrasound as well, infrasound measurements were additionally carried out parallel to immission measurements in one of the study areas (Study Area 5). There, both a Class-1 microphone mounted on a tripod and an infrasound microphone mounted on a ground plate were used.

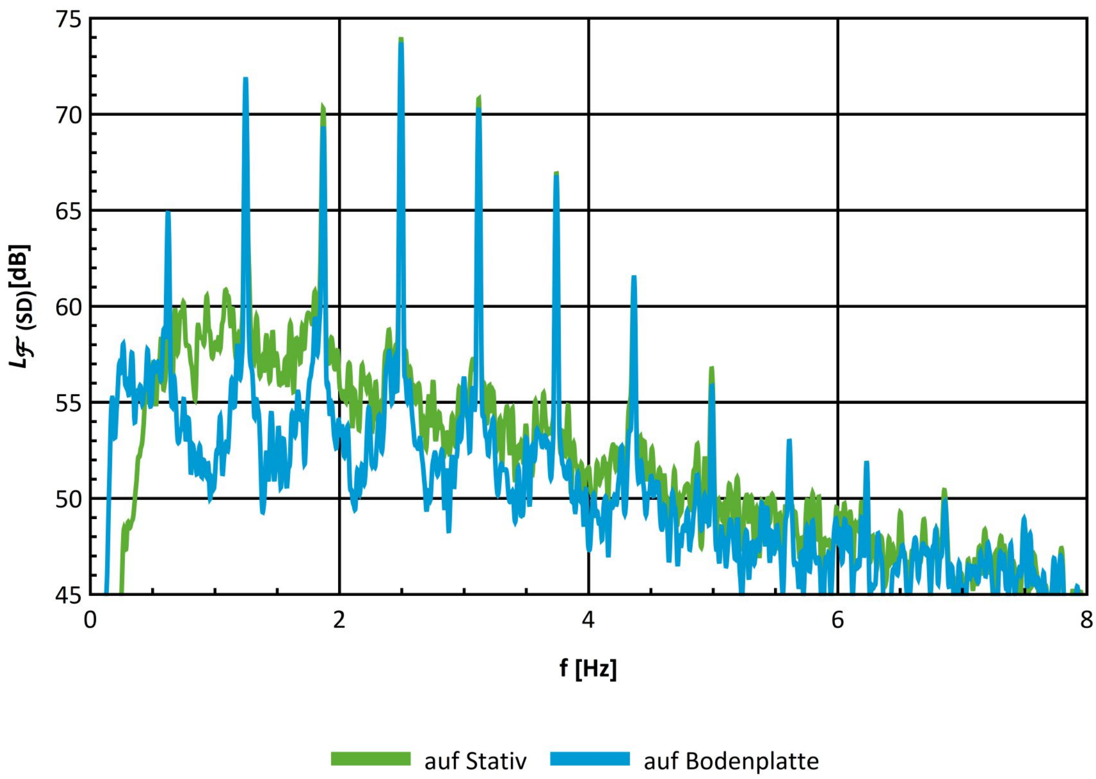
Figure 5 shows, by way of example, a spectrum measured in the vicinity of a residential building. The time segment shown was chosen because in this spectrum the individual lines can be seen particularly clearly at whole-number multiples of the frequency with which the rotor blades move past the wind turbine mast. These lines in the spectrum can thus be ascribed to the wind turbines as a source.

The measurements in study areas SA 1 to 4 were performed using a Class-1 microphone mounted on a tripod. These immission measurements differed from measurement using an infrasound microphone mounted on a ground plate in two key respects: At low frequencies, the Class-1 microphone is less sensitive than the infrasound microphone, and the influence of the wind is significantly greater if measurements are performed on a tripod rather than on a ground plate. Differences in microphone sensitivity were investigated by means of bass calibrations, using simultaneous measurements taken in Study Area 5 using the infrasound microphone mounted on the ground plate and the Class-1 microphone on the tripod to determine confidence intervals for the measurements. The influence of the wind was also analysed by comparing measurements in Study Area 5 and then factoring these as far as possible into measurements of sound levels in Study Areas 1 to 4.
With these observations, it was possible to express levels for a variety of infrasound ranges as a function of wind turbine output in SA 1 to 4. Infrasound caused by wind turbines was detected in all of the study areas, i.e. with levels rising with increases in the power output of the wind turbines.

All infrasound levels – whether measured with the infrasound microphone mounted to the ground plate or the tripod-mounted Class-1 microphone – are below the auditory threshold as defined pursuant to DIN 45680 (1997).

Figure 5: Spectrum of sound pressure

Sample spectrum for a 10-minute window at a distance of approx. 1000 m from the wind turbines (SA 5), measured with the infrasound microphone on the ground plate and the tripod-mounted Class-1 microphone.



Source: own presentation, deBAKOM GmbH

auf Stativ = On tripod; auf Bodenplatte = On ground plate

Performance and results of the annoyance surveys

The aim of the annoyance surveys was to record the degree of annoyance caused by wind turbine noise and to evaluate this as a function of the noise rating level. Residents were surveyed to identify the relationship between exposure to annoyance due to wind turbine noise and the impact of this exposure on respondents. The main acoustic and non-acoustic determinants of noise annoyance from wind turbines were identified. The effort consisted of a main survey (by telephone or optionally online) and in-depth interviews with residents. The purpose of the latter was to gain a detailed record of the impact the noise had on everyday life, particularly in light of respondents' perception of amplitude modulation.

The surveys were broken down into acoustic and non-acoustic factors and into different types of annoyance and disturbance of residents' activities. Specifically, the following aspects were asked with regard to respondents' living situation and any annoyance or disturbance they experienced due to noise exposure.

- Non-acoustic influencing factors
  - Respondents' attitudes towards wind energy and towards local wind turbines
  - General perceived stress (standardised questionnaire set PSS10[1])
  - Visual impact
    - Shadow casting
    - Sight of the wind turbines
    - Beacons on the wind turbines (aviation-obstruction lighting)
    - Rotational motion, effect on the landscape
  - Disturbance of activities
    - Disturbance of communication
    - Disturbance of the peace/concentration
    - Difficulty sleeping
  - Disturbance when outside the house
- Perceived acoustic influencing factors
  - Sound characteristics
    - Rumbling
    - Droning
    - Rushing
    - Humming
    - Pulsating
    - Whistling
    - Whooshing
    - Oscillations

The surveys were carried out in all of the study areas, with a total of 468 persons at distances of up to 3 km from the wind farms. A lack of geographic coordinates made it impossible to determine a noise rating level for five respondents. Hence, there are noise level and survey data in hand for a total of 463 persons for use in the exposure-response analyses.

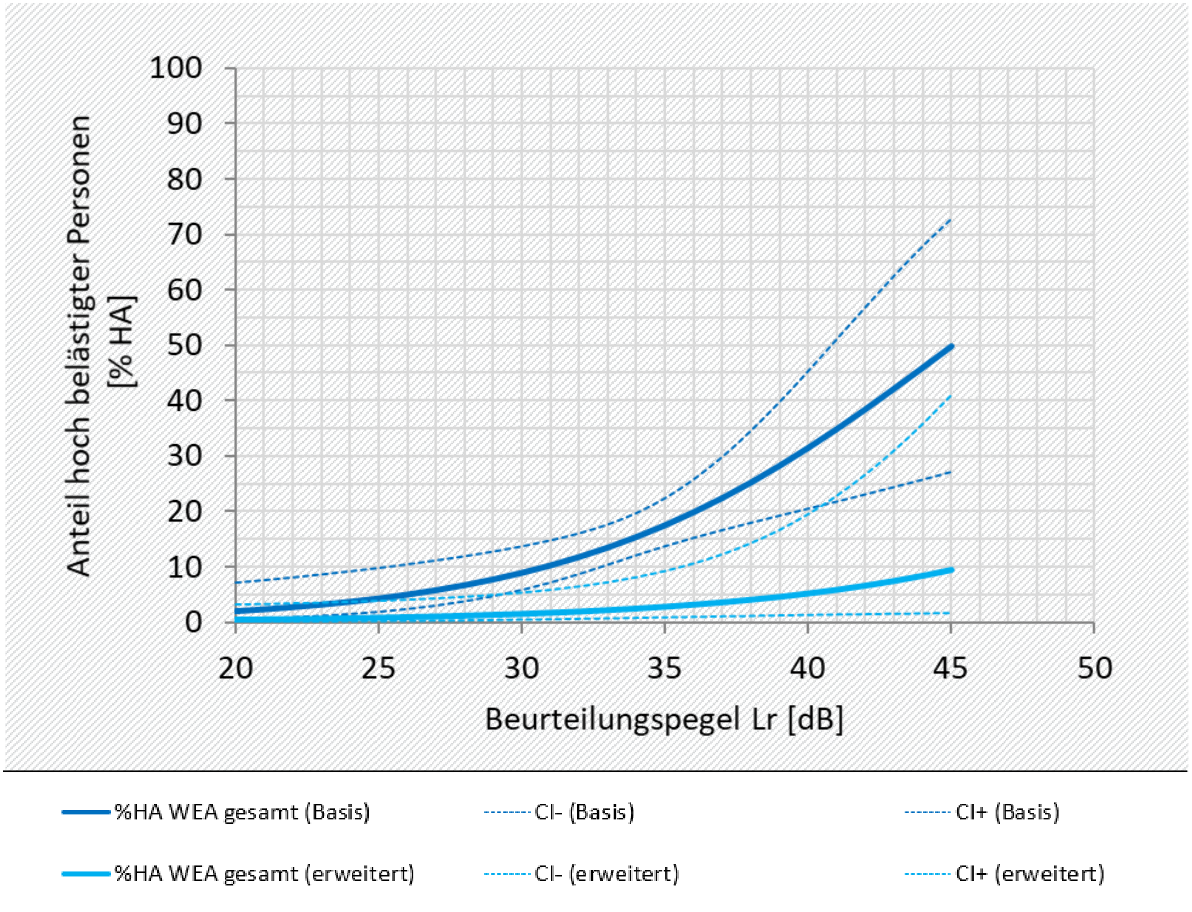
Overall, respondents rated noise annoyance from wind turbines as low on average (with average responses falling between 'not at all' and 'somewhat disturbed or annoyed'). The statistical relationship (the correlation) between noise rating level and annoyance is low.

The low overall level of noise annoyance (averaged across the entire sample) is apparently due to the relatively low noise exposure relative to other sources of noise, with a calculated noise

[1] *Perceived Stress Scale* (PSS-10; Cohen & Williamson, 1988) in the German version by Klein et al. (2016).

rating level of L_r < 43 dB. As soon as an L_r of approx. 35 dB is exceeded, however, there is a significant increase in the percentage of respondents indicating a high level of annoyance (%HA, % highly annoyed) (Figure 6). In its guidelines on environmental noise for the European region (WHO, 2018), the World Health Organisation (WHO) identifies a %HA level of 10% as a health-relevant threshold. According to the WHO (2018), based on a systematic review of the evidence by Guski et al. (2017), this %HA value is reached if road traffic noise reaches L_{den} = 53 dB, if rail traffic noise reaches L_{den} = 54 dB and if noise due to air traffic or wind turbines reaches L_{den} = 45 dB. These values are based on meta-analyses referencing base models, i.e. for reasons of comparability only the noise rating level L_{den} was regarded as an influencing variable (Guski et al., 2017). As can be seen in Figure 6 (dark blue curve), in this study, from a noise rating level L_r = 31 dB in the base model in which the share of highly annoyed persons is predicted exclusively by the noise rating level L_r, this share of highly annoyed persons is greater than or equal to 10%. Converted, L_r = 31 dB corresponds to a day-evening-night noise level of approx. L_{den} = 37 dB. Hence, this study confirms the findings of previous studies, which found higher levels of annoyance with noise caused by wind turbines than with noise caused by other environmental sources, such as road traffic. In the base model, the present study reveals an even higher %HA than under the WHO guidelines on environmental noise (WHO, 2018) or the underlying review (Guski et al., 2017).

Figure 6: Percentage of persons who are highly annoyed (% HA) by wind turbine noise, total



Quelle: eigene Darstellung, ZEUS GmbH

Anteil hoch belästigter Personen [%HA] = Percentage of highly annoyed persons [%HA]; Beurteilungspegel Lr [dB] = Noise rating level Lr [dB]; %HA WEA gesamt(Basis) = %HA WT total (basic); %HA WEA gesamt(erweitert) = %HA WT total (extended); CI- (Basis) = CI- (basic); CI- (erweitert) = CI- (extended); CI+ (Basis) = CI+ (basic); CI+ (erweitert) = CI+ (extended); Quelle: eigene Darstellung, ZEUS GmbH = Source: own presentation, ZEUS GmbH

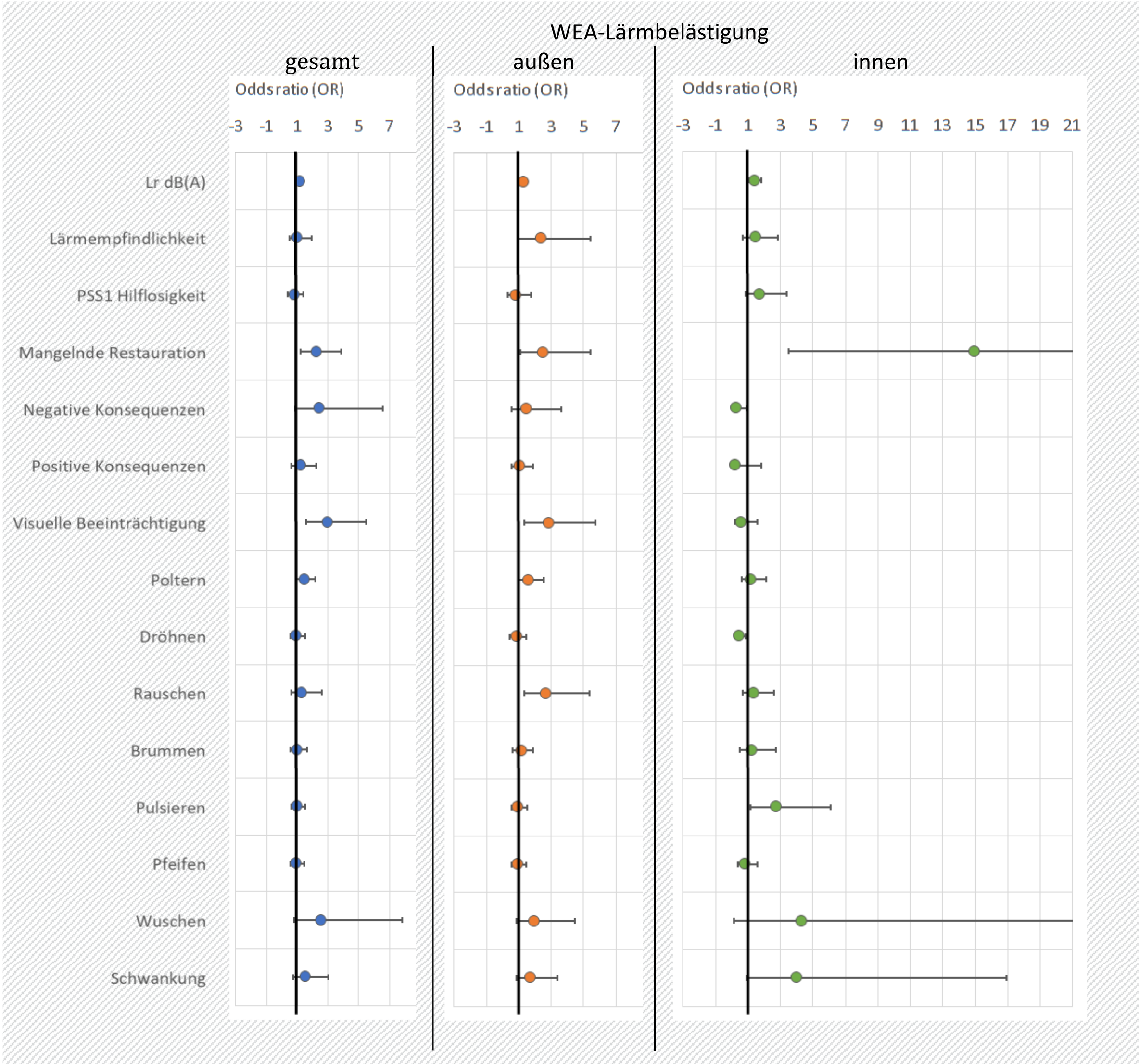
% HA = % highly annoyed; WT = wind turbine; CI-/+ = lower/upper limit of the confidence interval of the exposure-response curve; Basis: Influencing factor noise rating level L_r unadjusted; Extended: Influencing factors noise rating level L_r, noise sensitivity, attitude towards wind turbines, perceived stress, visual impact of wind turbines, sound characteristics

Noise annoyance is lower per noise rating level if additional influencing variables (non-acoustic variables, perceived sound characteristics) are also factored into the prediction model for the %HA component. If additional influencing factors are taken into account, the noise rating level plays less of a role in explaining annoyance over noise. In other words, the other influencing variables moderate the relationship between exposure to wind turbine noise and the impact of this exposure; these other variables play a stronger role in annoyance over wind turbine noise than the noise rating level itself. Among the non-acoustic factors, the following have the greatest impact on annoyance over wind turbine noise:

- Attitude towards the local wind turbine, particularly the perception of limited use of the outdoors and limited recreation outside the apartment/house;
- Visual impact due to shadow casting and rotation of the rotors, the blinking aviation-obstruction lighting, the sight of wind turbines in general and the negative view of the impact wind turbines have on the landscape.
- Perceived sound characteristics, such as ‘whooshing’. The semantic description plays a clear role in respondents’ judgements of whether or not the noise is annoying. ‘Whooshing’ is often understood as a subjective perception of amplitude modulations. It was also possible to show that differences in annoyance levels across study areas correspond to differences in the frequency of occurrence of identified, stable amplitude modulations.

Figure 7 shows the strength of the various influencing factors on overall annoyance due to wind turbine noise, both outdoors and indoors, with the odds ratio (OR) as a measure of how strong the effect is. The reference value is the value 1. If the odds ratio (coloured dot) including its confidence interval (the black line running through the dot) falls completely below or above the reference value of 1 (to the left or right of the value of 1 shown in the figure), the influence is considered to be statistically significant. The more the odds ratio, including its confidence interval, deviates from the value of 1, the stronger the effect.

Figure 7: Strength of effect (odds ratio) of the influencing variables of annoyance due to wind turbine noise overall



Quelle: eigene Darstellung, ZEUS GmbH

Lr dB(A) = Lr dB(A); Lärmempfindlichkeit = Noise sensitivity; PSS1 Hilflosigkeit = PSS1 Helplessness; Mangelnde Restauration = Lack of rest; Negative Konsequenzen = Negative consequences; Positive Konsequenzen = Positive consequences; Visuelle Beeinträchtigung = Visual impact; Poltern = Rumbling; Dröhnen = Droning; Rauschen = Rushing; Brummen = Humming; Pulsieren = Pulsating; Pfeifen = Whistling; Wuschen = Whooshing; Schwankung = Fluctuating; WEA-Lärmbelästigung = WT noise annoyance; Gesamt = Overall; Oddsratio(OR) = Odds ratio (OR); Außen = Outdoors; Oddsratio(OR) = Odds ratio (OR); Innen = Indoors; Oddsratio(OR) = Odds ratio (OR); Quelle: eigene Darstellung, ZEUS GmbH = Source: own presentation, ZEUS GmbH

The points shown depict the odds ratio (OR) as a measure of the effect strength of the respective influencing factor on wind turbine noise annoyance overall (blue dots), both outside (orange dots) and inside the home (green dots). The horizontal lines through the dots represent the 95% confidence interval of the OR. The reference is an OR = 1. If an OR value including its confidence interval is greater than 1 (shown at the right in the figure), then the impact of the influencing factor adds to the annoyance. If an OR value is less than 1 (shown at the left in the figure), then this influencing factor diminishes the annoyance.

As the in-depth survey with a small overall sample of 25 respondents at the five locations shows, those surveyed generally take a positive view of wind energy overall, and of the wind turbines in their local vicinity as well. Even if most respondents do not feel directly bothered by the wind turbines, they can imagine that other people might be bothered – by noise, for example, by shadow casting and by the way the turbines interfere with the landscape and ambient light conditions. For the most part, the noise the wind turbines produce is described as noise that is noticeable, particularly in the evenings. This 'rushing' noise is sometimes described as intermittent; this might be an indication of the pulsating character of wind turbine noise or of amplitude modulation. There are essentially very few differences across the five study areas. As it turned out through the in-depth survey, visual impacts also seem to play a role in addition to noise. Given the small size of the sample, however, no concrete conclusions can be drawn from the differences identified between the locations. In an overall sense, however, the data gleaned from the in-depth interviews confirm the findings of the main survey.

Performance and results of the listening tests

Listening tests were performed on-site with residents living near three of the study areas. A control experiment was carried out at the Cologne University of Applied Sciences and involving an approximately equal number of test subjects as in a study area; the experiment essentially confirmed the results observed in the individual study areas.

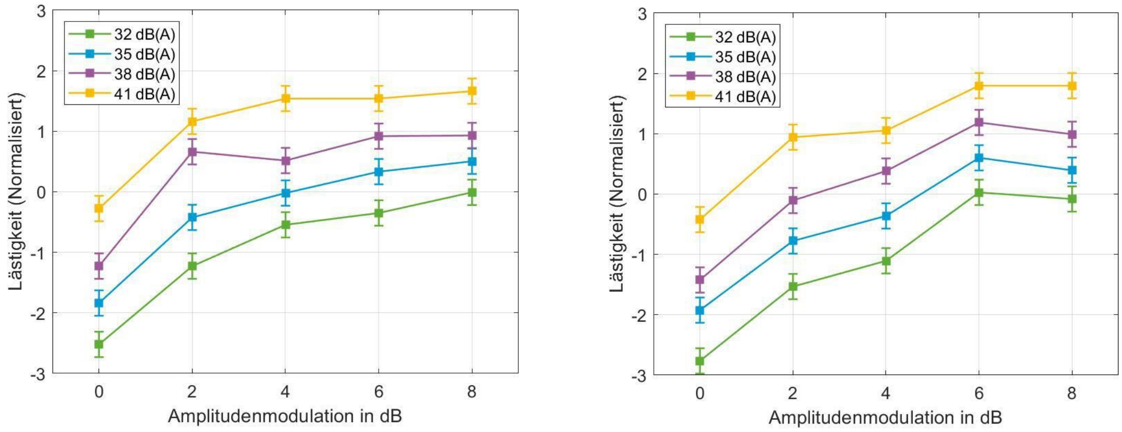
In the listening tests, subjects were presented with signals recorded at two measurement locations and featuring modulations of different magnitudes. The signals used for the listening tests had been extracted from these audio recordings and adjusted in level to give the stimuli comparable properties up to the modulation depth of the AM and the magnitude of the level. The listening tests also used recordings with time-constant AM and time-varying AM in order to compare the two with one another in terms of their annoyance.

The results of the listening tests demonstrate a significant influence of the noise level and AM on the degree of annoyance reported by study participants. These results confirm that the subjectively perceived annoyance clearly depends on the AM involved. The study of stimuli that varied with time showed no significant dependence of annoyance on behaviour of AM over time (increasing or decreasing).

The annoyance reported increased as AM increased. The results also showed that the mere perceptibility of an AM leads to an increase in annoyance level. The results are presented in Figure 8. The degree of annoyance reported as a result of fluctuation through the average level of different signals is almost identical across the three study areas.

Figure 8 : Annoyance of time-invariant amplitude modulations

Perceived (normalised) annoyance as a function of AM (x axis), the immission level presented (colour) and the measuring location (left: Measurement Location 1; right: Measurement Location 2). Shown here are the normalized nuisance assessments averaged over the subjects with 95% intra-subjective confidence intervals of the main effect for the factor of AM.



Source: own presentation, TH Köln

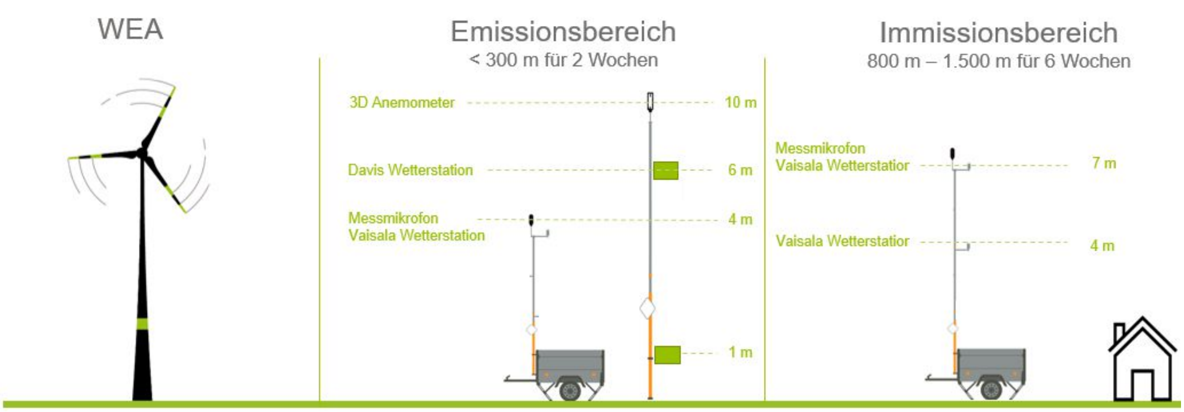
Lästigkeit (Normalisiert) = Annoyance (Normalised); Amplitudenmodulation in dB = Amplitude modulation in dB; Lästigkeit (Normalisiert) = Annoyance (Normalised); Amplitudenmodulation in dB = Amplitude modulation in dB

Zusammenfassung

Bei der Planung und Genehmigung von Windenergieanlagen steht das Thema Lärm häufig im Fokus der Diskussion. Dabei werden vielfältige Fragen aufgeworfen, die sowohl die Lärmentstehung und -minderung als auch die Auswirkungen des Lärms auf die Gesundheit und Lebensqualität der Bevölkerung betreffen. Geräusche von Windenergieanlagen unterliegen in ihrer Amplitude und Frequenzzusammensetzung starken räumlichen und zeitlichen Schwankungen. Die Geräusche variieren aufgrund von standort-, wetter- und windspezifischen Gegebenheiten und sind abhängig vom Typ, der Drehgeschwindigkeit und dem Betriebsmodus der Windenergieanlagen. Insbesondere die durch Windenergieanlagen induzierten Geräusche, welche häufig als „Wuschen“ bezeichnet werden, stehen im Fokus der Untersuchungen. Diese „Wuschgeräusche“ werden im vorliegenden Forschungsvorhaben als durch Windenergieanlagen induzierte amplitudenmodulierte Geräusche bezeichnet. Zum Zeitpunkt des Projektstarts war noch nicht klar, ob und in welcher Häufigkeit Amplitudenmodulationen (AM) in Entfernungen größer 1000 m von der Windenergieanlagen überhaupt detektierbar sind. Ziel war es daher zu untersuchen, in welchem Ausmaß Amplitudenmodulationen von Windenergieanlagen verursacht werden, ob diese im Immissionsbereich hör- und messbar sind und welchen Einfluss sie auf die Geräuschwahrnehmung von Anwohnenden haben.

Hierzu wurden in fünf Untersuchungsgebieten Langzeitschallmessungen im Immissionsbereich (> 800 m) über mindestens sechs Wochen und Emissionsbereich (< 300 m) über zwei Wochen durchgeführt. Auf der Basis der Langzeitschallmessungen wurden die geräuschspezifischen Einflüsse von Windenergieanlagen untersucht. Im Rahmen der Messauswertungen wurde ein Algorithmus entwickelt, um Amplitudenmodulation im Messsignal zu finden und zu quantifizieren. Zur Beurteilung der Wirkung der Geräusche auf den Menschen wurden in den Untersuchungsgebieten sowohl kontrollierte Hörversuche durchgeführt als auch Anwohnende in der Nachbarschaft von Windenergieanlagen bezüglich ihrer Wahrnehmung und Belästigungsempfindung befragt.

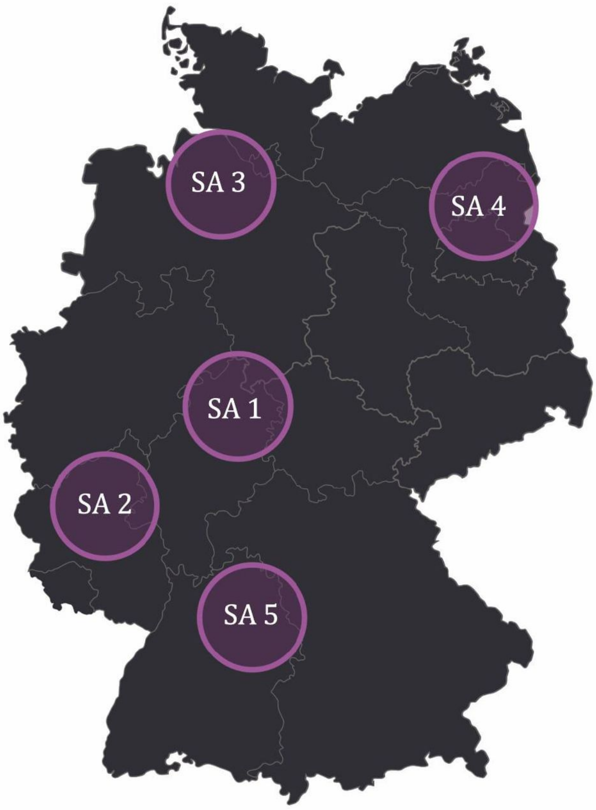
Abbildung 9: Schematische Darstellung des Messaufbaus



Quelle: eigene Darstellung, deBAKOM GmbH

Die Untersuchungsgebiete waren entsprechend Abbildung 10 deutschlandweit verteilt.

Abbildung 10: Lage der Untersuchungsgebiete in Deutschland



Quelle: eigene Darstellung, deBAKOM GmbH

Die Windparks in den Untersuchungsgebieten wiesen unterschiedliche Konstellationen auf. Dabei variierten:

- Anzahl der Windenergieanlagen (1 bis 21 Windenergieanlagen)
- Typ der Windenergieanlagen (vier Hersteller mit insgesamt sechs unterschiedlichen Modellen)
- Höhe der Windenergieanlagen (ca. 100 m bis ca. 140 m Nabenhöhe)
- Leistung der Windenergieanlagen (2 MW bis 3 MW)
- Rotordurchmesser (ca. 80 m bis ca. 135 m)
- Topografische Lage (flaches bis hügeliges Landschaftsbild)
- Entfernung der Messungen im Immissionsbereich (ca. 800 m bis 1500 m)
- Zeitraum der Messung (Frühling bis Winter)

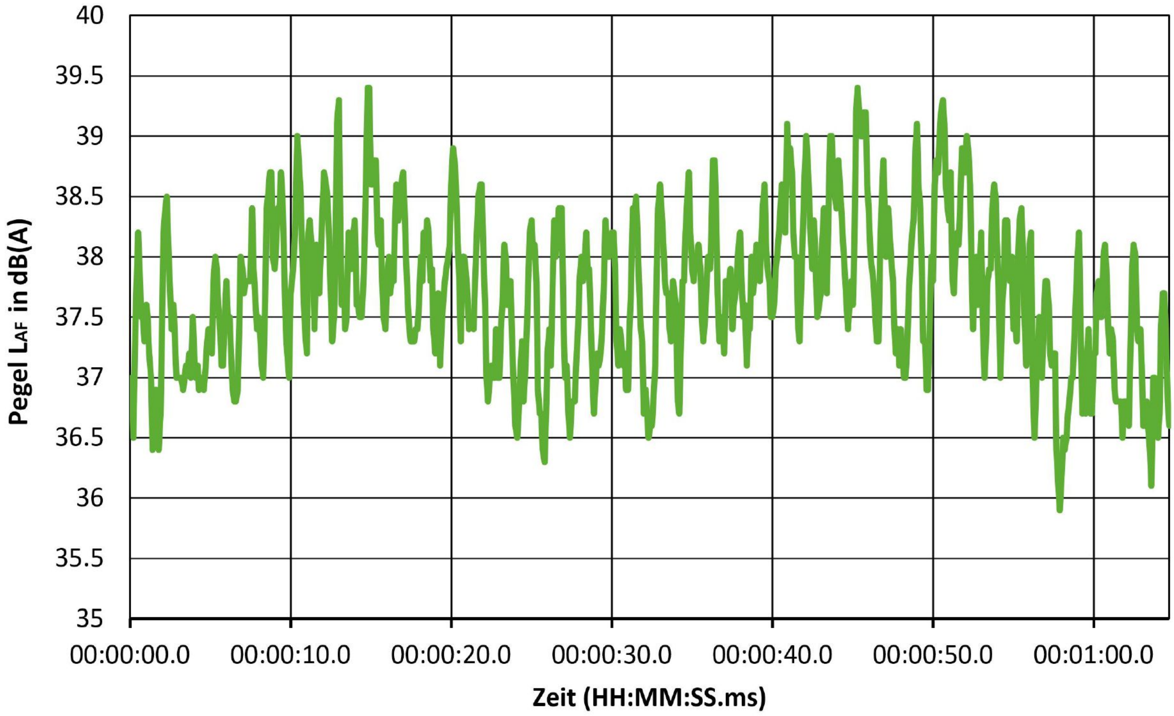
Die Messungen wurden mittels eines im Rahmen dieses Projektes entwickelten Verfahrens zur Erkennung von Amplitudenmodulation ausgewertet. Außerdem wurden Befragungen bezüglich der Belästigung von umliegenden Anwohnenden in allen fünf Untersuchungsgebieten durchgeführt. An drei Untersuchungsstandorten fanden zusätzlich Hörversuche mit zuvor aufgezeichneten Geräuschbeispielen statt.

Messung und Bewertung von Amplitudenmodulation

Als Amplitudenmodulation werden die durch Windenergieanlagen verursachten Geräusche bezeichnet, welche meist als ein „Wuschen“ wahrgenommen werden. Hierbei handelt es sich um ein periodisches Ansteigen und Abfallen des Schalldruckpegels.

Durch Windenergieanlagen verursachte Geräusche unterliegen auch anderen zeitlich unregelmäßigen Schwankungen, die von Menschen wahrgenommen werden können. Diese können z. B. durch Ausbreitungsvorgänge, Wind oder Interferenzen erzeugt werden und werden gelegentlich als amplitudenmodulierte Geräusche bezeichnet. Diese Schwankungen stehen aber meist nicht in direktem Zusammenhang mit der Rotationsfrequenz und werden von Anwohnenden nicht als „Wuschen“ beschrieben. In dieser Studie wird der Begriff Amplitudenmodulation für Pegelschwankungen im Zusammenhang mit der Drehfrequenz verwendet, wie sie in Abbildung 11 als schnelles an- und abschwellen des Pegels im 1,2 s Takt exemplarisch dargestellt sind.

Abbildung 11: Exemplarischer Pegelschrieb bei vorliegender Amplitudenmodulation



Quelle: eigene Darstellung, Dr. Kühner GmbH

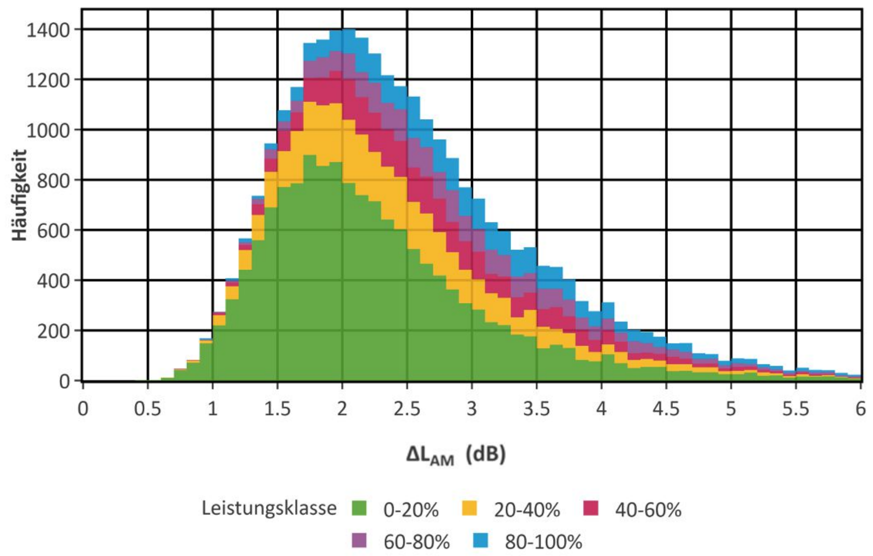
Zur Untersuchung der Messdaten wurde im Rahmen dieser Studie ein Algorithmus entworfen, der anhand der aufgezeichneten Audiodaten für Abschnitte mit einer Länge von 10 Sekunden die Modulationstiefe ΔL_{AM} und die Frequenz der Amplitudenmodulation f_{AM} bestimmt.

Die an den fünf Standorten gewonnenen Messdaten wurden hinsichtlich des Auftretens von Amplitudenmodulation ausgewertet. Die Messorte wurden so gewählt, dass die Messungen möglichst frei von Fremdgeräuschen waren. Dennoch waren amplitudenmodulierte Geräusche insbesondere im Nachtzeitraum detektierbar, da nachts keine sonstigen Geräusche, die Geräusche der Windenergieanlagen überlagerten.

Die Auswertung der Messdaten, in denen keine störenden Fremd- oder Windgeräusche vorhanden waren, zeigte, dass die Modulationstiefen für alle Standorte im Median über alle Leistungsbereiche der Anlagen bei ca. 1,5 dB bis 2,5 dB liegen (siehe exemplarisch für einen

Standort, Abbildung 12). Ein Vergleich der verschiedenen Untersuchungsgebiete zeigt, dass in den Untersuchungsgebieten 1 und 2 höhere Modulationstiefen auftraten. Bei diesen Standorten handelt es sich um Windparks mit wenigen Windenergieanlagen und relativ geringen Abständen zwischen den Windenergieanlagen und der Wohnbebauung bzw. der Messposition.

Abbildung 12: Häufigkeitsverteilung Modulationstiefe ΔL_{AM} im UG 2 nach Anlagenleistung klassiert



Quelle: eigene Darstellung, deBAKOM GmbH

Zur Untersuchung der meteorologischen Abhängigkeit der Amplitudenmodulation wurden die Datensätze nach elektrischer Leistung der Windenergieanlagen und Windrichtung klassiert. Diese Analyse zeigt, dass bei Querwind die Modulationstiefe im Immissionsbereich UG 2 um 1,2 dB mit steigender Leistung leicht zunimmt. Bei Mitwind nimmt dagegen die Modulationstiefe nur um 0.6 dB zu. Dieser Trend lässt sich nur für den Windpark mit einer Einzelanlage im UG 2 aus den Daten erkennen. Bei den anderen Untersuchungsgebieten (UG 1 und UG 3 bis 5) lassen sich keine eindeutigen Zusammenhänge zwischen Leistung und Windrichtung sowie Modulationstiefe erkennen.

Ein Vergleich der Ergebnisse mittels des entwickelten AM-Verfahrens mit dem Taktmaximalpegelverfahren nach TA Lärm (1998) zeigt, dass ein relativ lineares Verhältnis zwischen den beiden Verfahren besteht. Das Taktmaximalpegelverfahren unterscheidet jedoch nicht zwischen periodisch modulierten Geräuschen und anderen Geräuschverhalten. Insofern für einen Zeitraum sichergestellt werden kann, dass es sich bei den Geräuschen maßgeblich um ein periodisch amplitudenmoduliertes Geräusch handelt, zeigt sich für die hier untersuchten Gebiete, dass eine Abschätzung der Modulationstiefe anhand des Taktmaximalpegelverfahrens möglich ist.

Messung und Bewertung von Infraschallimmissionen

Luftschallwellen im Frequenzbereich kleiner 20 Hz werden als Infraschall bezeichnet. Obwohl die Tonhöhenwahrnehmung unterhalb 20 Hz physiologisch nicht gegeben ist, kann Infraschall bei hinreichend hoher Intensität z. B. als Pulsation oder Druckgefühl wahrgenommen werden. Dabei variiert die Wahrnehmungsschwelle individuell. So können empfindliche Menschen schon dann deutliche akustische Wahrnehmungen haben, wenn andere noch nichts hören.

Da Windenergieanlagen sehr groß sind und sehr niedrige Drehzahlen haben, können sie Infraschall erzeugen. Ob und in welchem Maß WEA Infraschallimmissionen in durchaus üblichen

Entfernungen für Wohnbebauung von ca. 1000 m zu Windenergieanlagen verursachen, sollte anhand der Langzeitmessungen untersucht werden.

Da das Hauptziel der Messungen die Untersuchung der Amplitudenmodulationen war, haben sich Messtechnik und Messkonzept an diesem Ziel orientiert. Um dennoch belastbare Ergebnisse auch für Infraschall zu ermitteln, wurden in einem der Untersuchungsgebiete, im UG 5, parallel zu den Immissionsmessungen zusätzlich Infraschallmessungen durchgeführt. Dabei wurde sowohl ein Klasse-1-Mikrofon auf Stativ als auch ein Infraschallmikrofon auf einer Bodenplatte eingesetzt.

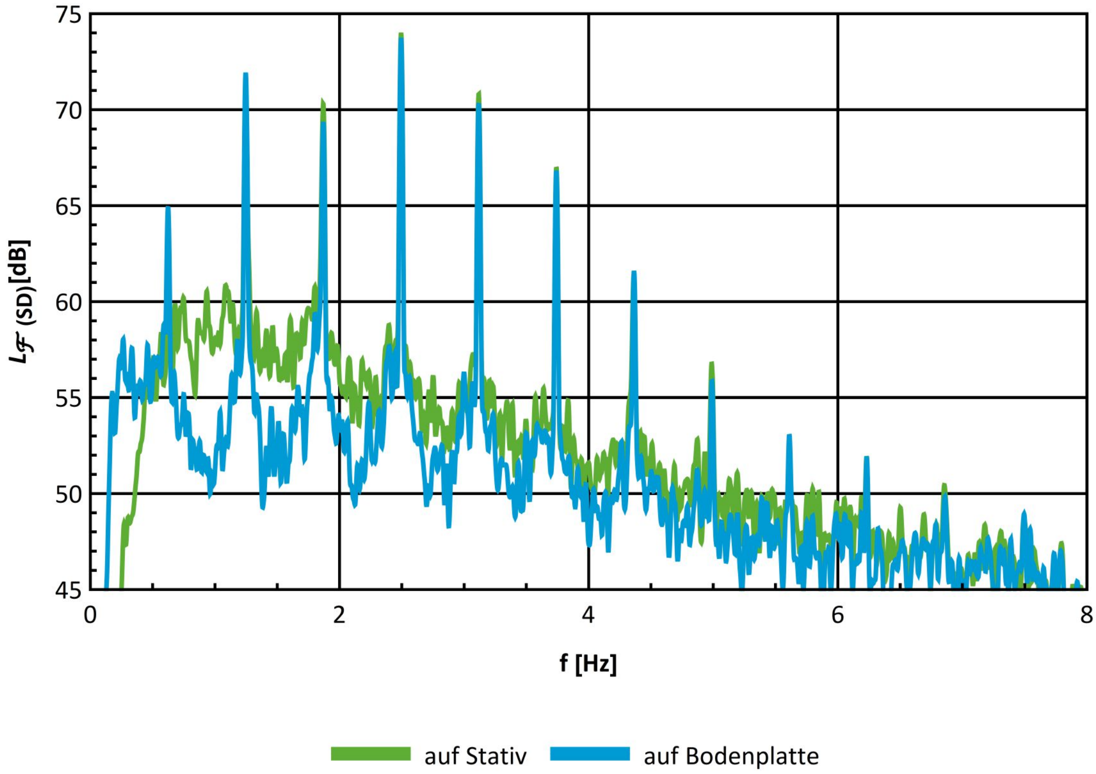
In Abbildung 13 ist exemplarisch ein Spektrum dargestellt, das in der Nähe eines Wohnhauses gemessen wurde. Der dargestellte Zeitausschnitt wurde gewählt, weil in diesem Spektrum besonders deutlich die Einzellinien zu erkennen sind, deren Frequenzen bei ganzzahligen Vielfachen der Frequenz liegen, mit der Rotorblätter sich am Mast der Windenergieanlagen vorbei bewegen. Diese Linien im Spektrum können somit den Windenergieanlagen als Quelle zugeordnet werden.

Die Messungen in den Untersuchungsgebieten UG 1 bis 4 wurden mit einem Klasse-1 Mikrofon auf Stativ durchgeführt. Diese Immissionsmessungen unterschieden sich von der Messung mit Infraschallmikrofon auf einer Bodenplatte in zwei wesentlichen Punkten: Das Klasse-1-Mikrofon ist bei kleinen Frequenzen unempfindlicher als das Infraschallmikrofon, und durch die Messung auf einem Stativ statt auf einer Bodenplatte ist der Windeinfluss deutlich größer. Die Unterschiede in den Empfindlichkeiten der Mikrofone wurden durch Tieftonkalibrierungen untersucht, die zeitgleichen Messungen mit Infraschall-Mikrofon auf Bodenplatte und Klasse-1-Mikrofon auf Stativ im UG 5 zur Ermittlung von Vertrauensbereichen für die Messungen genutzt. Auch der Einfluss von Wind wurde durch Vergleich der Messungen im UG 5 analysiert, und für die Bestimmung der Schallpegel in den Untersuchungsgebieten 1 bis 4 so weit möglich berücksichtigt.
Aufgrund dieser Betrachtungen konnten für die UG 1 bis 4 Pegel für verschiedene Infraschallbänder in Abhängigkeit der Leistung der WEA bestimmt werden. In allen Untersuchungsgebieten wurde durch Windenergieanlagen verursachter Infraschall festgestellt, d. h. mit zunehmender Leistung der Windenergieanlagen wurden steigende Pegel gemessen.

Alle für Infraschall bestimmten Pegel, ob mit Infraschallmikrofon auf Bodenplatte oder Klasse-1-Mikrofon auf Stativ, liegen unter der Hörschwelle nach DIN 45680 (1997).

Abbildung 13: Spektrum des Schalldrucks

Beispielspektrum für ein 10-Minuten-Fenster in ca. 1000m Entfernung von den Windenergieanlagen (UG 5), gemessen mit dem Infraschallmikrofon auf Bodenplatte und dem Klasse-1-Mikrofon auf Stativ.



Quelle: eigene Darstellung, Dr. Kühner GmbH

Durchführung und Ergebnisse der Belästigungsbefragungen

Ziel der Belästigungsbefragungen war es, den Grad der Belästigung durch Geräusche von Windenergieanlagen zu erfassen und in Abhängigkeit vom Beurteilungspegel auszuwerten. Dazu wurden Befragungen von Anwohnenden durchgeführt, um eine Ermittlung der Expositions-Wirkungsbeziehung zur Lärmbelästigung durch Windenergieanlagen abzuleiten. Dabei wurden die wesentlichen erfassten akustischen sowie die nicht akustischen Bestimmungsfaktoren der Lärmbelästigung durch Windenergieanlagen identifiziert. Hierzu wurde zum einen eine Hauptbefragung (telefonisch oder optional online) und zum anderen vertiefende Interviews mit Anwohnenden durchgeführt. Letzteres diente der detaillierten Erfassung der Geräuschwirkung im Alltag unter dem besonderen Aspekt der Wahrnehmung von Amplitudenmodulation.

Die Befragungen untergliederten sich in akustische und nicht akustische Faktoren, sowie in verschiedene Arten von Belästigung und Störung bei Aktivitäten der Anwohnenden. Konkret wurden folgende Aspekte zur Wohnsituation der Befragten und deren Lärmbelästigung und Störungen abgefragt.

- Nicht akustische Einflussfaktoren
  - Einstellung der Befragten zu Windenergie und zu lokalen Windenergieanlagen
  - Allgemeines Stressempfinden (standardisierter Fragebogenblock PSS10[2])
  - Visuelle Beeinträchtigung
    - Schattenwurf
    - Anblick der Windenergieanlagen
    - Lichtsignale der Windenergieanlagen (Hinderniskennzeichnung)
    - Drehbewegung, Wirkung im Landschaftsbild
  - Störung von Aktivitäten
    - Kommunikationsstörung
    - Ruhe-/Konzentrationsstörung
    - Schlafstörung
  - Störung beim Aufenthalt außerhalb des Hauses
- Wahrgenommene akustische Einflussfaktoren
  - Geräuschmerkmale
    - Poltern
    - Dröhnen
    - Rauschen
    - Brummen
    - Pulsieren
    - Pfeifen
    - Wuschen
    - Schwankungen

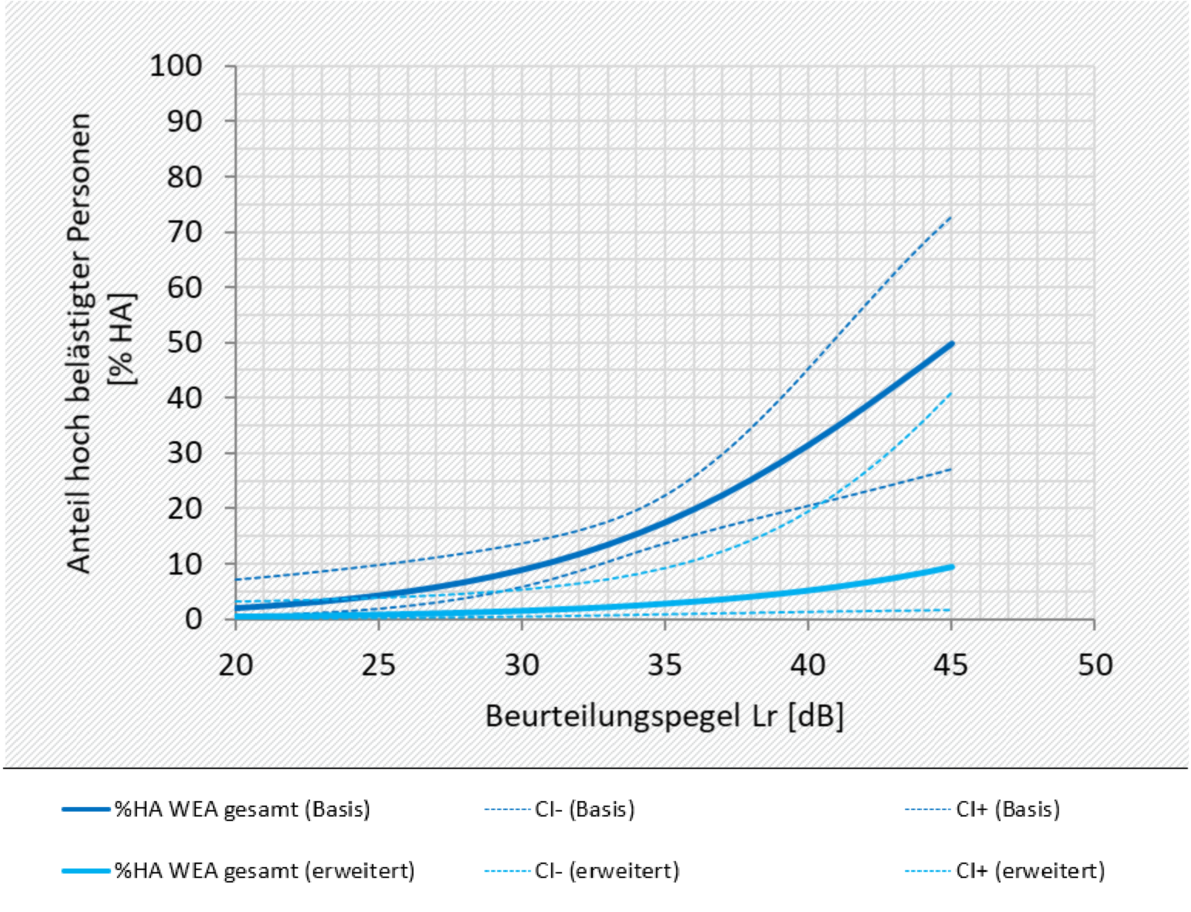
Die Befragungen wurden in allen Untersuchungsgebieten, bei insgesamt 468 Personen in einer Distanz bis zu 3 km von den Windparks durchgeführt. Bei fünf Personen konnten aufgrund fehlender Geokoordinaten keine Beurteilungspegel bestimmt werden, so dass insgesamt von 463 Personen Geräuschpegel- und Befragungsdaten für die Expositions-Wirkungsanalysen vorliegen.

Die Befragten stuften die Lärmbelästigung durch Windenergieanlagen insgesamt durchschnittlich als gering ein (im Durchschnitt zwischen „überhaupt nicht“ und „etwas gestört oder belästigt“). Der statistische Zusammenhang (die Korrelation) zwischen Beurteilungspegel und den Belästigungen ist gering.

[2] *Perceived Stress Scale* (PSS-10; Cohen & Williamson, 1988) in der deutschen Fassung von Klein et al. (2016).

Die insgesamt gering ausgeprägte Lärmbelästigung (im Mittel über die ganze Stichprobe) ist offenbar der mehrheitlich relativ im Vergleich zu anderen Geräuschquellen geringen Geräuschexposition mit einem berechneten Beurteilungspegel von L_r < 43 dB geschuldet. Sobald aber ein L_r von ca. 35 dB überschritten wird, steigt der Prozentanteil der hoch belästigten Personen (%HA, % highly annoyed) deutlich an (Abbildung 14). Die Weltgesundheitsorganisation (WHO) nennt in ihren Leitlinien zum Umgebungslärm für die europäische Region (WHO, 2018) einen %HA-Anteil von 10% als eine gesundheitliche Relevanzschwelle. Dieser %HA-Wert wird nach den Angaben der WHO (2018) basierend auf einem systematischen Evidenz-Review von Guski et al. (2017) bei Straßenverkehrsgeräuschen bei einem L_{den} = 53 dB, beim Schienenverkehrsgeräuschen bei einem L_{den} = 54 dB und bei Luftverkehrsgeräuschen sowie bei Windenergieanlagengeräuschen bei einem L_{den} = 45 dB erreicht. Diese Werte basieren auf Meta-Analysen, die sich auf Basismodelle beziehen, d. h. nur der Beurteilungspegel L_{den} wurde aus Gründen der Vergleichbarkeit als Einflussgröße betrachtet (Guski et al., 2017). Aus Abbildung 14Figure 6 (dunkelblaue Kurve) geht hervor, dass in dieser Studie ab einem Beurteilungspegel L_r = 31 dB im Basismodell, in dem der Prozentanteil hoch belästigter Personen ausschließlich durch den Beurteilungspegel L_r vorgesagt wird, dieser Prozentanteil hoch belästigter Personen größer gleich 10% beträgt. Ein L_r = 31 dB entspricht umgerechnet einem Tag-Abend-Nachtpegel von ca. L_{den} = 37 dB. Damit bestätigt diese Studie den auch in bisherigen Untersuchungen festgestellten Befund einer – bei gegebenen Beurteilungspegel – höheren Belästigung durch Windenergieanlagen-Geräusche im Vergleich zu anderen Umgebungslärmquellen wie etwa dem Straßenverkehrslärm. Die vorliegende Studie zeigt im Basismodell sogar einen höheren %HA-Anteil als nach Angaben in den WHO-Umgebungslärmleitlinien (WHO, 2018) oder dem zugrundeliegenden Review (Guski et al., 2017).

Abbildung 14: Prozentanteil hoch belästigter Personen (% HA) durch Windenergieanlagen insgesamt



Quelle: eigene Darstellung, ZEUS GmbH

% HA = % hoch Belästigte; WEA = Windenergieanlage; CI-/+ = untere/obere Grenze des Konfidenzintervalls der Expositions-Wirkungs-Kurve; Basis: Einflussfaktor Beurteilungspegel L_r ohne Adjustierung; Erweitert: Einflussfaktoren Beurteilungspegel L_r, Lärmempfindlichkeit, WEA-Einstellung, wahrgenommenen Stress, visueller WEA-Beeinträchtigung, Geräuschmerkmalen

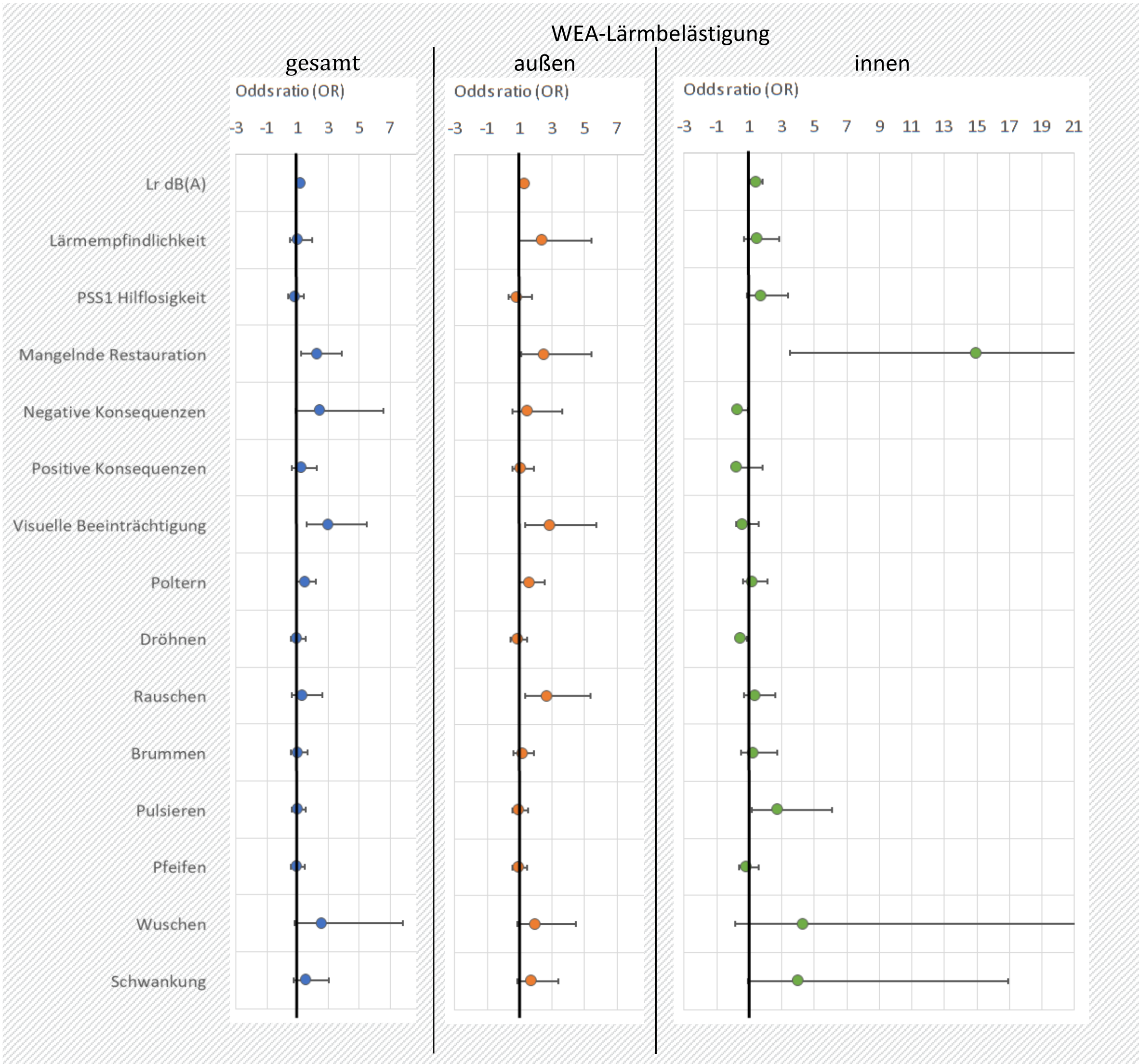
Die Lärmbelästigung fällt pro Beurteilungspegel geringer aus, wenn in dem Vorhersagemodell zum % HA-Anteil weitere Einflussgrößen (nicht-akustische Größen, wahrgenommene Geräuschmerkmale) ebenfalls berücksichtigt werden. Durch die zusätzlich berücksichtigten Einflussfaktoren verliert der Beurteilungspegel an Erklärungseffekt auf die Lärmbelästigung. Das heißt, die anderen Einflussgrößen moderieren die Expositions-Wirkungsbeziehung zur WEA-Lärmbelästigung und üben einen stärkeren Effekt auf die WEA-Lärmbelästigung aus als der Beurteilungspegel selbst. Unter den nicht-akustischen Faktoren sind es vor allem die folgenden, die einen Einfluss auf die WEA-Lärmbelästigung ausüben:

- Einstellung zur lokalen Windenergieanlage, insbesondere die Wahrnehmung einer eingeschränkten Außennutzung und Erholungsmöglichkeit im Außenbereich der Wohnung/des Hauses;
- Visuelle Beeinträchtigungen durch den Schattenwurf und Drehbewegungen der Rotoren, der blinkenden Hinderniskennzeichnung, der Ansicht von Windenergieanlagen insgesamt sowie durch die negativ bewertete Wirkung der Windenergieanlagen auf das Landschaftsbild.

- Wahrgenommene Geräuschmerkmale, wie das „Wuschen". Die semantische Beschreibung prägt deutlich das Lärmbelästigungsurteil. Das Wuschen wird oftmals als subjektive Wahrnehmung von Amplitudenmodulationen verstanden. Zudem konnte gezeigt werden, dass Lärmbelästigungsunterschiede zwischen den Untersuchungsgebieten mit Unterschieden in der Auftrittshäufigkeit der erkannten, stabil vorliegenden Amplitudenmodulationen korrespondieren.

Abbildung 15 zeigt die Stärke der verschiedenen Einflussfaktoren auf die Windenergieanlagen-Lärmbelästigung insgesamt, im Außen- sowie im Innenbereich mit dem Odds Ratio (OR) als Maß der Effektstärke. Referenzwert ist der Wert 1. Ist das Odds Ratio (farbiger Punkt) einschließlich seines Konfidenzintervalls (schwarze durch den Punkt verlaufende Linie) vollständig unterhalb oder oberhalb des Referenzwertes 1 (in der Abbildung links oder rechts vom Wert 1), handelt sich um einen statistisch signifikanten Einfluss. Je mehr das Odds Ratio einschließlich seines Konfidenzintervalls vom Wert 1 abweicht, desto größer ist die Effektstärke.

Abbildung 15: Effektstärke (Odds ratio) der Einflussgrößen der Windenergieanlagen-Lärmbelästigung insgesamt



Quelle: eigene Darstellung, ZEUS GmbH

Die dargestellten Punkte geben das Odds Ratio (OR) als Maß der Effektstärke des jeweiligen Einflussfaktors auf die Windenergieanlagen-Lärmbelästigung insgesamt (blaue Punkte), im Außenbereich (orange Punkte) und im Wohnungsinneren (grünen Punkte) wieder. Die waagerechten Linien durch die Punkte geben das 95%-Konfidenzintervall des OR wieder. Referenz ist ein OR = 1. Liegt ein OR-Wert einschließlich seines Konfidenzintervalls oberhalb (in der Abbildung rechts) von 1, dann hat der Einflussfaktor einen belästigungserhöhenden Einfluss. Liegt der OR-Wert unterhalb (in der Abbildung links) von 1, dann hat diese Einflussgröße einen belästigungsmindernden Einfluss.

Aus den Vertiefungsbefragung mit einer insgesamt kleinen Stichprobe von 25 Personen an den fünf Standorten geht hervor, dass die befragten Personen generell eine positive Einstellung gegenüber Windenergie allgemein und den lokalen Windenergieanlagen haben. Auch wenn die meisten Befragten sich nicht direkt durch die Windenergieanlagen gestört fühlen, können sie sich vorstellen, dass sich andere Personen beispielsweise durch Lärm, Schattenwurf sowie den Eingriff in das Landschaftsbild und die Beleuchtung gestört fühlen. Die Geräusche, die von den Windenergieanlagen ausgehen, werden größtenteils als Rauschen beschrieben, das vor allem abends auffällt. Dieses Rauschen wird zum Teil als intervallartig beschrieben, was ein Hinweis auf den pulsierenden Charakter der Windenergieanlagen-Geräusche bzw. die Amplitudenmodulation sein kann. Grundsätzlich gibt es sehr wenige Unterschiede zwischen den fünf Untersuchungsgebieten. Neben Lärm scheinen auch in der Vertiefungsbefragung visuelle Auswirkungen relevant zu sein. Aufgrund der kleinen Stichprobe lassen sich aus den identifizierten Unterschieden zwischen den Standorten jedoch keine konkreten Schlüsse ziehen. Jedoch bestätigen insgesamt die Vertiefungsinterviewdaten die Erkenntnisse aus der Hauptbefragung.

Durchführung und Ergebnisse der Hörversuche

Die Hörversuche wurden an drei Untersuchungsgebieten vor Ort mit Anwohnenden durchgeführt. Ein Kontrollversuch wurde an der TH Köln mit einer etwa gleich großen Anzahl an Probanden wie in einem Untersuchungsgebiet durchgeführt, welcher im Wesentlichen die Ergebnisse in den einzelnen Untersuchungsgebieten bestätigte.

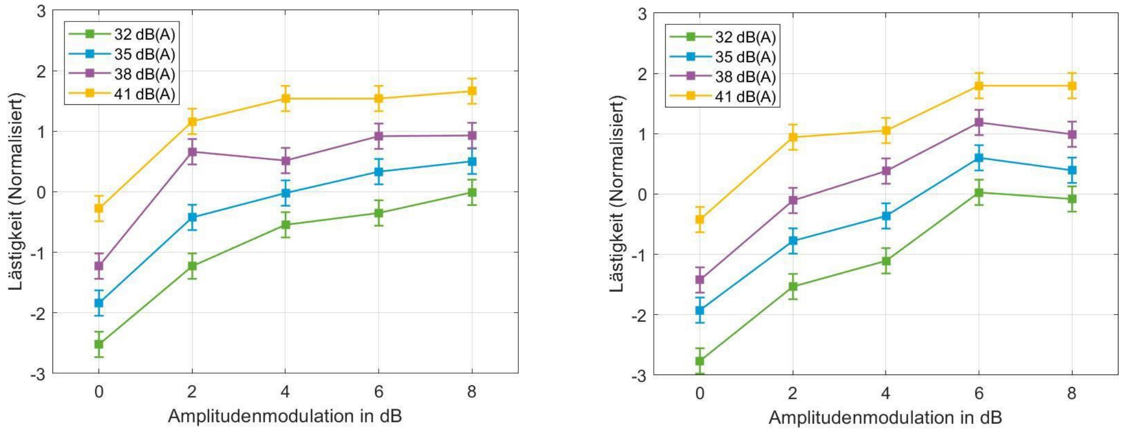
In den Hörversuchen wurden Signale dargeboten, die an zwei Messorten aufgenommen wurden und über unterschiedlich starke Modulationen verfügten. Die für die Hörversuche verwendeten Signale wurden aus diesen Audioaufnahmen extrahiert und in dem Pegel angepasst, so dass die Stimuli bis auf die Modulationstiefe der AM und die Höhe des Pegels vergleichbare Eigenschaften aufwiesen. Zudem wurden im Rahmen der Hörversuche Aufnahmen eingesetzt, die zeitkonstante AM sowie zeitlich variierende AM aufwiesen, um diese hinsichtlich ihrer Lästigkeit miteinander zu vergleichen.

Die Ergebnisse der Hörversuche belegen einen signifikanten Einfluss von Pegel und von AM auf die von den Untersuchungsteilnehmenden bewertete Lästigkeit. Sie bestätigen, dass die subjektiv wahrgenommene Lästigkeit deutlich von der AM abhängt. Die Untersuchung der zeitveränderlichen Stimuli zeigte keine signifikante Abhängigkeit der Lästigkeit von dem Zeitverlauf (ansteigend oder abfallend) der AM.

Die bewertete Lästigkeit nahm mit zunehmender AM zu. Darüber hinaus zeigten die Ergebnisse, dass die bloße Wahrnehmbarkeit einer AM eine Erhöhung der Lästigkeit bewirkt. Die Ergebnisse sind in Abbildung 16 dargestellt. Die Bewertung der Lästigkeit aufgrund der Schwankung durch den mittleren Pegel unterschiedlicher Signale ist für die drei Untersuchungsgebiete nahezu identisch.

Abbildung 16 : Lästigkeit zeitinvariante Amplitudenmodulationen

Wahrgenommene (normalisierte) Lästigkeit in Abhängigkeit von der AM (x-Achse), von dem dargebotenen Immissionspegel (Farbe) sowie von dem Messort (links: Messort 1; rechts: Messort 2). Dargestellt sind die über die Probanden gemittelten normalisierten Lästigkeitsbewertungen und 95% Inner-Subjekt-Konfidenzintervalle des Haupteffekts für den Faktor AM.



Quelle: eigene Darstellung, TH Köln

1 Introduction

Wind turbines are crucially important to Germany's plan for transition to renewable energy. Deliberations concerning the planning and approval of these installations often revolve around the issue of noise. A wide range of questions are raised that concern both noise generation and noise reduction as well as the impact of noise on the health and quality of life of the population. The amplitude and frequency of the noise generated by wind turbines is subject to spatial and temporal fluctuation. The noise varies due to factors specific to location, weather and wind and is a function of the type, rotational speed, and operating mode of the wind turbines themselves. The generation of noise is significantly influenced by the flow behaviour along the rotor blades which, in today's ever-larger turbines, pass through different wind and air-layer profiles. A special characteristic of the noise generated concerns so-called 'amplitude-modulated noise'. This noise is distinguished by a recurring change in noise level relative to the rotational frequency of the wind turbines.

This research project was carried out in an interdisciplinary collaboration involving three firms and one university. The long-term sonic measurements and metrological detection of meteorological parameters were performed by deBAKOM GmbH. Dr. Kühner GmbH took part in the evaluation of the amplitude-modulated noise and its classification, and in the evaluation of infrasound. Zeus GmbH provided the implementation, evaluation and analysis of the surveys on location. The listening tests were carried out by the Cologne University of Applied Sciences.

The research project addressed the following questions in detail:

- How frequently are amplitude modulations (AM) observed?
- Is there a connection between AM and operating, plant, location or weather data?
- Taking noise-impact research into account, is AM-dependent annoyance on the part of residents observable?
- Can conclusions be drawn about the general situation with regard to annoyance of the population due to wind turbine noise in Germany?
- Is the periodic amplitude-modulated noise created by wind turbines perceived as particularly annoying?

In total, long-duration measurements in the immission range (distance of 800 m to 1500 m to the nearest wind turbines) were carried out and evaluated in five study areas, and additionally in the emission range (distance of 150 m to 200 m to the nearest wind turbines) in three study areas. Surveys were performed in all of the study areas, listening tests in three study areas.

2 Conceptual design of the study

To investigate the impacts of noise generated by land-based wind turbines, and amplitude-modulated noise in particular, the study was designed to consist of three modules.

Module 1: Long-duration measurements of wind turbine noise

Module 2: Survey of residents in the vicinity of wind turbines

Module 3: Listening tests on the impact of amplitude-modulated noise

In Module 1, measurements of wind turbine noise were performed at five locations distributed throughout Germany. The aim was to determine factors that influence amplitude modulation through a comparison with data on operations (times, output), turbine type, the topographical situation and meteorological conditions. The frequency of occurrence and modulation depth of stable, periodic amplitude modulations were identified on a site-specific basis; the core results of long-duration measurements also formed the basis for the other modules.

The object of Module 2 was to survey residents at the same five locations where the long-duration measurements were conducted. The aim was to determine the degree of annoyance experienced by residents as a result of wind turbine noise, based on forecast noise rating levels. The module set out to examine the extent to which location-specific parameters of amplitude modulation, subjective perception of amplitude modulations and other contextual factors influenced noise annoyance above and beyond the forecast noise rating level. Methodologically speaking, the survey is a cross-sectional study, i.e. it is conducted at a certain point in time, survey data are correlated with acoustic data, and the associations between noise annoyance and potential influencing variables are quantified in static prediction models (regression analyses). Correlations between the noise annoyance and the influencing factors can be investigated with the aid of statistical analyses; strictly speaking, a clear cause-and-effect attribution is not possible. Hence, although the survey can suggest a relationship between amplitude modulation, or rather subjective perceptions thereof, and the annoyance caused by wind turbine noise in the resident population, whether and to what degree the acoustic impact of amplitude-modulated noise is the cause of the noise annoyance due to wind turbine noise can only be investigated by means of a systematic, experimental study.

With this in mind, in Module 3, under controlled or standardised conditions, listening tests were performed with residents of three of the five locations as well as a control group of individuals not living in the vicinity of wind turbines. Subjects were presented with various amplitude-modulated sounds, and any reactions of acute annoyance were recorded. Controlled presentation of noise scenarios permits unambiguous attribution and quantification of the cause, i.e. differences in reaction to noise scenarios can be ascribed to differences in the noise scenarios themselves, and to the quantitative extent of the manipulated amplitude modulations presented in the scenarios.

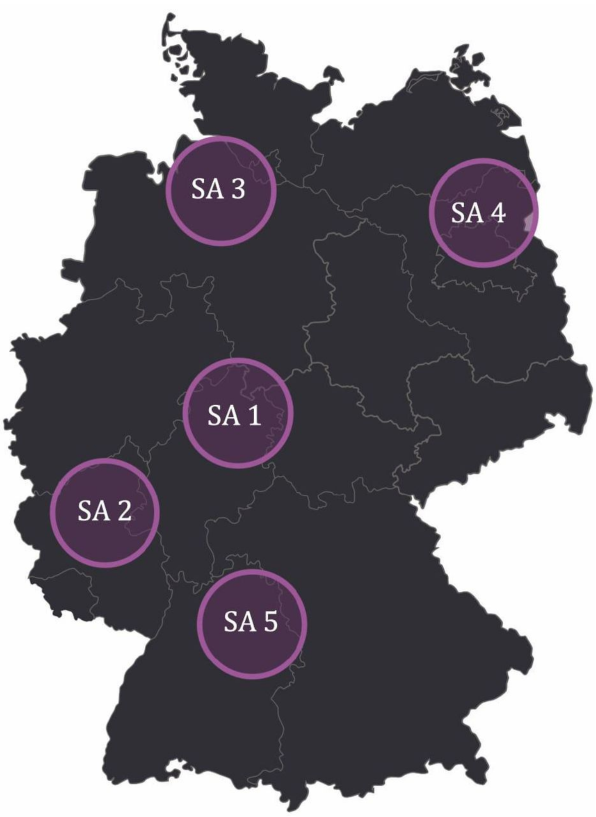
3 Study areas

The measurement campaigns were carried out at a total of five locations in Germany. These study areas (SA) were selected in such a way as to take the different topographical conditions in Germany into account. This was achieved by distributing the study areas throughout the entire territory of Germany. The study areas were located in the following regions and German states:

- SA 1 – Central Germany, Hesse
- SA 2 – Western Germany, Rhineland-Palatinate
- SA 3 – Northern Germany, Lower Saxony
- SA 4 – Eastern Germany, Brandenburg
- SA 5 – Southern Germany, Baden-Württemberg

The locations of the study areas are listed in Figure 17.

Figure 17: Location of the study areas in Germany



Source: own presentation, deBAKOM GmbH

The power classes of the wind turbines considered in the study were in the range of 2 MW to 3 MW, with a hub height of 100 m to 140 m and a rotor diameter of 80 m to 135 m. Generally speaking, there were no relevant sources of noise in the vicinity of the measurement locations, such as larger industrial plants, larger commercial installations or motorways.

At four of the five locations, the measurements were carried out in consultation with the operators of the respective turbines; system signals were available at the locations for use in evaluating the measurement data. Measurements at one location were carried out without the operator's knowledge. The locations are described in greater detail below and are summarized in Table 1.

Table 1: Key figures of the study areas

	SA 1	SA 2	SA 3	SA 4	SA 5
Location in Germany	Central	West	North	East	South
Number of wind turbines	3	1	6	21	10
Wind turbine power class	2 – 3 MW	3 MW	2 – 2.5 MW	2.5 – 3 MW	2.5 MW
Wind turbine rotor diameter	80 – 100 m	approx. 130 m	90 – 100 m	110 – 120 m	approx. 120 m
Wind turbine hub height	approx. 140 m	approx. 135 m	approx. 100 m	approx. 140 m	approx. 140 m
Measurement distance to the immission location	1100 m	800 m	1500 m	1000 m	1000 m
Wind turbine location	Open field	Edge of forest	Open field	Open field	Forest
Topography	Slightly hilly	Very hilly	Flat	Flat	Hilly
Surrounding elevation above sea level	350 – 450 m	200 – 400 m	7 – 14 m	40 – 60 m	280 – 400m
Immission location elevation above sea level	380 m	345 m	7 m	50 m	340 m
Wind turbine elevation above sea level	400 – 410 m	320 m	10 – 14 m	35 – 55 m	360 – 380 m

A state road with a relatively high level of traffic runs between the wind farm in SA 1 and the immission location. The number of vehicles passing at night decreased significantly, however.

Southwest to south of the wind turbines in SA 2, there is a narrow, wooded valley extending approx. 500 m to 700 m and featuring an altitude difference of up to 110 m. The turbine is located at the forest's edge, in the immediate proximity of the edge of the valley.

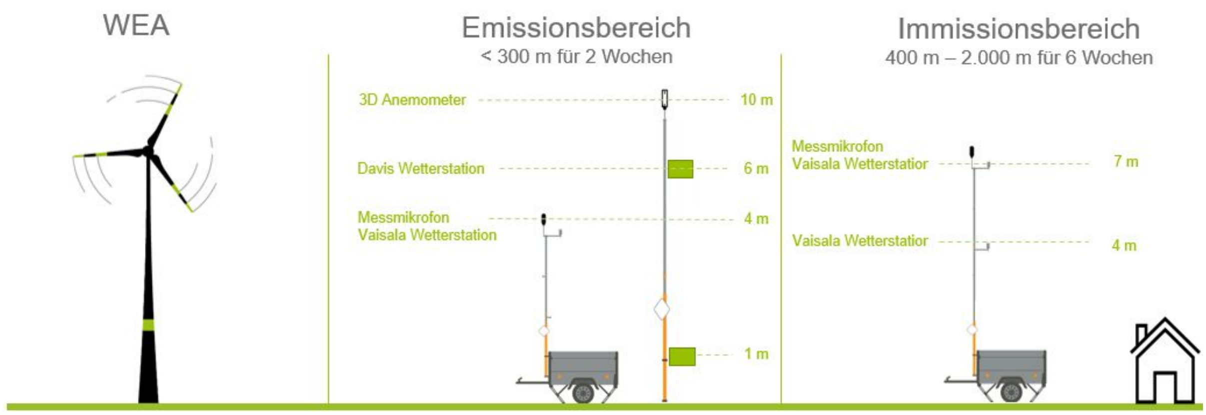
The broader area surrounding SA 3 (at a distance of approx. 1 km) included three older wind turbines of the 1-MW class with a hub height of approx. 60 m and a rotor diameter of approx. 50 m.

4 Measurement campaigns

4.1 Measurement procedure

The measurement set-up was installed in two areas. One set-up was installed in an area near a possible immission location, the other in an emission area in the immediate vicinity of a wind turbine. Figure 18 illustrates the measuring arrangement.

Figure 18: Schematic representation of the measurement set-up



WEA = Wind turbine; Emissionsbereich < 300 m für 2 Wochen = Emission area < 300 m for 2 weeks; 3D Anemometer = 3D anemometer; Davis Wetterstation = Davis weather station; Messmikrofon Vaisala Wetterstation = Measuring microphone Vaisala weather station; Immissionsbereich 800m-1.00m für 6 Wochen = Immission area 800 m - 1500 m for 6 weeks; Messmikrofon Vaisala Wetterstation = Measuring microphone Vaisala weather station, Vaisala Wetterstation = Vaisala weather station

A long-duration measurement was carried out over a period of six weeks in the immission range of each of the five study areas. Parallel to this, measurements were carried out over a two-week period using an automatically operating measuring station with a microphone height of 4 m and located in the emission range of turbines in three of the five study areas. At the same time, meteorological data were recorded in each case at the same height of the microphone, and additionally at heights of 10 m, 6 m and 1 m on an extra stand (Figure 19). Noise levels in the immission range were measured at a height of 7 m. Meteorological data for the immission range were available at heights of 7 m and 4 m (Figure 20).

System signals either were recorded using a data logger in the tower base of a wind turbine or were provided by the manufacturer as a data record.

Figure 19: Measurement set-up in the emission range of the wind turbines

Source: own presentation, deBAKOM GmbH

Figure 20: Measurement set-up in the immission range of the wind turbines

Source: own presentation, deBAKOM GmbH

4.2 Recording of measurement data

Measurement data were recorded using calibrated measuring stations by the company deBAKOM using Class-1 microphones. An additional, secondary wind baffle was used to reduce wind noise on the external microphone. The measuring stations made continuous recordings, regularly storing the following data:

- L_{eq} values with 10-Hz writing frequency
- Continuous narrow-band spectra (frequency structure of noise / FFT) with a frequency resolution of 3 Hz
- Levels over time
- Raw audio data in a 24-bit / 48-kHz format for subsequent processing.

The following variables were recorded for the meteorological data:

- Wind speed, wind direction, rain, relative humidity, air pressure and temperature

These data are generated at 1-second intervals by the Vaisala and Young sensors (3D anemometers) and at 10-second intervals by the Davis sensor. The 3D anemometer by Young also recorded vertical wind speed at 1-second intervals.

The system signals were either recorded using a data logger or were provided by the operator. The following signals were recorded with a time resolution of 1 second:

- Wind speed at hub height, turbine output, rotational speed of the turbine, wind direction

All data are synchronously collected and compiled in a database. Measurements were carried out for each location within the following periods:

- SA 1 (Central Germany): 7 May 2018 to 26 June 2018
- SA 2 (Western Germany): 11 November 2018 to 18 December 2018
- SA 3 (Northern Germany): 15 November 2019 to 9 February 2019
- SA 4 (Eastern Germany): 18 June 2020 to 29 August 2020
- SA 5 (Southern Germany): 12 November 2020 to 11 January 2021

4.3 Data evaluation

4.3.1 Foundations

Extensive data were collected using the measuring system described. The foundations of data evaluation are presented by way of example, based on the measurement results for SA 4. Further details, together with the results from the other areas, are presented in Appendix B.

In keeping with the operating behaviour of a wind turbine, it can be assumed that emissions will fluctuate significantly on an ongoing basis. For this reason, average sound levels with a frequency of 10 minutes (a total of 48 average sound levels per night) were used to determine the relevant value for the noise rating level.

Only 10-minute averages were used to evaluate sound measurement data meeting the following meteorological conditions:

- Maximum 20% chance of rain[3]
- Relative humidity < 95%.
- Temperature > 0 °C

The evaluation was based on periods in which wind speeds near the ground are low and wind speeds at hub height are high. This helps minimise wind-induced noise at the microphone as well as any noise induced by vegetation in the vicinity of the immission location. This procedure ensured that measurements could be performed with low extraneous noise (relative to wind-induced noise) for all wind turbine load conditions. Periods with conspicuous noise level curves as well as with anomalous spectra were checked, monitored where appropriate, and excluded from the evaluation. There was no need for any further corrections of extraneous noise. Accordingly, the evaluation offers a reliable estimate of the sound pressure levels generated by the wind turbines.

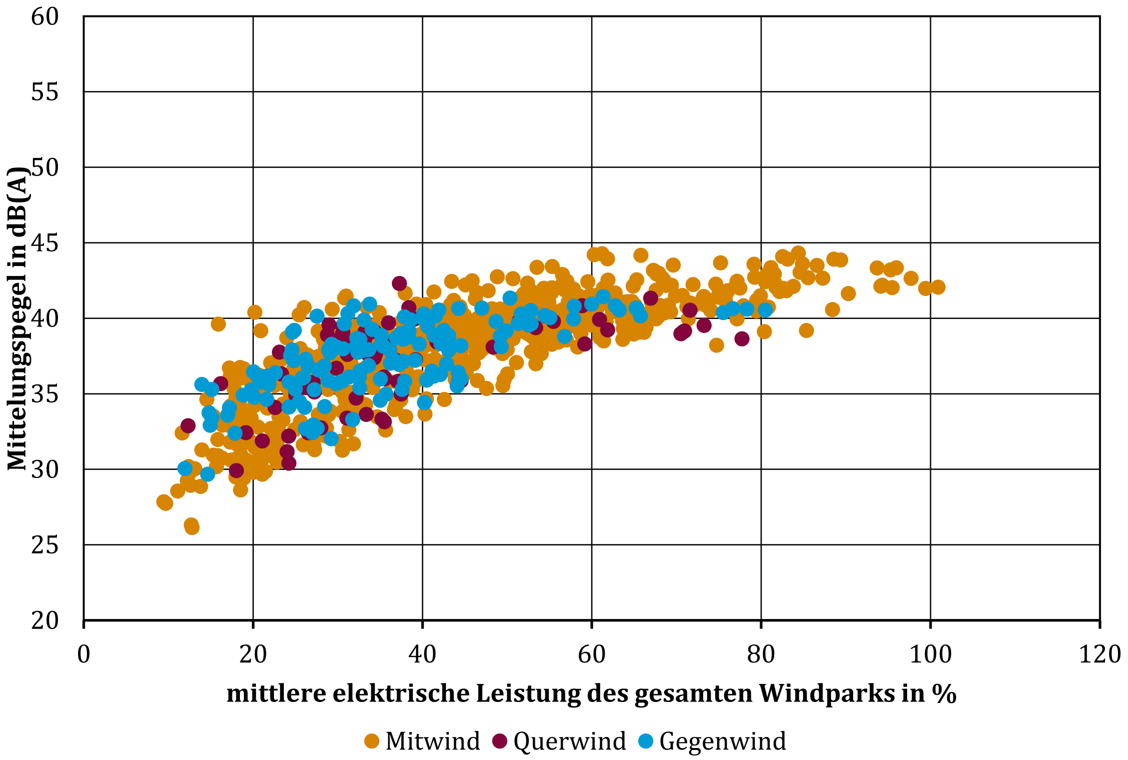
Because the noise emissions of wind turbines are a direct function of wind speed at hub height, and sound propagation is directly influenced by wind direction and speed, the results were broken down into individual classes. The breakdown of wind directions is the result of comments contained in VDI 3723 Sheet 2 (Beuth 2006) in two sectors of +/- 60° for tailwind and headwind conditions as well as two sectors of +/- 30° for crosswinds. Wind speeds are divided into classes at intervals of 2 m/s.

4.3.2 Results

By way of example, the results of the noise level evaluations are shown for SA 4. For the sound pressure levels recorded during the measurement period at the immission location in SA 4, what results are the distributions shown in Figure 21 of the averaged levels over the average output of the turbines and the distributions shown in Figure 22 relative to wind direction and wind speed at hub height.

[3] Experience has shown that a 20% chance of rain has no relevant influence on the 10-minute average sound level.

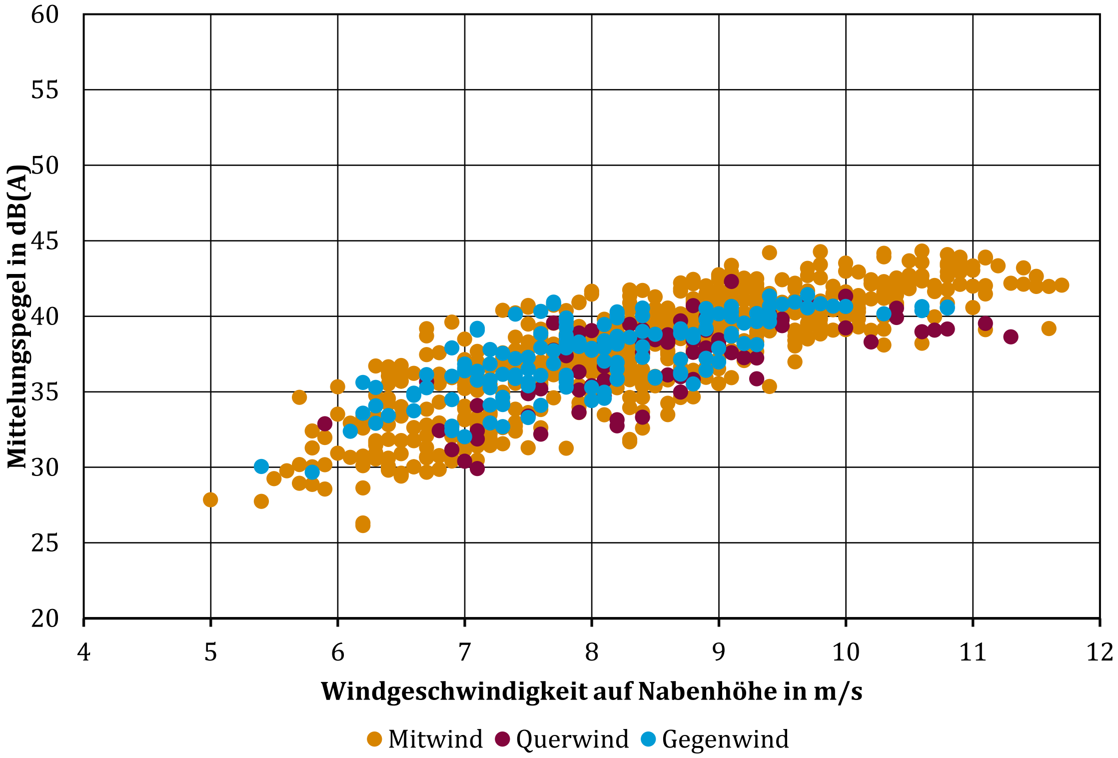
Figure 21: 10-min. average sound level during average output of the wind farm in SA 4



Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB[A] = Averaging level in dB[A]; Mittlere elektrische Leistung des gesamten Windparks in % = Average electrical output of the entire wind farm in % ; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

Figure 22: 10-min. average sound level during average wind speed at the wind farm in SA 4



Source: own presentation, deBAKOM GmbH

Mittelungspegel dB[A] = Averaging level dB[A]; Windgeschwindigkeit auf Nebenhöhe in m/s = Wind speed at hub height in m/s; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

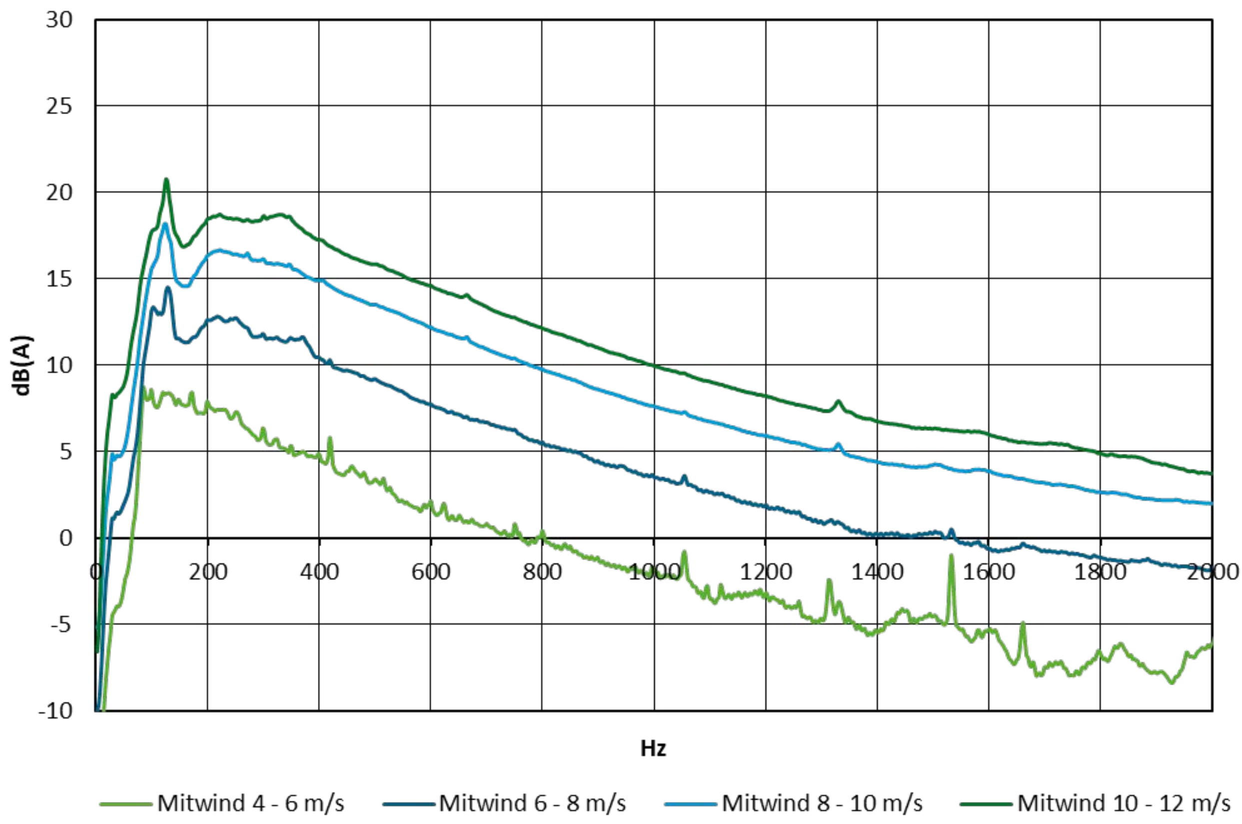
In keeping with the distribution of measured levels, the energetic average sound levels resulting for the individual wind-speed or wind-direction classes at hub height are those listed in Table 2.

Table 2: Average sound levels for individual wind-speed or wind-direction classes at hub height

Wind direction	Average sound level per class $L_{AFeq;m}^{(h)}$ in dB(A)			
	4 - 6 m/s	6 - 8 m/s	8 - 10 m/s	10 - 12 m/s
Tailwind	30.5	35.8	39.6	42.0
Crosswind	32.9	35.6	38.3	39.7
Headwind	29.8	36.8	38.8	40.5

For the entire duration of measurement during the period from 10:00 p.m. to 6:00 a.m. (night-time), the energetically averaged spectra shown by way of example in Figure 23 present the tailwind situation for the respective wind-speed class.

Figure 23: Tailwind, narrow-band spectra (resolution 2.9 Hz, A-weighted)



Source: own presentation, deBAKOM GmbH

dB(A) = dB(A); Mitwind 4-6 m/s = Tailwind 4-6 m/s ; Mitwind 6-8 m/s = Tailwind 6-8 m/s; Mitwind 8-10 m/s = Tailwind 8-10 m/s; Mitwind 10-12 m/s = Tailwind 10-12 m/s

The A-weighted narrow-band spectra with a linewidth of 2.9 Hz for the individual classes manifest typical structures of wind turbines during long-duration measurements in the immission range. The sum of all the individual lines of the narrow-band spectrum, in turn, yields the average sound levels listed in Table 2. Experience has shown that a spectral anomaly in the range between 100 Hz and 200 Hz is to be expected in most types of wind turbines on account of the meshing frequencies of gears or a slot frequency in the case of gearless turbines. Analysis of the narrow-band spectra relative to tonality in accordance with DIN 45681 (Beuth 2005) shows that wind turbine noise at the measurement location has no tonal component that would lead to a metrological tone adjustment.

The measurements were carried out in accordance with the provisions of DIN 45645-1 (Beuth 1996), Sections 6.2 to 6.5. These are representative measurements that accurately characterise the immission situation. To specify the measurement uncertainty when assessing noise immissions, DIN 45645-1 (Beuth 1996) refers to VDI Guideline 3723-1 (Beuth 1993), which in 2008 was confirmed for use by the Joint Committee for Guides in Metrology (JCGM 2008). The two-sided confidence interval of the noise rating levels for each class is calculated for the night time (Table 3) in accordance with this VDI guideline. Statistical independence was taken into account in the calculation of uncertainties.

Table 3: Two-sided confidence interval of the noise rating levels per class in accordance with VDI 3723-1

Wind direction	Two-sided confidence interval per class $L_{AFeq;m}^{(h)}$ in dB(A)			
	4 - 6 m/s	6 - 8 m/s	8 - 10 m/s	10 - 12 m/s
Tailwind	- 2.2 / + 1.9	- 0.7 / + 0.7	- 0.3 / + 0.5	- 0.5 / + 0.5
Crosswind	- 3.0 / + 3.0	- 2.4 / + 1.9	- 1.0 / + 1.0	- 1.7 / + 1.4
Headwind	- 3.0 / + 3.0	-0.7 / + 1.0	-0.5 / + 0.7	-0.3 / + 0.3

The slightly wider confidence intervals for the crosswind situation or wind-speed class 4 - 6 m/s are the result of a smaller number of measured values. In addition, at low wind speeds and the lower noise levels in which they result, extraneous noise (e.g. road traffic) has a greater influence at times. With a two-sided confidence interval of 0.3 dB to 1.0 dB, the measurement falls in the expected range for long-duration measurements in the immission range of wind turbines.

According to DIN EN 61672-2 (Beuth 2018), a level of < ± 0.7 dB(A) is indicated for the contributions to measurement uncertainty originating from Class-1 measuring instruments.

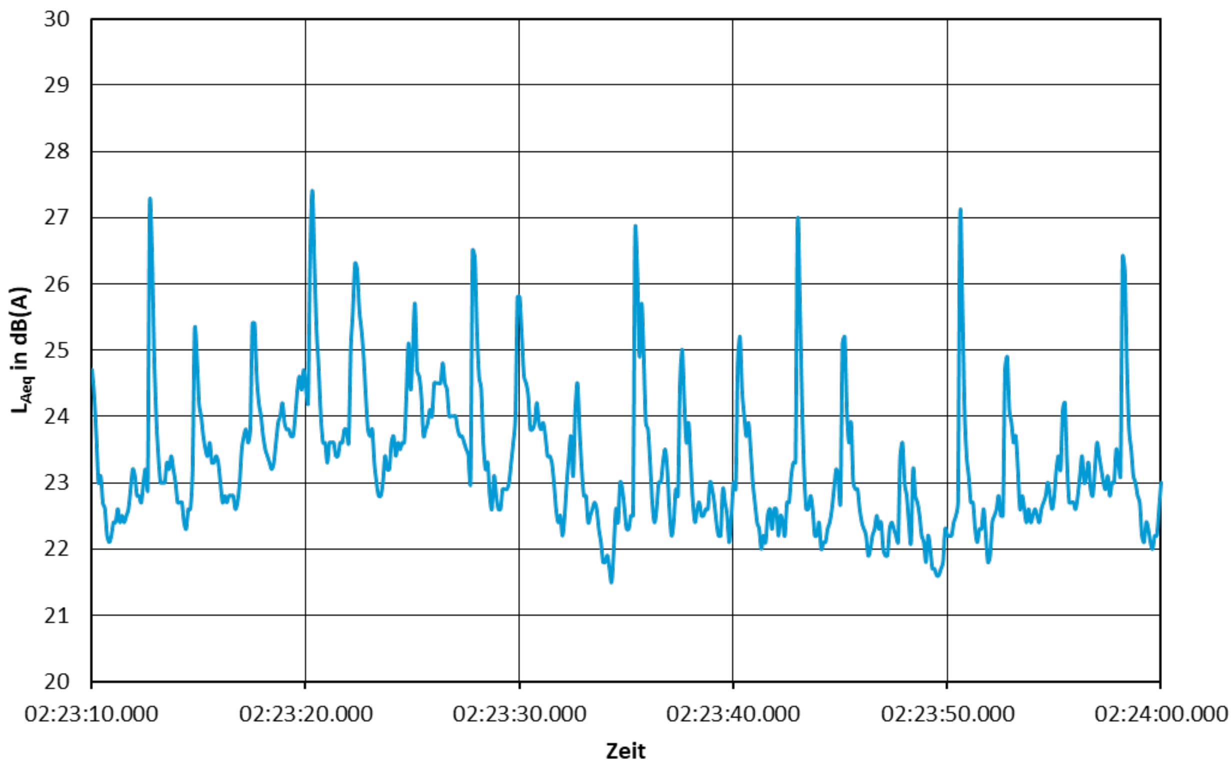
4.3.3 Anomalies in data evaluation in SA 1 and SA 5

In Study Area 1, impulsive noise occasionally occurred at low wind speeds in the range of the cut-in wind speed. According to the manufacturer's service team, the noise was the result of a defect in the nacelle of one of the wind turbines. According to the information provided by the service team, the defect was corrected following the measurement campaign. The impulsive noise is discernible in the noise level curve shown in Figure 24. These noise level curves resemble amplitude-modulated wind turbine noise but are markedly steeper. As this noise caused by the defect is not aerodynamically generated, amplitude-modulated noise at the wind turbine rotors, it was excluded from the evaluation.

In SA 5, a tonal component occurred at 300 Hz, which is assessed with a tone adjustment of 1 dB to 2 dB during approx. 4% of the measuring time. As the investigation in this area was conducted without the support of the turbine operators, there were no system signals available for the evaluation. Based on the classification into different wind speeds, however, it was possible to show that the audio frequency held constant at 300 Hz over all wind speeds. Because wind turbines are subject to variable-speed operation in the lower power range, they can largely be excluded as the cause of the tonality. Furthermore, the tonal component occurred particularly at very low wind speeds, even at wind speeds estimated to be less than 1 m/s at hub height.

Figure 25 shows the averaged spectra over the total measuring time with a class width of 0.5 m/s in the 0 m/s to 4 m/s range. Because this component occurred even at very low wind speeds, it can be assumed that the turbines were not in operation at these times. An exhaust system from a nearby pigsty, located at a distance of approx. 220 m, could be the source of the tonality. No relevant influence on the average sound level was identified.

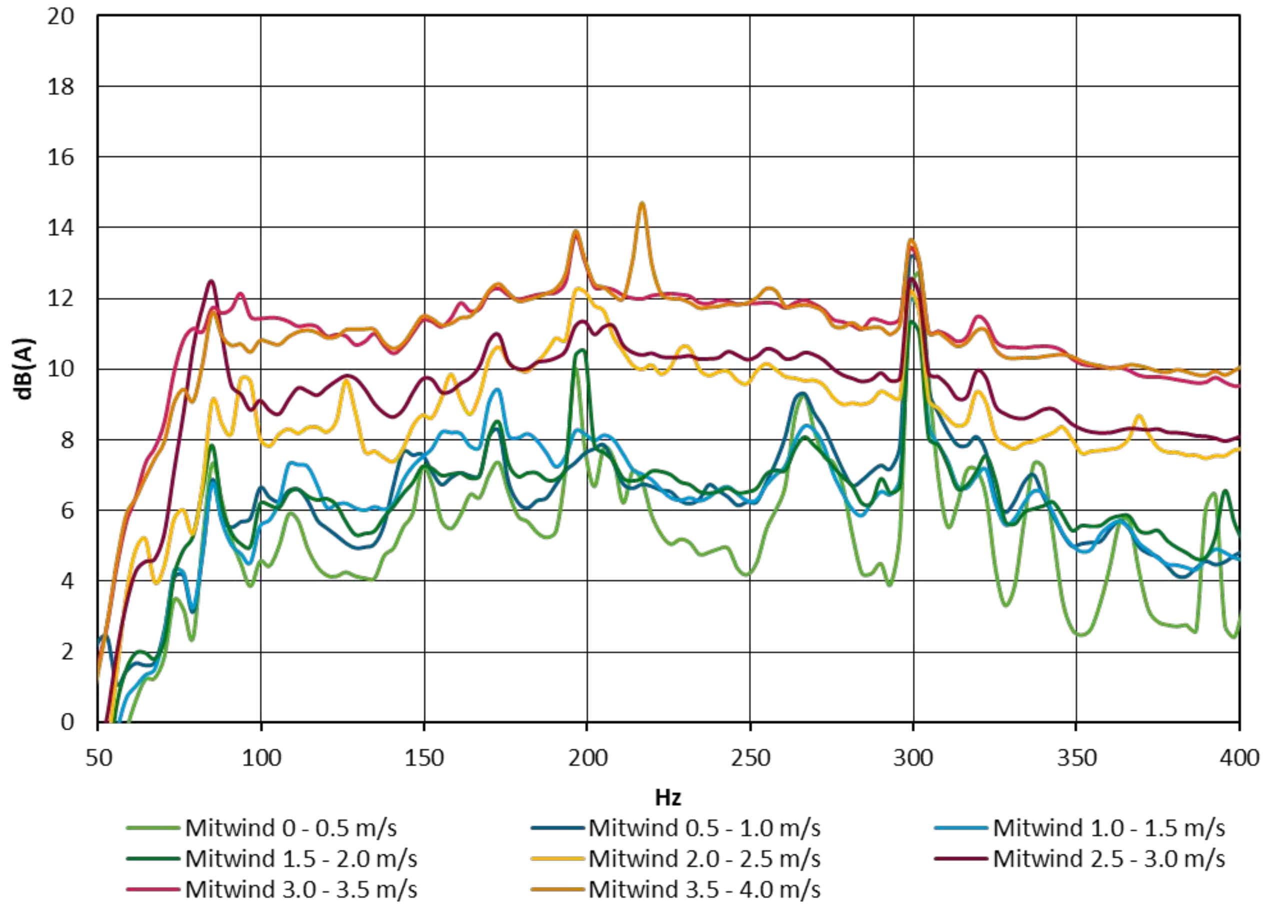
Figure 24: Sample sound-level curve over time in SA 1



Source: own presentation, deBAKOM GmbH

L_{Aeq} in dB(A) = L_{Aeq} in dB(A); Zeit = Time

Figure 25: A-weighted, averaged tailwind narrow-band spectra in SA 5 in 0.5 m/s classes



Source: own presentation, deBAKOM GmbH

dB(A) = dB(A); Mitwind 0-0,5 m/s = Tailwind 0-0.5 m/s; Mitwind 1.5-2.0 m/s = Tailwind 1.5-2.0 m/s; Mitwind 3.0-3.5 m/s = Tailwind 3.0-3.5 m/s; Mitwind 0.5-1.0 m/s = Tailwind 0.5-1.0 m/s; Mitwind 2.0-2.5 m/s = Tailwind 2.0-2.5 m/s; Mitwind 3.5 4.0 m/s = Tailwind 3.5-4.0 m/s; Mitwind 1.0-1.5 m/s = Tailwind 1.0-1.5 m/s; Mitwind 2.5-3.0 m/s = Tailwind 2.5-3.0 m/s

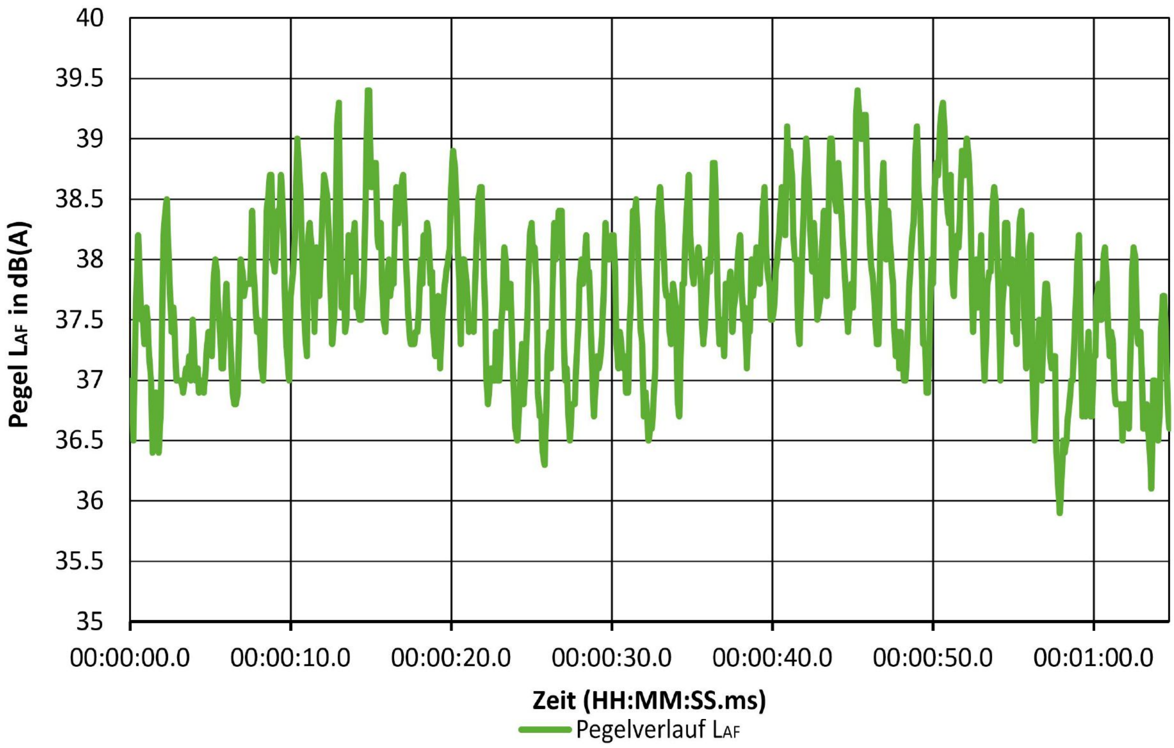
4.4 Amplitude modulation

4.4.1 Foundations of the evaluation

The following is first defined as the foundation for the evaluation of the measurement data relative to the occurrence of amplitude modulation: The amplitude modulation of wind turbines to be investigated is directly related to the rotational frequency of the turbine and, as shown in Figure 26, must be discernible as a periodic fluctuation in noise level based on the underlying recording of noise levels.

The noise generated by wind turbines is also subject to other temporally irregular fluctuations that are perceptible to humans. These can be generated, for example, by propagation processes, wind or interference; the technical literature sometimes refers to this noise as amplitude-modulated noise. These fluctuations are typically not directly related to rotational frequency, and residents do not describe them as ‘whooshing’. In what follows, the term ‘amplitude modulation' describes fluctuations in volume level in connection with the rotational frequency; in Figure 26, this can be seen as a rapid swelling and fading in volume level in 1.2-s cycles.

Figure 26: Sample fluctuation in volume levels due to amplitude modulation



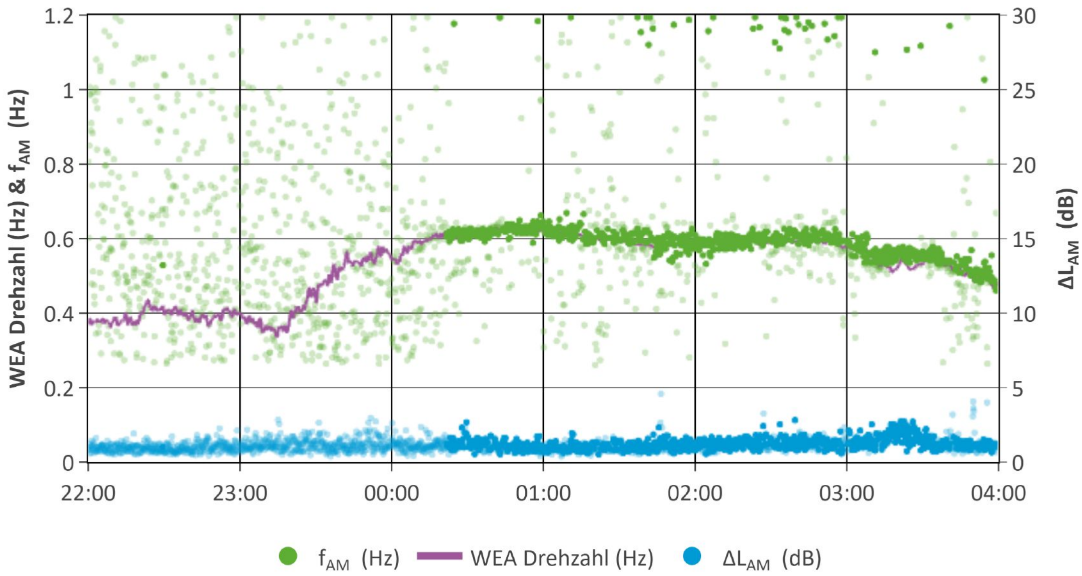
Source: own presentation, Dr. Kühner GmbH

Pegel L_{AF} in dB(A) = Level L_{AF} in dB(A); Zeit (HH:MM:SS.) = Time (HH:MM:SS.); Pegelverlauf L_{AF} = Level curve L_{AF}

To investigate amplitude modulation within the scope of this study, an algorithm was created that determines the modulation depth ΔL_{AM} and the frequency of the modulation f_{AM} based on the audio data recorded for segments 10 seconds in length. The algorithm is described in detail in Appendix C. Summarised in simplified terms, the noise level is examined for its frequency composition in the range from 0.3 Hz to 1.2 Hz in an effort to determine the prevailing frequency f_{AM} of the modulation. In this case, the periodicity expected from wind turbines based on their rotational speed is taken into account in order to determine the measure of the modulation depth based on the difference between minimum and maximum noise levels. Irrespective of the actual occurrence of periodically amplitude-modulated noise, data are first generated for f_{AM} and ΔL_{AM}.

As seen in Figure 27, the algorithm itself can determine the rotational speed of the wind turbines on the basis of the sound measurements. If data are available on the turbines' rotational speed, e.g. as provided by the turbine operator or manufacturer, these data can be enlisted to augment the reliability of results generated using the algorithm. As part of the measurements performed, turbine data for SA 1 through SA 4 were available and factored into the validation of the algorithm.

Figure 27: Emission-side 2D frequency of occurrence (modulation frequency vs. wind turbine rotational speed)



Source: own presentation, Dr. Kühner GmbH

WEA Drehzahl (Hz) & f_{AM} (Hz) = Wind turbine rotational speed (Hz) & f_{AM} (Hz); f_{AM} (Hz) = f_{AM} (Hz); WEA Drehzahl (Hz) = Wind turbine rotational speed (Hz); ΔL_{AM} (dB) = ΔL_{AM} (dB)

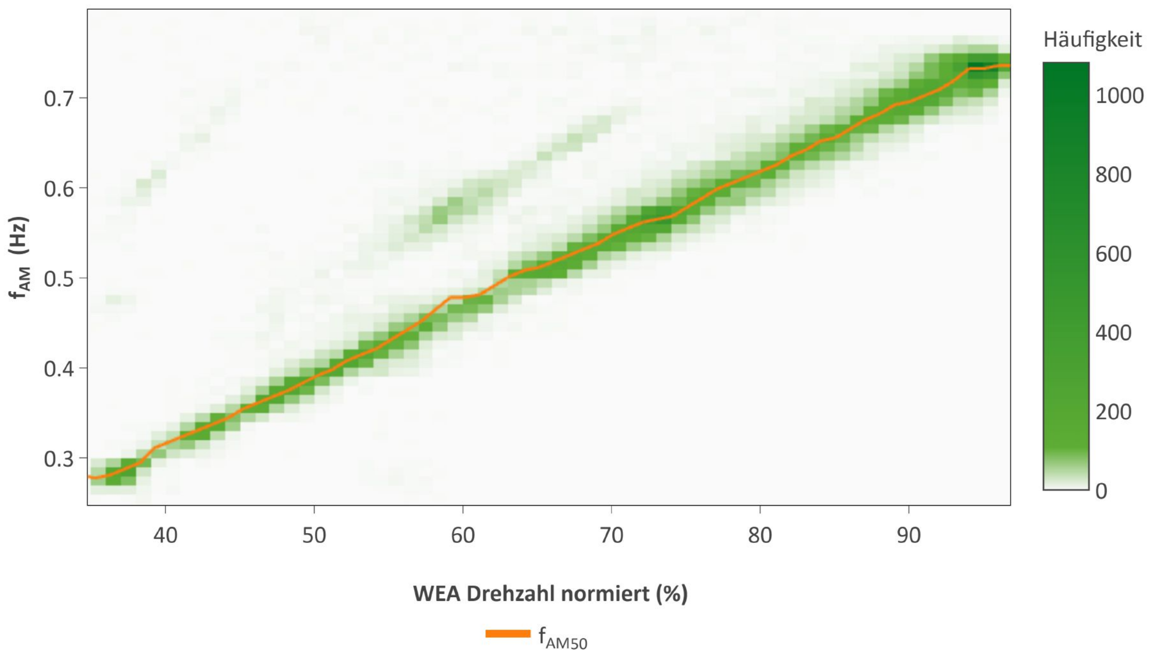
In the next step, the calculated data recorded are automatically examined to determine whether one or several of the modulation frequencies present remain(s) stable over time. Figure 27 shows 10:00 p.m. to 12:20 a.m., a period with no modulation remaining stable over time. The frequency f_{AM} scatters irregularly from 0.3 Hz to 1.2 Hz. Continuous and unambiguous automated attribution of the calculated AM to the noise of wind turbines is not possible during this period.

Figure 27 shows 12:20 a.m. to 4:00 a.m., a time range in which AM occurred continuously at a frequency close to the rotational speed logged for the wind turbine. The associated points f_{AM} and ΔL_{AM} for the recorded noise levels are marked clearly (for identified) or pale (for not identified), in keeping with their assignment to the class of 'AM identified' and 'AM not identified'.

The data points for which a high correlation exists between wind turbine speed and modulation frequency are collected in a database. Targeted statistical evaluation of these data points can be used to evaluate further characteristics of the sound measurement and AM.

Once categorisation is complete, the frequency of occurrence of the detected modulation frequency and the rotational speed of the wind turbine can be represented through a 2D plot of the occurrence density for the period of time in which AM was detected (Figure 28). Using the data measured in the emission range, this presentation offers a clear example of the strong correlation between the acoustic modulation frequency and the rotational frequency of the wind turbine. The paler, nearly parallel line in the middle range of rotational frequency can be explained through simultaneous measurement of the AM of other, non-logged turbines with higher rotational speeds. When the measurements were performed, rotational speeds were not recorded for some of the turbines in a wind farm.

Figure 28: Emission-side 2D frequency of occurrence (modulation frequency vs. wind turbine rotational speed)



Source: own presentation, Dr. Kühner GmbH

f_{AM} (Hz) = f_{AM} (Hz); WEA Drehzahl normiert (%) = Wind turbine speed standardised (%); f_{AM50} = f_{AM50}

An evaluation of the measurements carried out on this basis revealed that the period of low external noise, from 10:00 p.m. to 4:00 a.m., is a particularly suitable period for evaluating the overall data. Automatic identification of amplitude-modulated noise as described functions reliably here. All of the study areas are easily comparable with one another during this time window. Depending on the season and location, different situations of extraneous noise arose (e.g. traffic, birds, etc.), particularly during the early morning hours. The only data points used for further analysis were those that met the following criteria:

- No rain
- Humidity < 95% (excluding fog)
- Wind speed < 6 m/s at the microphone
- Turbine output of the reference turbine > 1% of the rated output

The operator did not provide any data about turbine output for SA 5. Accordingly, the final criterion for evaluation in this study area is omitted.

4.4.2 Comparison with other algorithms for recording AM

Very generally speaking, amplitude modulations are associated with fluctuations in volume level. In the special case of wind turbines, volume fluctuations occur rhythmically with the revolutions of the rotor. The aim in quantifying AM is to locate a value for the difference between these levels’ maximum and minimum. The maxima and minima can be marked manually; this way, for example, it can be determined in each case how far a maximum lies above the minimum.

A first problem arises concerns the manner in which levels are expressed in the records of noise levels. As the modulated signal consists of a broadband rushing sound, minimum and maximum levels are a function of the integration with which the levels were formed. A noise level record using fast assessment fluctuates less than one with 100-ms equivalence levels, which in turn fluctuates less than a record with 10-ms equivalence levels, and the difference between instantaneous maximum and minimum sound pressure levels within a given time segment is several dB greater. Even for maximum and minimum values, then, the differences can be significant, depending on how the values are formed.

In addition to the fluctuations in noise level due to AM, the base level at which the fluctuations occur changes over time. Wherever possible, these trends in levels should be separated from the AMs, i.e. the value for the AM should only express brief ups and downs. The fluctuations in noise level themselves are not strictly periodic, either. Any quantification of the magnitude of AM is thus always relative to a time segment. The weighting applied within these time periods can be different as well. A question remains as to how to take the periodicity of the noise into account. There is a presumption that the disturbing effect of the noise relates to its repetition at a constant rhythm.

The procedure developed for this report assigns priority to repetitions of noise at constant time intervals. The rate of repetition of the dominant noise is identified for each particular time segment. The rate of repetition is determined with such high accuracy that it can be assigned directly to the rotational speed of the wind turbine causing the noise. The time segment is divided into parts with the length of a period, and an average, trend-adjusted noise curve over a period length is determined through energetic averaging. The modulation depth is determined based on the difference between the maximum and minimum of this mean noise curve over a period.
Modulation depths are each determined in 10-second steps.

Some other approaches offer very similar results for the idealised case of a very clear, amplitude-modulated signal. A very simple method for quantifying fluctuations in level is the maximum cyclical noise level method pursuant to the Technical Instructions on Protection Against Noise [Technische Anleitung zum Schutz gegen Lärm – TA Lärm (1998)] (cf. Section 4.4.4). This method measures the extent to which the highest fast level exceeds the averaging level over a 5-second average sound level. The drawback to this approach is that it does not take trends in level into account, that it can lead to excessive results, and that the periodicity of amplitude modulations is not taken into account. The situation is similar with all methods that reflect the difference between maximum and minimum levels or percentile levels for time segments, for example between the 5% and the 95% fast or 100-ms level.

Absent further determination of whether a particular signal is an amplitude modulation of wind turbines, these methods are as responsive to AM generated by wind turbines as they are to AM emanating from a chirping bird, a passing car or other forms of interference.

Martinez et al. used a wavelet analysis to determine AM, Martinez (2017). In this case, the trend and any signals with undesired periodicities are simultaneously removed and a synthetic noise curve subsequently produced with trend and interference signals removed. AM is quantified based on percentiles of the synthetic noise curve. In contrast to the method used in this report, the synthetic noise curve permits multiple periodicities, such as those that may be created by different wind turbines rotating at different speeds.
Because the signal is noise-adjusted, the levels of AM pertain to a cleaned signal, not the actual audible signal. While this can be a good approach to take when investigating the physical

properties of the formation and propagation of AM, it poses a drawback when analysing immissions, as it fails to assess actual audible noise.

As part of the Renewable UK (2013) study, a method was developed for quantifying AM in which noise level records are considered for each 10-second window. The value of the spectral line protruding from the spectrum for the noise level record of individual bandpass-filtered time series is selected and used as a measure of modulation depth. This value represents the pure periodic component of modulation. It is a measure that is easy to determine and which can lead to overestimation of modulation depth in certain noise situations, if, for example, the minima do not follow the course of the sine. While in the case of Martinez (2017) assessment through noise adjustment can provide a result that does not refer to actually audible noise, assessment according to Renewable UK (2013) can clearly differ not only from the signal form that actually exists but from an idealized signal form as well. This problem is exacerbated by the fact that the frequency analysis for which Renewable UK (2013) provides is rough, with frequencies of the identified AMs determined so inaccurately that it is nearly impossible to assign them to the turbines causing them. In addition to the incorrect determinations of periodicity, this can also lead to an incorrect assessment of AM.

4.4.3 Evaluating amplitude modulation

4.4.3.1 Parameters

The criteria defined in Section 4.4.1 (e.g. exclusion of the measurement data due to rain) result in the evaluable measurement times listed in Table 4 relative to the entire measuring time. In order to evaluate AM, frequencies of occurrence were determined for the parameter ΔL_{AM}. The frequency of occurrence describes the percentage share of the evaluable time in which AM was detected. In some cases, it varies greatly across the individual study areas. In SA 3, for example, the frequency of occurrence of detected and stable AM at the immission measuring point is just 1.7%, yet it is nearly 50% in SA 2.

When the immission locations are compared against measurements in the emission range, it can be seen that the detected AM always exhibits a higher frequency of occurrence on the emission side than it does in the immission range.

The parameters ΔL_{AM95} through ΔL_{AM05} are known as ‘percentile levels’. For the frequency distribution of AM, this indicates which modulation depth is reached or exceeded during 95%, 50% or 5% of the evaluation time.

Table 4: Parameters for amplitude modulation in the immission range (10:00 p.m. to 4:00 a.m.)

Measurement position	Evaluable time in %	Frequency of occurrence of AM in %	ΔL_{AM95} in dB	ΔL_{AM50} in dB	ΔL_{AM05} in dB
Immission range SA 1	82.0	10.8	1.1	2.0	4.2
Immission range SA 2	80.6	47.4	1.3	2.4	4.7
Immission range SA 3	81.4	1.7	0.6	1.4	5.5
Immission range SA 4	86.6	42.0	0.9	1.5	3.3
Immission range SA 5	95.8	22.3	0.8	1.6	2.9

Table 5: Parameters for amplitude modulation in the emission range (10:00 p.m. to 4:00 a.m.)

Measurement position	Evaluable time in %	Frequency of occurrence of AM in %	ΔL_{AM95} in dB	ΔL_{AM50} in dB	ΔL_{AM95} in dB
Emission range SA 1	77.7	36.4	1.0	2.1	4.5
Emission range SA 3	52.5	58.0	1.2	2.2	4.4
Emission range SA 4	91.8	60.0	0.9	1.5	2.5

The evaluable time for amplitude modulation in the immission range in SA 5 lies 10% to 15% higher than in the other locations. Measurements in this study area were conducted without the provision of system data by the operator. By contrast, periods during which the turbines were not in operation were excluded in locations SA 1 through SA 4. These periods could not be excluded in SA 5. Because periods in which turbines were not in operation also had to be included to determine the frequency of occurrence, this reduces the relative frequency of occurrence of AM.

The low 52.5% frequency of occurrence in the emission range in SA 3 can be explained based on the characteristics of the study area. This is the study area with the greatest distance between the measurement location and the wind turbines (distance of approx. 1500 m between measurement and turbine locations).

The turbine location in SA 1 has a conspicuously low frequency of occurrence when compared to similar wind-farm constellations. As there were different types of turbine in use within the wind farm, with comparable distances to the immission position, this resulted in few time periods of stable-frequency amplitude modulation. This is because different turbines emit different modulation frequencies at the same time.

The different evaluable times on the emission side are due to the effects of shorter measurement times there in combination with different seasons. Depending on the season, individual periods experienced stronger influences due to environmental factors (strong winds, rain, birds).

The data evaluation shows median modulation depths of approx. 1.5 dB to 2.5 dB for all locations. The overall evaluation does not point to any difference in modulation depth between the emission and immission ranges. In the comparison of different study areas, SA 1 and SA 2 stand out for their greater modulation depths. These locations are the wind-farm constellations with the smallest number of turbines, in combination with relatively small distances between the wind turbines and the immission measuring position.

Given the differences across measurement campaigns (season, topography, wind-farm constellation, measurement distance), only certain tendencies with regard to the number of turbines and the measurement distance can be derived from the observations.

4.4.3.2 Dependency between AM and the operating states of the wind turbines

Table 6 lists the respective median of the modulation depths, classified by standardised electrical output per measurement location. Here, 100% corresponds to the rated output of the respective reference wind turbine. For Study Area 5, due to the absence of system signals, frequencies are classified based on the wind speed measured at the immission-side microphone. In this case, 100% corresponds to 6 m/s at the immission height. Experience has shown that wind speeds at hub height are greater than they are at the measurement location.

Table 6: Classification of modulation depth based on standardised electrical output

Percentile	Class	Immission range					Emission range		
		SA 1	SA 2	SA 3	SA 4	SA 5	SA 1	SA 3	SA 4
ΔL_{AM50} in dB	1-20%	2.1	2.1	1.8	1.6	1.5	2.0	1.8	1.4
	20-40%	2.0	2.5	1.2	1.5	1.6	2.2	2.2	1.6
	40-60%	2.2	2.9	1.1	1.5	1.5	1.9	2.7	1.6
	60-80%	2.2	3.0	1.2	1.5	1.3	1.9	2.9	1.6
	80-100%	1.7	3.0	1.2	1.4	1.4	1.8	2.7	1.6

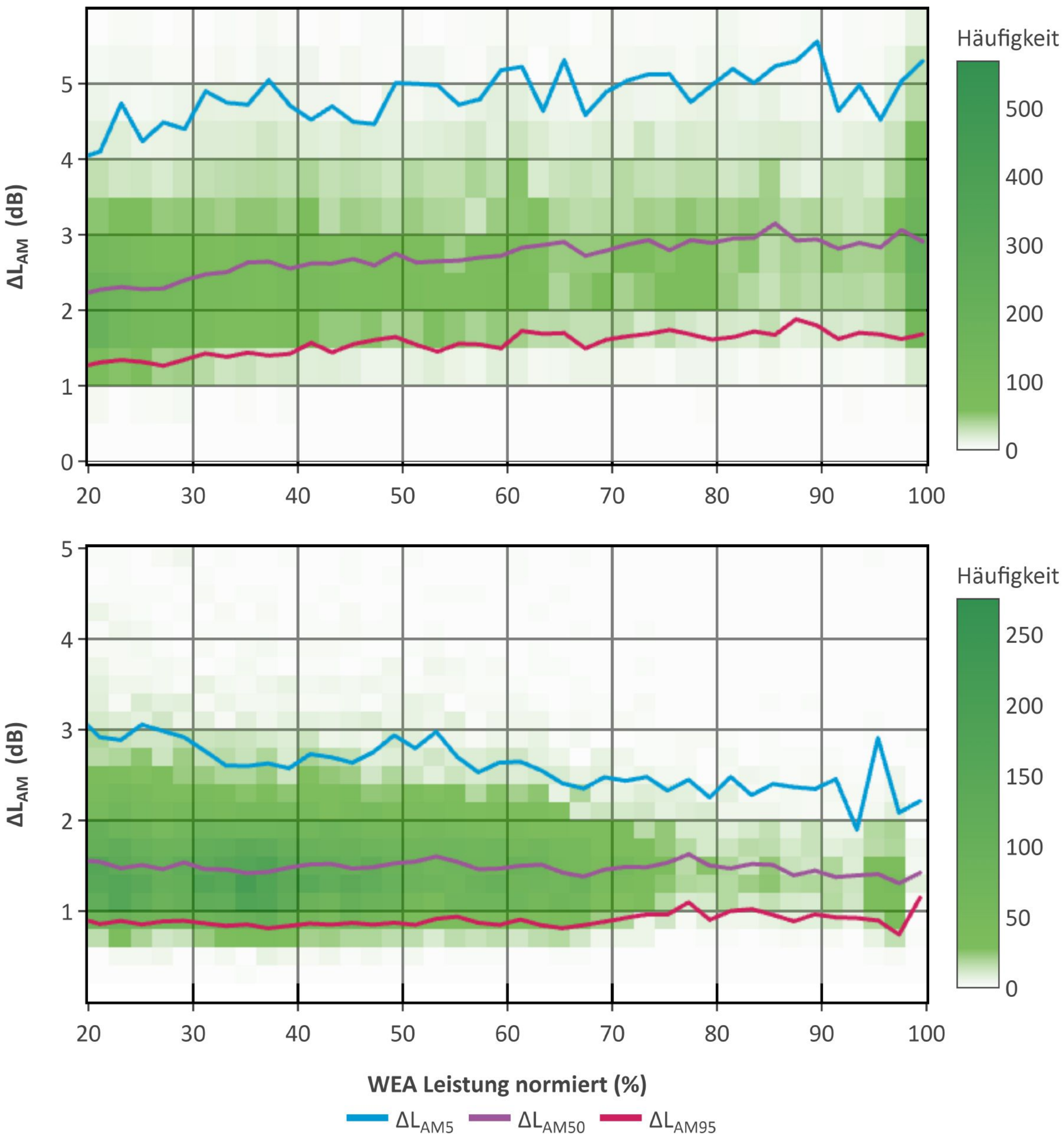
For Study Areas 1, 3, 4 and 5, the median modulation depth holds constant or decreases slightly with increases in electrical output power or wind speed.

The picture that emerges for Study Area 2 is different. Here, the modulation depth rises above the median as output increases. SA 2 is the study area with just a single wind turbine.

For SA 1 and SA 4, analyses of measurements in wind-farm emission ranges reveal a constant or slightly downward-trending median modulation depth with increasing electrical output. In SA 3, the median increases with increases in turbine output.

Each of the density plots shown compares output values standardised to rated output against the measured modulation depth. Figure 29 shows, by way of example, the slight upward trend in SA 2 and the constant progression in SA 4.

Figure 29: Modulation depth vs. output immission (SA 2 top, SA 4 bottom)



Source: own presentation, Dr. Kühner GmbH

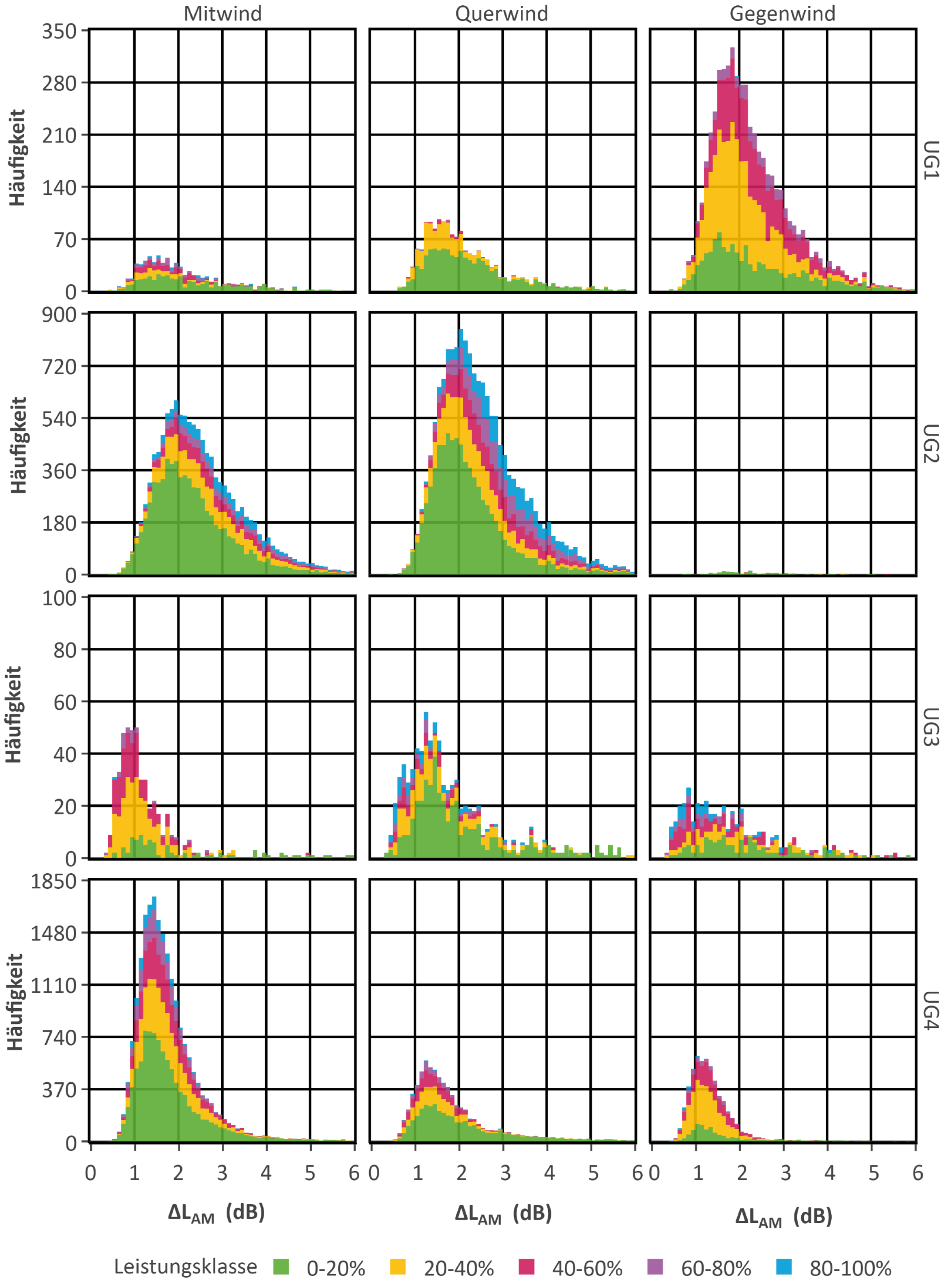
ΔL_{AM} (dB) = ΔL_{AM} (dB); Häufigkeit = Frequency; ΔL_{AM} (dB) = ΔL_{AM} (dB); WEA Leistung normiert (%) = Wind turbine output standardised (%); ΔL_{AM5} = ΔL_{AM5}; ΔL_{AM50} = ΔL_{AM50}; ΔL_{AM95} = ΔL_{AM95}; Häufigkeit = Frequency

4.4.3.3 Meteorological influences

To examine the meteorological dependence of AM, the data records were classified based on electrical output and wind directions in the following Figure 30 and

Figure 31. Due to the prevailing weather conditions during measurements, it should be noted that it was not possible to detect all wind directions with the same frequency at each measuring location. Hence, there are clear differences in the frequencies of the wind directions detected. The focus of the L_{AM} lies between 1 and 2 dB. AM with a depth of up to 6 dB are occasionally detected in all wind directions.

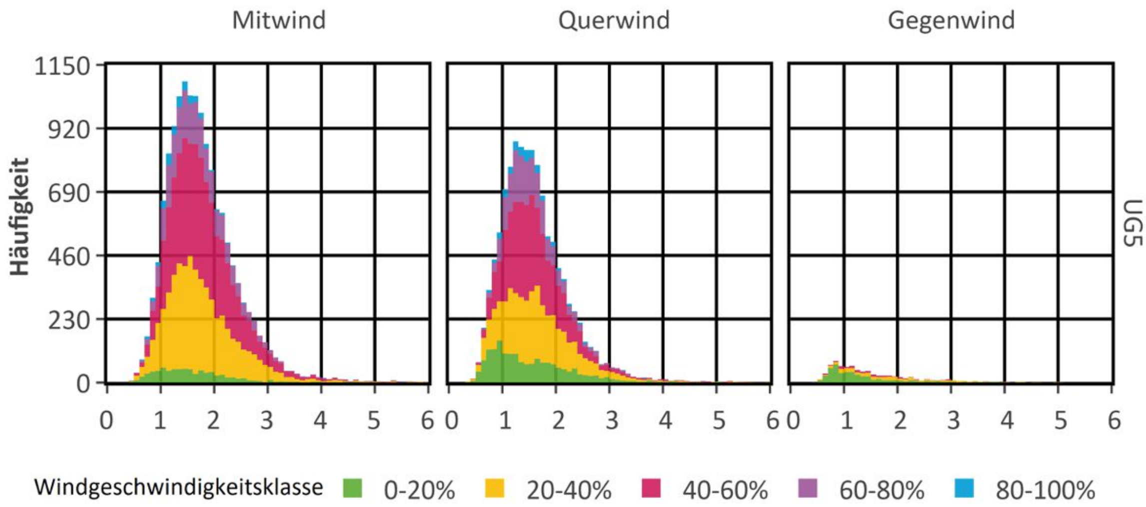
Figure 30 Frequency distribution ΔL_{AM} classified by wind direction and output, SA 1 to SA 4



Source: own presentation, deBAKOM GmbH

Häufigkeit = Frequency; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind; UG1-4 = SA 1-4; Leistungsklasse = Power class

Figure 31 Frequency distribution ΔL_{AM} classified by wind direction and wind speed, SA 5



Source: own presentation, deBAKOM GmbH

Häufigkeit = Frequency; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind; UG5 = SA 5; Windgeschwindigkeitsklasse = Wind speed class

By way of example, Table 7 presents modulation depths in the immission range according to standardised electrical output and wind direction for SA 2.

Table 7: Classification of modulation depth based on standardised electrical output and wind direction in SA 2

Percentile	Class	Immission range SA 2		
		Tailwind	Crosswind	Headwind
ΔL_{AM50} in dB	1-20%	2.0	1.8	-
	20-40%	2.3	2.2	-
	40-60%	2.4	2.6	-
	60-80%	2.7	2.8	-
	80-100%	2.6	3.0	-

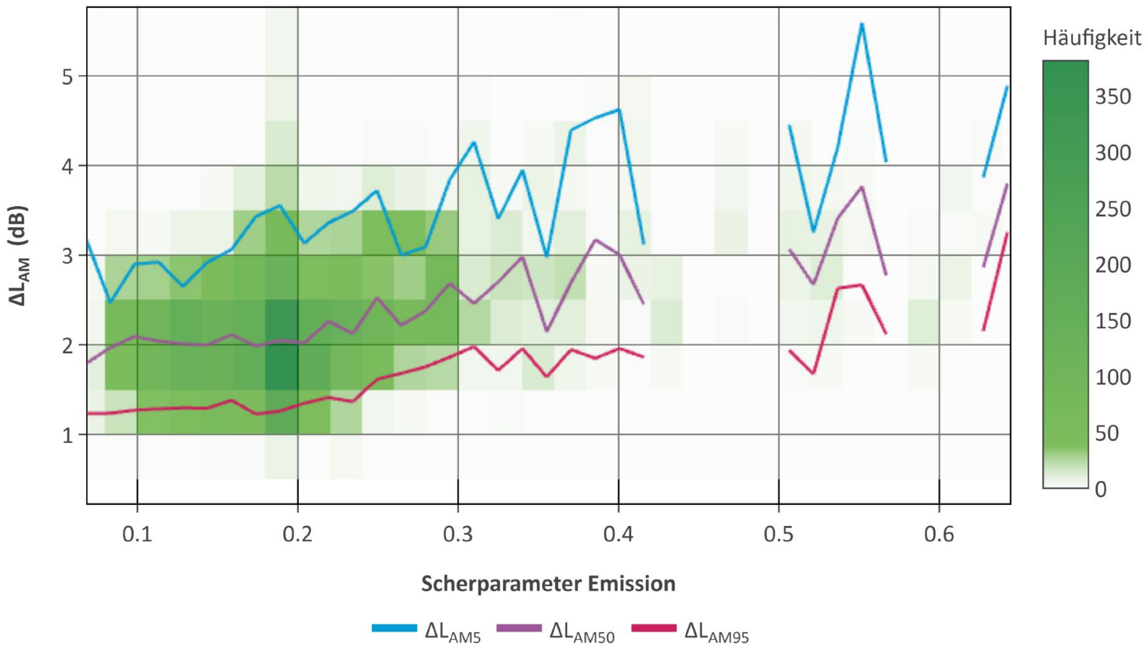
As an analysis of the measured data following classification with regard to wind direction and the electrical output of the wind turbines shows, in crosswind conditions the modulation depth in the immission range in SA 2 increases slightly by 1.2 dB with increasing output. In tailwind situations, on the other hand, the modulation depth increases by just 0.6 dB. Based on the data, this trend is discernible only for the wind farm with the single turbine. Where the other study areas are concerned (SA 1 and SG 3 to 5), there is no discernible correlation between output and wind direction or modulation depth.

4.4.3.4 Wind shear as a noise-source mechanism

There can be significant differences in how quickly and in what form wind speed increases with atmospheric height. A shear parameter is used to describe the shape of the wind profile. To investigate the influence of wind shear as a noise-source mechanism, the meteorological variables measured were used to dynamically identify shear parameters for 10-minute segments, which were then plotted against the measured modulation depth in density distributions.

Emission-side measurement of the AM resulted in a value for modulation depth that increases with the shear parameter. The curve in Figure 32 is presented by way of example for this measurement in the emission range of SA 1. On the immission side, on the other hand, there is no noticeable increase in the regression line across all locations. The curve in Figure 33 is presented by way of example for the immission location of SA 2. Thus, it must be pointed out that the measured AM at the immission location does not follow any trend and is not influenced by the identified wind shear. For the emission range, on the other hand, a trend was observed indicating a slight increase in modulation depth concomitant to increasing shear parameter.

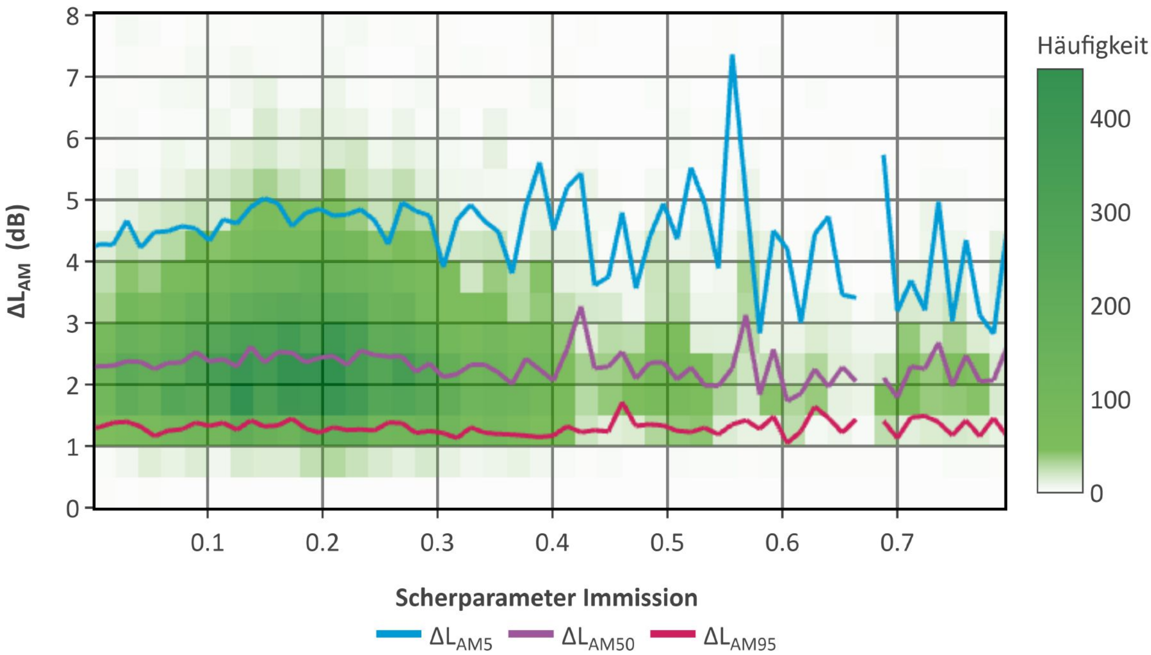
Figure 32: Modulation depth versus shear parameters in the emission range in SA 1



Source: own presentation, Dr. Kühner GmbH

Scherparameter Emission = Shear parameter, emission; Häufigkeit = Frequency

Figure 33: Modulation depth versus shear parameters in the immission range in SA 2



Source: own presentation, Dr. Kühner GmbH

Scherparameter Immission = Shear parameter, immission; Häufigkeit = Frequency

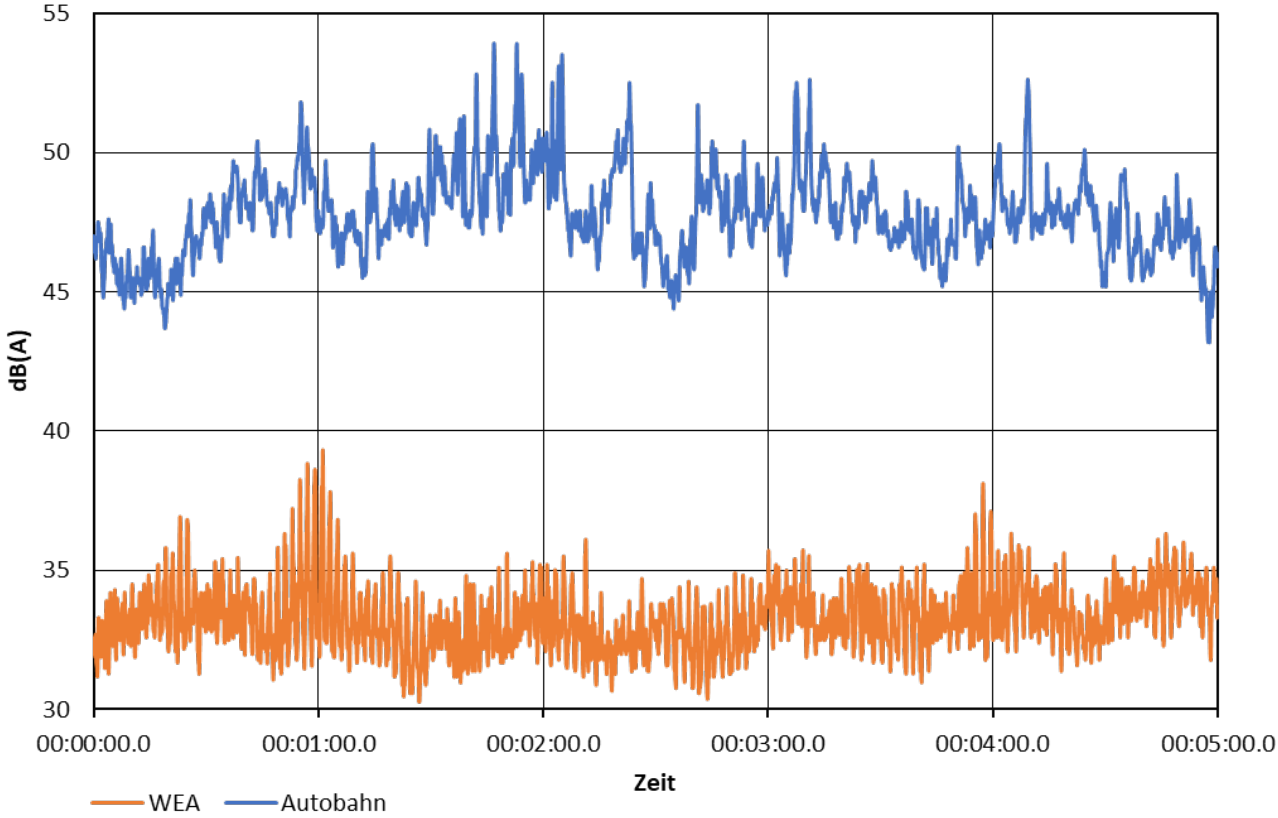
4.4.4 Analysis of AM using the maximum cyclical noise level method pursuant to the Technical Instructions on Protection Against Noise

4.4.4.1 Foundations of the evaluation and limitations

What follows is an examination of whether the amplitude-modulated noise of wind turbines can also be described sufficiently well by means of a maximum cyclical noise level method. The 'Technical Instructions on Protection Against Noise' [TA Lärm (1998)] use the average maximum cyclical noise level L_{AFTeq} to assess impulsive noise. For this purpose, the difference $L_{\mathrm{AFTeq}} - L_{\mathrm{Aeq}}$ is defined as an adjustment for impulsiveness. The cycle time is 5 seconds.

By way of example, Figure 34 shows a noise level curve from Study Area 2 and a noise level curve measured near a motorway (3 lanes per direction of travel, measurement distance to the motorway approx. 400 m). Each of the noise level curves stems from the night time between 12:00 a.m. and 1:00 a.m.. For both curves, the difference $L_{\mathrm{AFTeq}} - L_{\mathrm{Aeq}}$ is 2.1 dB. This shows that a maximum cyclical noise level method does not distinguish between the amplitude-modulated noise of a wind turbine and other noise with changing amplitudes. Accordingly, absent detailed detection of periods in which AM determines noise levels, this method is subject to relevant errors.

Figure 34: Comparison of 10-Hz noise curve along a motorway with wind turbines



Source: own presentation, Dr. Kühner GmbH

WEA = Wind turbine; Autobahn = Motorway; Zeit = Time

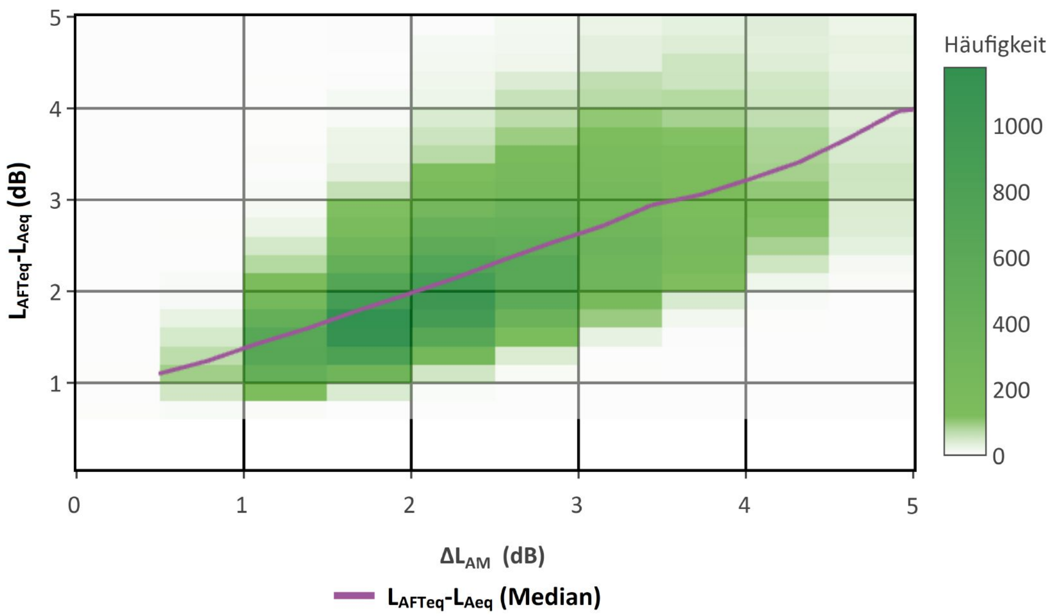
4.4.4.2 Comparison of AM method with maximum cyclical noise level method

An analysis of the noise level curve for the wind turbine shown in Figure 34 with the AM method developed in this study resulted in a value of ΔL_{AM50} = 2.8 dB. In an effort to compare this method with the maximum cyclical noise level method pursuant to the Technical Instructions on Protection Against Noise (1998), below shows time periods analysed in which the AM method has identified a modulation frequency that is stable over time. Accordingly, for these time periods it can be assumed that periodic amplitude-modulated noises will be found here.

Study areas UG 2, UG 4 and UG 5 are considered, as they provide the largest data basis in regard to modulation frequencies that remain stable over time. The results of the maximum cyclical noise level method ($L_{\mathrm{AFTeq}} - L_{\mathrm{Aeq}}$) are applied in Figure 35 through Figure 37 with regard to the results of the AM method. As the figures show, the median result is a relatively linear relationship between the results of the AM method and the results of the maximum cyclical noise level method. At higher AMs, the maximum cyclical noise level method results in a slight underestimation compared to the AM method.

Insofar as it can be ensured for a certain time period that the noise in question is essentially a periodically amplitude-modulated noise, study areas SA 2, SA 4 and SA 5 show that the maximum cyclical noise level method set forth in the Technical Instructions on Protection Against Noise (1998) can be used to estimate modulation depth.

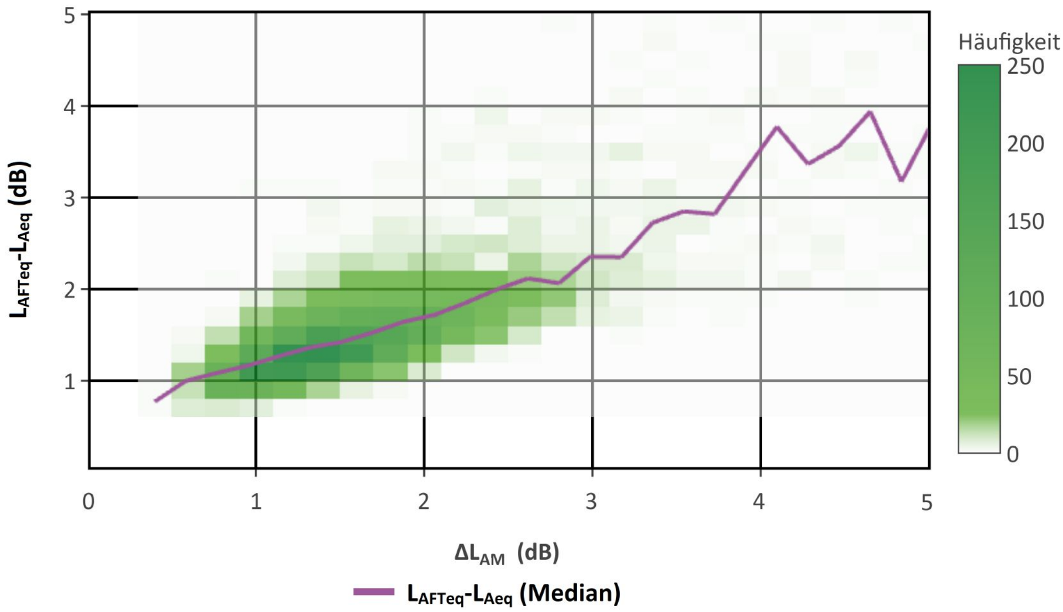
Figure 35: Comparison of AM method with maximum cyclical noise level method (SA 2)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency

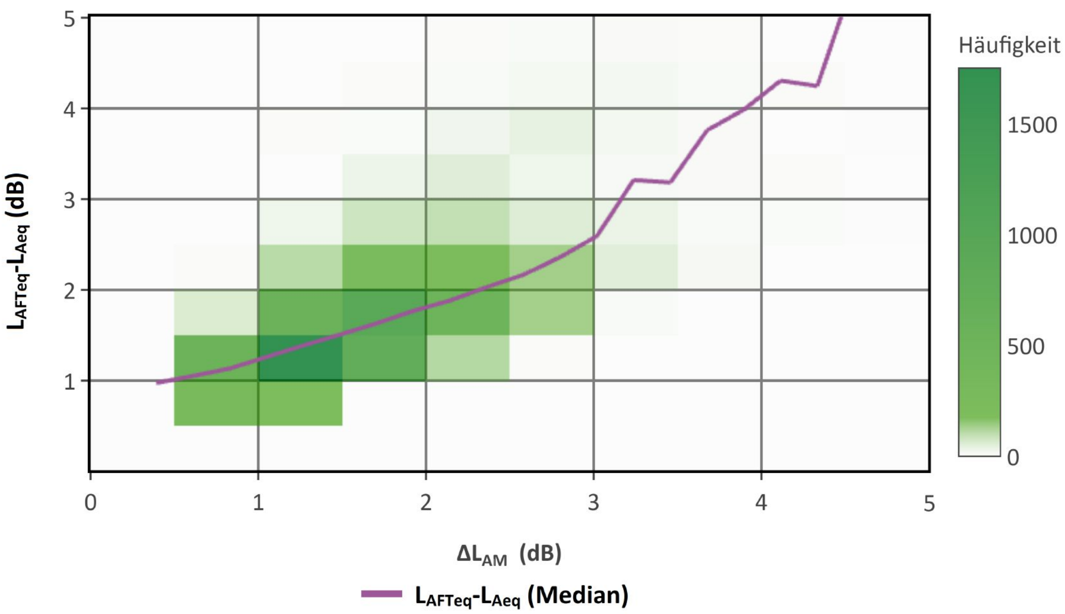
Figure 36: Comparison of AM method with maximum cyclical noise level method (SA 4)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency

Figure 37: Comparison of AM method with maximum cyclical noise level method (SA 5)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency

5 Infrasound measurements

5.1 What is infrasound?

Human hearing is most sensitive at frequencies around 1000 Hz. As frequencies grow lower, our sense of hearing becomes less and less sensitive; i.e. the sound pressures for these noises need to become higher and higher in order to be heard. If, for example, you follow the keys of a piano to the left, the sounds would appear quieter and quieter if not for the actual increase in sound pressures.

The A-weighting takes into account that hearing becomes less sensitive at very high frequencies and at low frequencies, and shifts levels in such a way that tones with different frequencies and the same A-level appear approximately equally loud.

Although hearing becomes less sensitive at low frequencies, (pure) tones at sufficient levels are still audible as tones. If two tones are not too close together – i.e. if their frequencies are sufficiently different – they can be heard as two different tones with different pitches.

The human ear can no longer hear these tones properly at very low frequencies. Sounds are still perceptible but can no longer be heard as a tone in the proper sense of the term. Two adjacent tones can no longer be distinguished from one another, and a tone transmitted at a single frequency cannot be distinguished from a broadband rushing sound. This is the case regardless of whether the sound pressure level is increased or not.

From this point on, instead of audible sound we will refer to infrasound. The literature contains disparate definitions of infrasound; the limit is given as 20 Hz (DIN 45680 (1997), ISO 7196 (1995)) or as 16 Hz (DIN 1320 (2009)). In this study, noise with a frequency of less than 20 Hz is referred to as infrasound. Standards almost universally also specify a lower limit of 1 Hz. There is no common separate description for the range below 1 Hz. This study considers frequencies in the range of less than 1 Hz to be infrasound.

5.2 How infrasound is created

Wind turbines have low rotational speeds; fluctuations in sound pressure that have a direct relationship to rotational speed can correspondingly occur at low frequencies, i.e. deep in the infrasound range. The creation of infrasound is described in detail in Appendix A.

The important distinction to keep in mind is that infrasound is generated at wind turbines through a process completely different to the generation of amplitude modulations.

5.3 Study objective

The aim of the study is to determine whether infrasound caused by wind turbines, even in the immission range,

- is measurable;
- is assignable to the wind turbines;
- leads to relevant noise levels.

The measurement equipment used and the measurement concept were selected specifically for purposes of measuring the amplitude modulations in Section 4.4. Additional measurements specifically targeting the contributions of infrasound were performed only during the last measurement campaign in Study Area 5.

Along with direct evaluation, the measurements in SA 5 will be used to determine results for infrasound from measurements in the other study areas as well.

5.4 Measurements in Study Area 5

5.4.1 Measurement procedure

In addition to the tripod-mounted Class-1 microphone, SA 5 also used an infrasound microphone on a ground plate to check the sound-measurement technology (see also Appendix F). Both parameters – measurement on the ground plate and measurement using an infrasound microphone – pose the disadvantage that they do not meet the requirements of the Technical Instructions on Protection Against Noise (1998) for measurements of audible sound. On the other hand, the measurement at low frequencies is less problematic with this measurement set-up; the disturbing influence of wind is less pronounced than on a tripod, and sensitivity at very low frequencies is greater than with a Class-1 microphone.

The measurements on the ground plate were carried out using a measuring system by the SINUS company with an infrasound microphone by Microtech Gefell. The view from the microphone on the ground plate to the nearest wind turbines can be seen in Figure 38.

Figure 38: Infrasound microphone on ground plate

Source: own presentation, deBAKOM GmbH

5.4.2 Lines in the sound-pressure spectrum

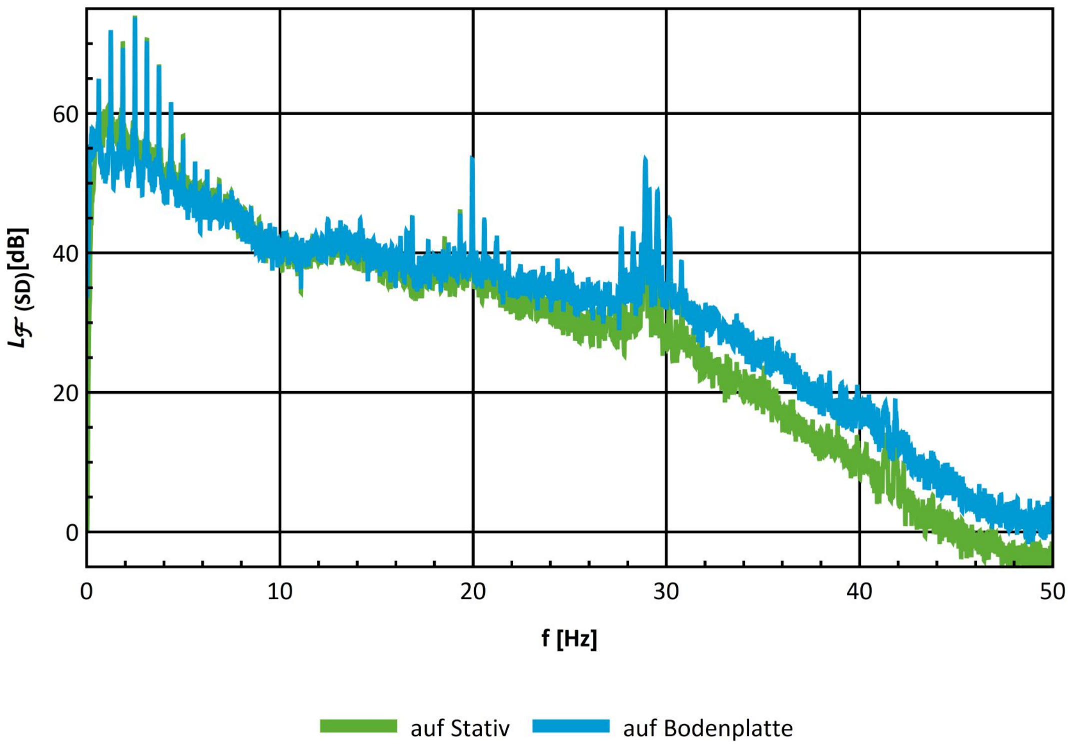
Wind turbines can produce infrasound that, in the clearest case, causes lines in the spectrum, with frequencies that correspond to the integral multiple of the rotational speed of the wind turbines multiplied by three. Three as a multiplier is obtained because a wind turbine has three rotor blades, and a fluctuation in pressure can occur each time a rotor blade passes the mast.

By way of example, Figure 39 shows the sound-pressure spectrum over a 10-minute segment. In an enlargement, Figure 40 shows the same spectrum in the range of up to 8 Hz. The comb-shaped lines in the spectrum are clearly discernible.

The selected time segment is neither random nor representative; it was selected precisely because it contains a particularly clearly discernible line structure.

Figure 39: Sound-pressure spectrum with individual lines

10 minutes on 14 December 2020 between 12:30 a.m. and 12:40 a.m. in Study Area 5. The spectrum is standardised in such a way that equivalence levels can be formed by integration over 1 Hz.

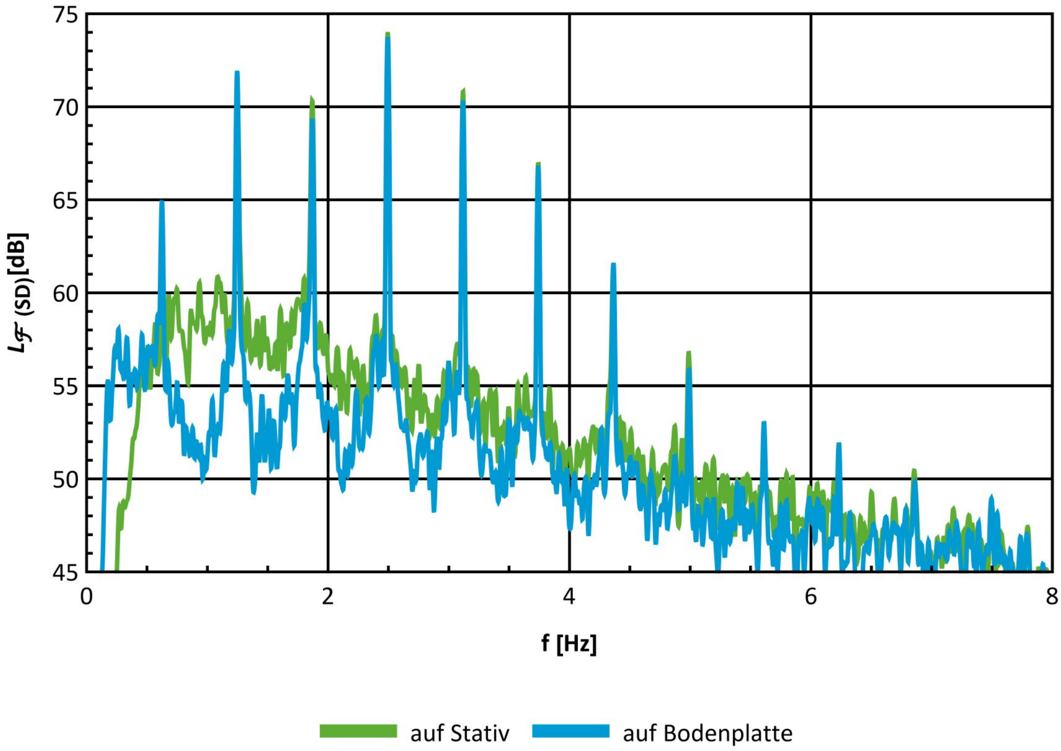


Source: own presentation, Dr. Kühner GmbH

auf Stativ = On tripod; auf Bodenplatte = On ground plate

Figure 40: Sound-pressure spectrum with individual lines, enlarged

Same time period as in Figure 39.



Source: own presentation, Dr. Kühner GmbH

auf Stativ = On tripod; auf Bodenplatte = On ground plate

There are no operating data available for the wind turbines in SA 5. However, if clearly identifiable AMs with a constant periodicity are measured, then the rotational speed of the system can be determined via the periodicity of the AM. In this case, the AMs were very stable over the time segment. This made it possible to determine the precise rotational speed of the wind turbine that caused the AM (see Appendix F.2.4). If the same wind turbine that causes the AM is also the dominant source of infrasound, then the rotational speed determined via the AM should match the frequencies of the lines in the infrasound spectrum.

The frequency determined via the AM and its harmonics, i.e. its integer multiples, are shown in Table 8; the equivalent sound-pressure levels of the lines in the spectrum are indicated alongside each. The correspondence between the frequencies of the lines in the infrasound spectrum and the integral multiples of the frequency of the AM is a clear indication of a common source.[4] A spectrum such as this, with a fundamental tone frequency that matches up with the rotational speed and further tones at integral multiples of this frequency, corresponds to what one would expect in a spectrum caused by the interaction between the rotor blades and mast of the wind turbines (see Appendix A.2).

[4] There are multiple wind turbines in SA 5 that cause immissions at the measuring location. It is not possible to ascertain whether the immissions in the selected time segment were caused by exactly one turbine, or whether several turbines were running at the same precise speed. With frequency determination so acute, wind turbines would also be a proven source if the AM were caused by one turbine and the infrasound by the other turbines.

Table 8: Frequencies of AM and lines in the infrasound range

		Tripod		Ground plate	
n	n * f_{AM} [Hz]	f [Hz]	$L_{Zeq,line}$ [dB]	f [Hz]	$L_{Zeq,line}$ [dB]
1	0.624			0.624	53.5
2	1.247	1.247	60.0	1.247	60.5
3	1.871	1.869	58.9	1.871	58.0
4	2.494	2.494	62.6	2.494	62.3
5	3.118	3.118	59.4	3.118	58.9
6	3.742	3.740	55.6	3.740	55.4
7	4.365	4.362	50.0	4.363	50.2
8	4.989	4.989	45.4	4.990	44.5
31	19.331	19.324	34.8	-	-
32	19.955	19.951	41.6	19.951	42.0

In addition to the lines shown in Table 8, further lines not matching the integral multiples of the fundamental frequency can be seen in the spectrum (Figure 39) in the region just below 30 Hz. The wind turbines measured have a gearbox with a transmission ratio that leads to a frequency of 28.940 Hz as a result of rotational speed multiplied by transmission ratio. 28.917 Hz and 41.9 dB were measured in this frequency range using the ground plate. While the assignment is thus far from as clear as for the integer multiples of the fundamental tone in Table 8, transmission noises are a possible explanation for the lines in the range of around 30 Hz.

5.4.2.1 Frequency response and confidence intervals

When measuring audible sound, the properties of the measurement systems are ensured in accordance with DIN EN 61672-1. No specific standard applies to the measurement of infrasound, and at low frequencies, a DIN EN 61672-1 Class 1-compliant system may show practically arbitrarily large deviations.

In order to determine the sensitivity of the measuring systems more precisely, the low-frequency response was determined for the deBAKOM measurement system and for the SINUS measurement system, in each case in a pressure-chamber measurement; the details are presented in Appendix F.1.2.

Frequency responses determined by pressure-chamber measurement and the comparison of the simultaneous measurements result in confidence intervals for the sound levels specified.

Taking the frequency responses of the measurement systems into account yields the following results:

- for the line at 1.247 Hz, a confidence interval of approx. 62 to approx. 84 dB,
- for the line at 2.494 Hz, a confidence interval of approx. 62 to approx. 72 dB,
- for the line at 3.742 Hz, a confidence interval of approx. 54 to approx. 61 dB,
- for the line at 4.989 Hz, a confidence interval of approx. 44 to approx. 49 dB.

The confidence intervals grow narrower and narrower with increases in frequency, and the deviations between the measured level and the centre of the confidence interval grow smaller and smaller.

5.4.2.2 Uncertainties

Together with the uncertainty of the measurement due to the frequency response, wind is the prime source of uncertainty. As frequency decreases, local fluctuations in pressure due to wind lead to increasing disturbances. This can be seen in the spectrum in Figure 39 , particularly in the background below the individual lines. Because measurements at the ground plate are exposed to fewer wind effects, the background below the individual lines is significantly lower than for the tripod-based measurements.

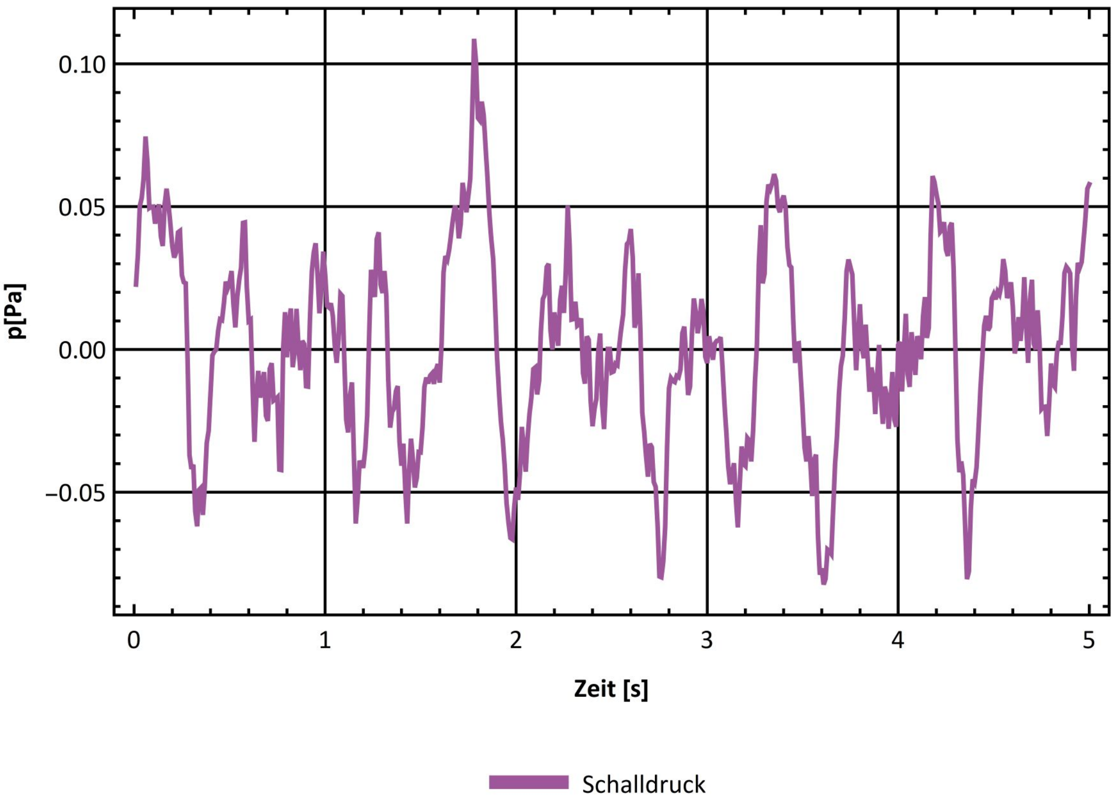
This background raised by wind can influence the levels specified for lines in Table 8. The level offset of the line from the background at 4.9 Hz, for example, is small enough to explain the 1-dB deviation of the measurement between the base plate and the tripod. In the case of lines below 4 Hz, the offset between the line maximum and the background exceeds 10 dB, i.e. a contribution from wind would distort the result by less than 0.5 dB.

In the time interval selected for the example, the signal is particularly clear and the disturbance due to wind particularly weak. In the statistical evaluations across all measuring times, the disturbances caused by wind are particularly taken into account in the following.

5.4.3 Periodic pressure fluctuations

The sound pressure curve for a time segment from the sample time used above is presented in Figure 41. The cause of the noise emissions of wind turbines in the infrasound range, and thus the individual lines that emerge in the spectrum, are fluctuations in air pressure, as in all other processes involving sound pressure. The more periodic these fluctuations are, the finer the lines in the spectrum become. Although the lines in the spectrum in Figure 40 are very clear, in the time segment shown in Figure 41 it can be seen that the individual fluctuations differ quite clearly from one another in this example as well.

Figure 41: Profile of the sound-pressure level over time



Source: own presentation, Dr. Kühner GmbH

Schalldruck = Sound pressure

To compare levels in the spectrum and the sound-pressure record, the energetic sum of the levels of the individual lines in Table 8 is formed, resulting in an L_{Zeq} of 66.9 dB. This corresponds to a sound pressure of 0.044 Pa. The maximum sound pressure in the sample period is 0.12 Pa, and the corresponding maximum pressure level is 75.5 dB. This maximum pressure level must not be confused with an equivalence level that corresponds to the average sound pressure square and is therefore always lower.

The sound pressures shown are the readings measured; the frequency response cannot be taken into account in an effort to estimate a 'true' sound pressure curve.

5.4.4 Measurement results: Long-duration measurement on ground plate

5.4.4.1 Frequency distributions of low-frequency sound

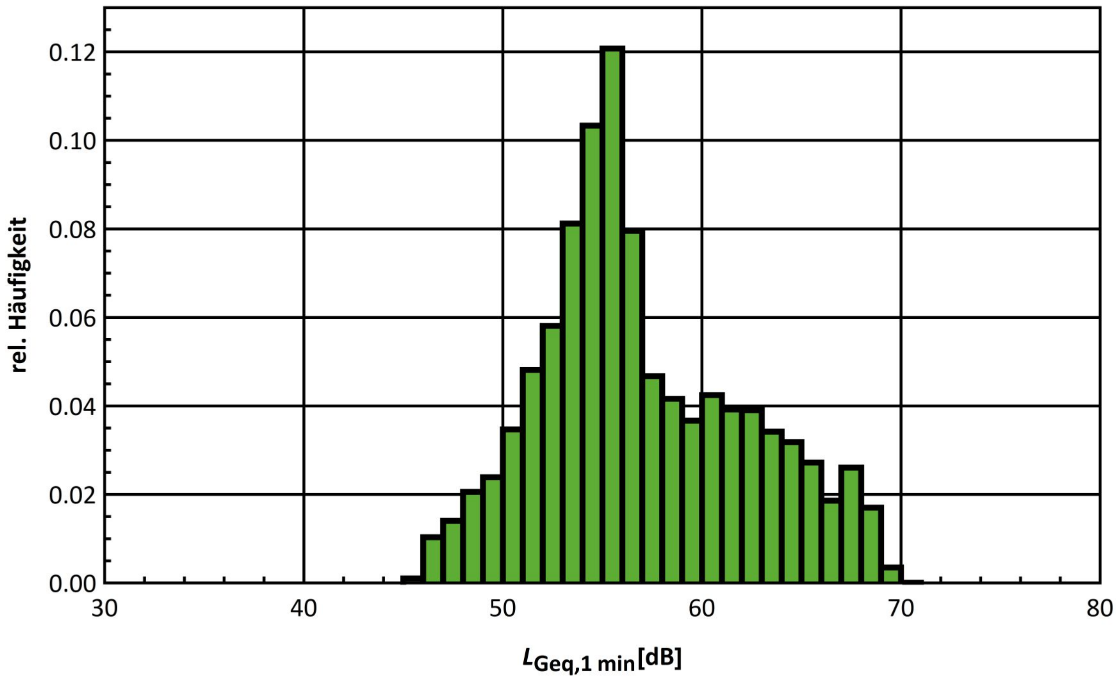
A variety of levels can be created for use in analysing infrasound. Audible sound is generally A-weighted, for example, because A-weighting approximates the sensitivity of human hearing at different frequencies. In this case, it is assumed that different noises with the same A level are annoying on a roughly equal scale, even at different frequencies.[5] Because the approach of A-

[5] This assumption has its limits, because assessment adjustments for tonality, impulsiveness or information content should be applied precisely where the pure A-weighted level does not sufficiently reflect the equivalent degree of annoyance experienced with noises with the same level. The question of the particular annoyance level of periodically amplitude-modulated noise is the central topic of this study.

weighting does not transfer over in the range of very low frequencies, G-weighting was introduced here (ISO 7196). While A-weighting reacts with the greatest sensitivity to sounds at around 1000 Hz and grows less sensitive in response to high and low frequencies as in the case of human hearing, the G-weighting is most sensitive at 20 Hz, i.e. reacts particularly to the low tones at the juncture between infrasound and audible sound.

By way of example, Figure 42 presents the frequency distribution of G-weighted levels for SA 5. As the assessment curve used for G-weighting is not identical to that used for A-weighting, the numerical values are not directly comparable. To classify the values, the rough assumption can be made that the level of a tone at 20 Hz must exceed 80 dB if the sound is to cross over the auditory threshold, while higher-frequency noises can be audible even at lower G-weighted levels.

Figure 42: Frequency distribution of G-weighted levels in SA 5



Source: own presentation, Dr. Kühner GmbH

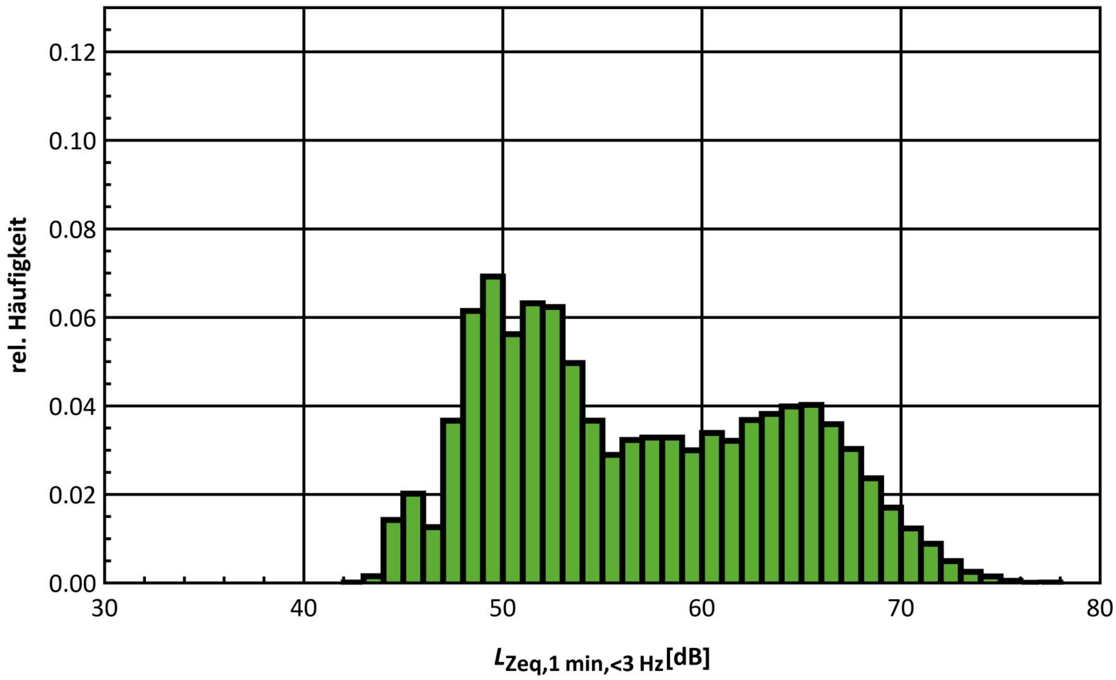
rel. Häufigkeit = Relative frequency

Based on G-weighted levels and absent further information about frequency content, it is not possible to read anything directly about how great the contribution at low frequencies actually is; hence, Z-weighted levels for different frequency bands are used below. The bands selected were

- $L_{Zeq,<3Hz}$ very low frequencies
- $L_{Zeq,4\text{-}7Hz}$ the extended infrasound range
- $L_{Zeq,4\text{-}20Hz}$ the classic infrasound range
- $L_{Zeq,25\text{-}80Hz}$ low frequencies above the infrasound range

Figure 43 through Figure 46 presents the frequency distributions for noise levels in the four bands.

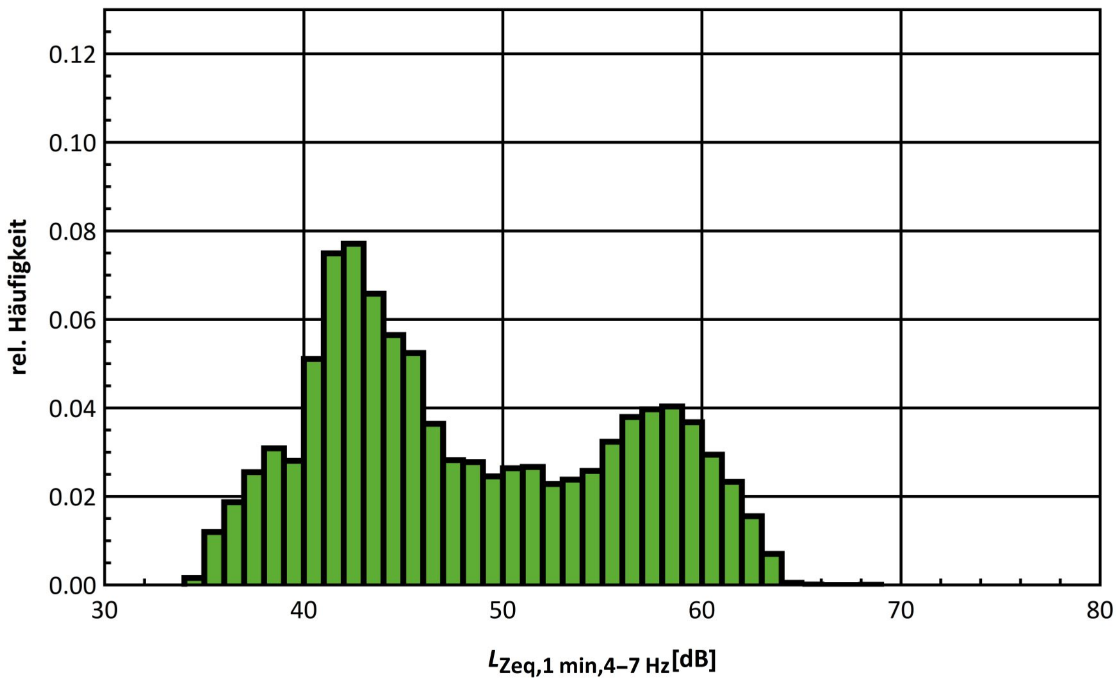
Figure 43: Frequency distribution of levels for band up to 3 Hz in SA 5



Source: own presentation, Dr. Kühner GmbH

rel. Häufigkeit = Relative frequency

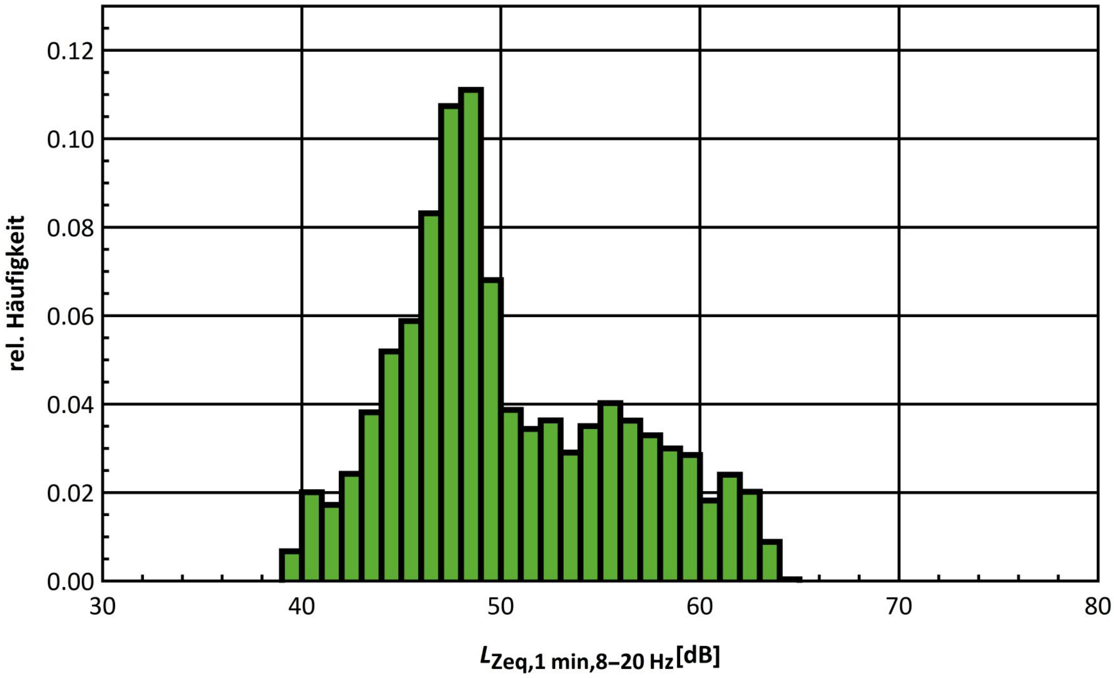
Figure 44: Frequency distribution of levels for band up to 4 to 7 Hz in SA 5



Source: own presentation, Dr. Kühner GmbH

rel. Häufigkeit = Relative frequency

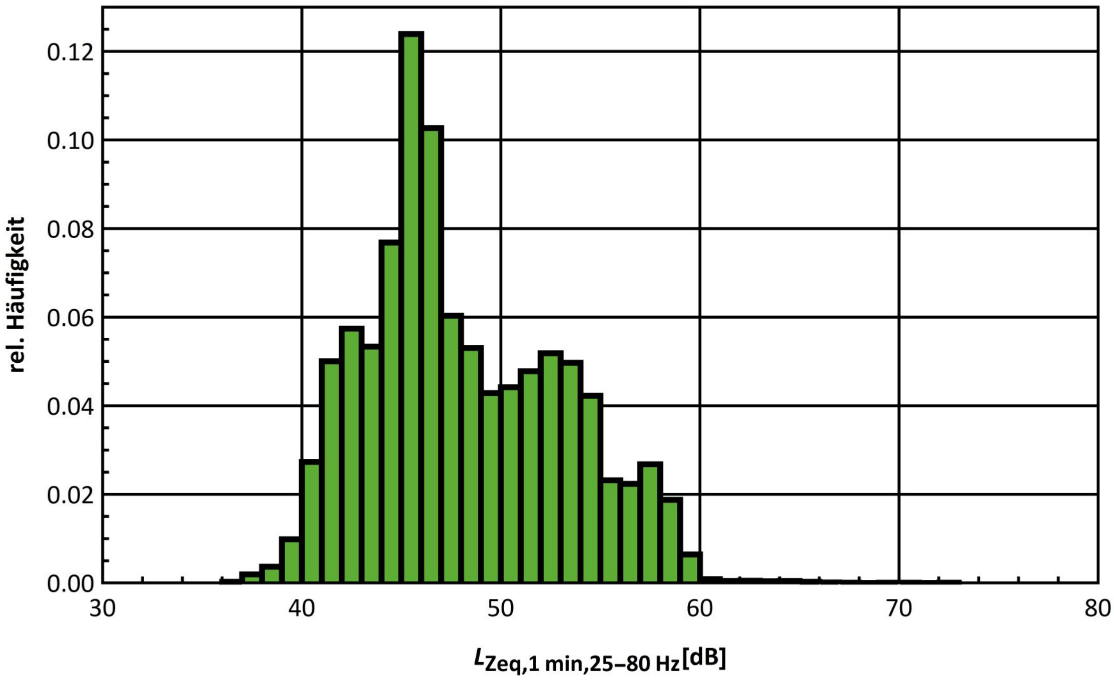
Figure 45: Frequency distribution of levels for band up to 8 to 20 Hz in SA 5



Source: own presentation, Dr. Kühner GmbH

rel. Häufigkeit = Relative frequency

Figure 46: Frequency distribution of levels for band up to 25 to 80 Hz in SA 5



Source: own presentation, Dr. Kühner GmbH

rel. Häufigkeit = Relative frequency

Table 9: Confidence intervals: Level on ground plate

Effect of measurement sensitivity on the bands formed/assessment taking the shape of the spectra into account

Band/assessment	Rel. Confidence interval
G	-0.5 to +2.0 dB
<3 Hz	+3 dB to +23 dB
4-7 Hz	-0.5 dB to +3.5 dB
8-20 Hz	-0.5 dB to +1.5 dB
25-80 Hz	-0.5 to +0.5 dB

5.4.4.2 Assessment of the frequency distributions

The levels shown in Figure 42 through Figure 46 are the levels measured for the bands. The confidence intervals for these bands can be determined from the confidence intervals of the individual one-third-octave (Appendix F.3.4).

In terms of the measured level, a relative confidence interval results in each case; the values are shown in Table 9.

This means, for example, that an $L_{\mathrm{Zeq},<3\ \mathrm{Hz}}$ of 72 dB has a confidence interval of 75 dB to 95 dB.

DIN 45680 (1997) specifies auditory thresholds:

- For frequencies of up to 8 Hz: >103 dB
- For frequencies of up to 20 Hz: >71 dB
- For frequencies of up to 80 Hz: >28 dB

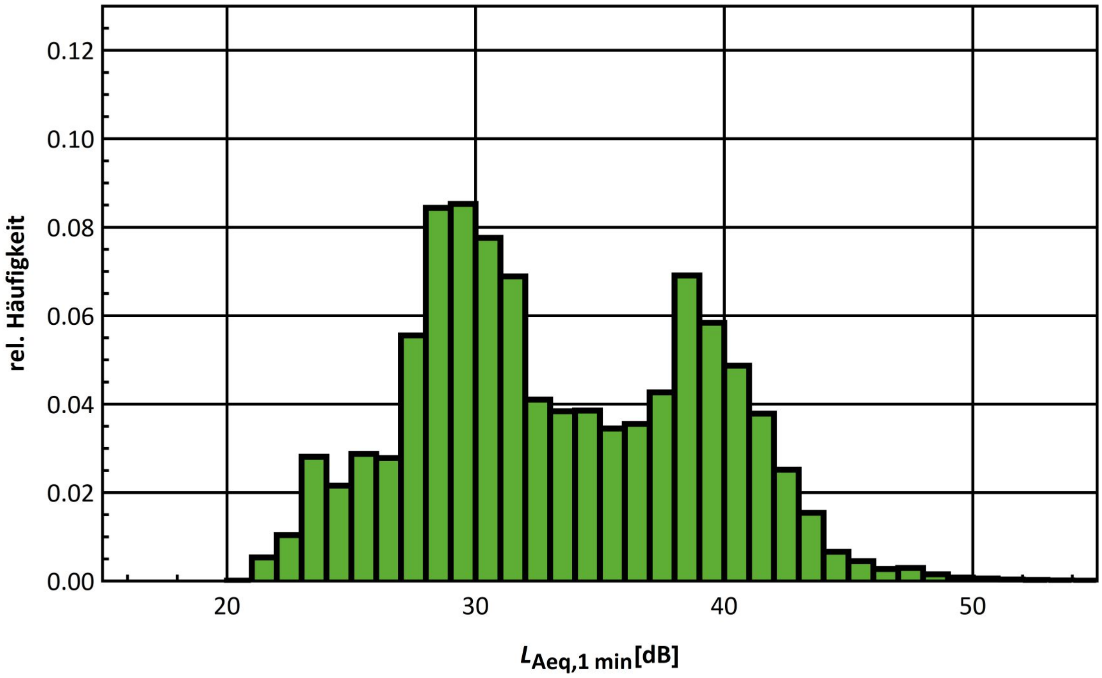
All levels for the bands up to 20 Hz lie in ranges below the auditory thresholds specified in DIN 45680. The upper limits of the confidence intervals for these levels also lie below the auditory or perception thresholds.

As the band of 25 to 80 Hz lies above the infrasound range, it falls in the range of low-frequency audible sound. The levels shown in Figure 46 are largely above the auditory threshold, i.e. while the measured infrasound falls below the auditory threshold, low-frequency audible sound occurs at levels that render it audible.

5.4.4.3 Frequency distributions of audible sound

For purposes of comparison with the sound-pressure levels for low-frequency sound, the frequency distribution of the A-weighted level is shown in Figure 47. The same times as those involved in the other figures are taken into account. Extraneous noise detection to exclude measuring times was not applied. Hence, the levels shown may contain wind noise and the noise of nocturnal birds found in local vegetation.

Figure 47: Frequency distribution of A-weighted levels in SA 5

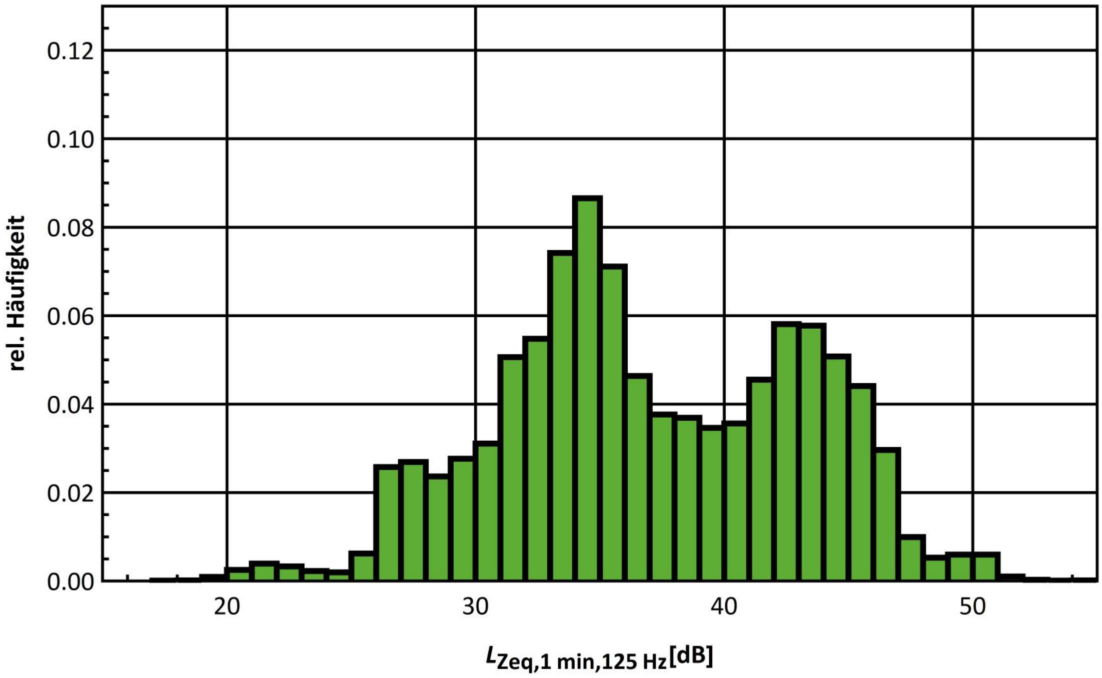


Source: own presentation, Dr. Kühner GmbH

rel. Häufigkeit = Relative frequency

If wind turbines cause immissions, they typically have a maximum of around 125 Hz in audible sound. In order to determine what the wind turbines' contribution to audible sound looks like, Figure 48 shows the frequency distribution for the 125-Hz band. This frequency distribution presents two maxima, similar to the frequency distribution of the A-weighted levels. However, the influence of extraneous noise on the 125-Hz band is significantly smaller than it is on the A-weighted level, as most extraneous noise occurs at higher frequencies. Birds specifically cause immissions at much higher frequencies and for this reason can be ruled out as a source for the second maximum in the frequency distribution.

Figure 48: Frequency distribution of levels for the 125-Hz band in SA 5



Source: own presentation, Dr. Kühner GmbH

rel. Häufigkeit = Relative frequency

All in all, the frequency distributions of all levels show roughly two maxima. A possible reason for such distributions may be that the maximum at the right is the result of a temporarily active source, while the maximum at left is traceable to the background distribution without the additional source. The following examines whether wind turbines can be considered to be this additional source – even in the infrasound range.

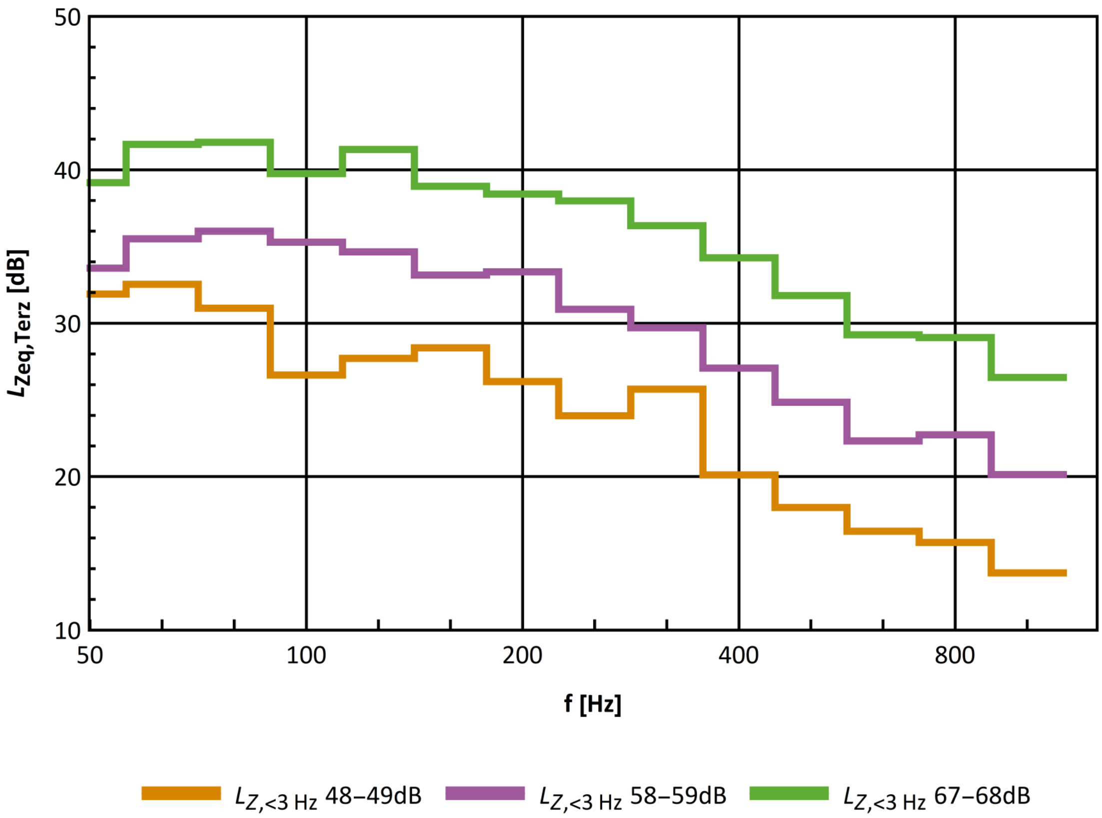
5.4.4.4 The relationship between audible sound and infrasound

Section 5.4.2 presented a single-case consideration of whether the wind turbines in SA 5 cause infrasound at the expected frequencies. The question to be considered now is whether the levels in the infrasound range bear a systematic relationship to the output levels of wind turbines. For this purpose, and representative for the infrasound measured, $L_{\mathrm{eqZ,<3Hz}}$ is shown as the total of sound-pressure levels in the frequency range of 0.5 to 3 Hz.

The one-third-octave spectra for three $L_{\mathrm{eqZ,<3Hz}}$ are presented in Figure 49 ($L_{\mathrm{eqZ,<3Hz}}$ = 48 to 49 dB, $L_{\mathrm{eqZ,<3Hz}}$ = 58 to 59 dB and $\mathrm{L}_{\mathrm{eqZ,<3Hz}}$ = 67 to 68 dB). Because the levels in the one-third-octave spectra also apparently increase with increases in $L_{\mathrm{eqZ,<3Hz}}$ in the vicinity of audible sound (shown here between 50 Hz and 900 Hz), it is assumed that the strength of the infrasound signal could have something to do with the strength of audible sound. The three spectra could then be ascribed to different turbine states – low load, medium load and high load.

Figure 49: One-third-octave spectra in the audible-sound range in SA 5

1-minute one-third-octave spectra according to $L_{eqZ,<3Hz}$. Each of the spectra shown was specified by combining all spectra for 1-minute blocks during the period from 11:00 p.m. through 5:00 a.m. with the selected $L_{eqZ,<3\,Hz}$ and forming the 70% percentile.



Source: own presentation, Dr. Kühner GmbH

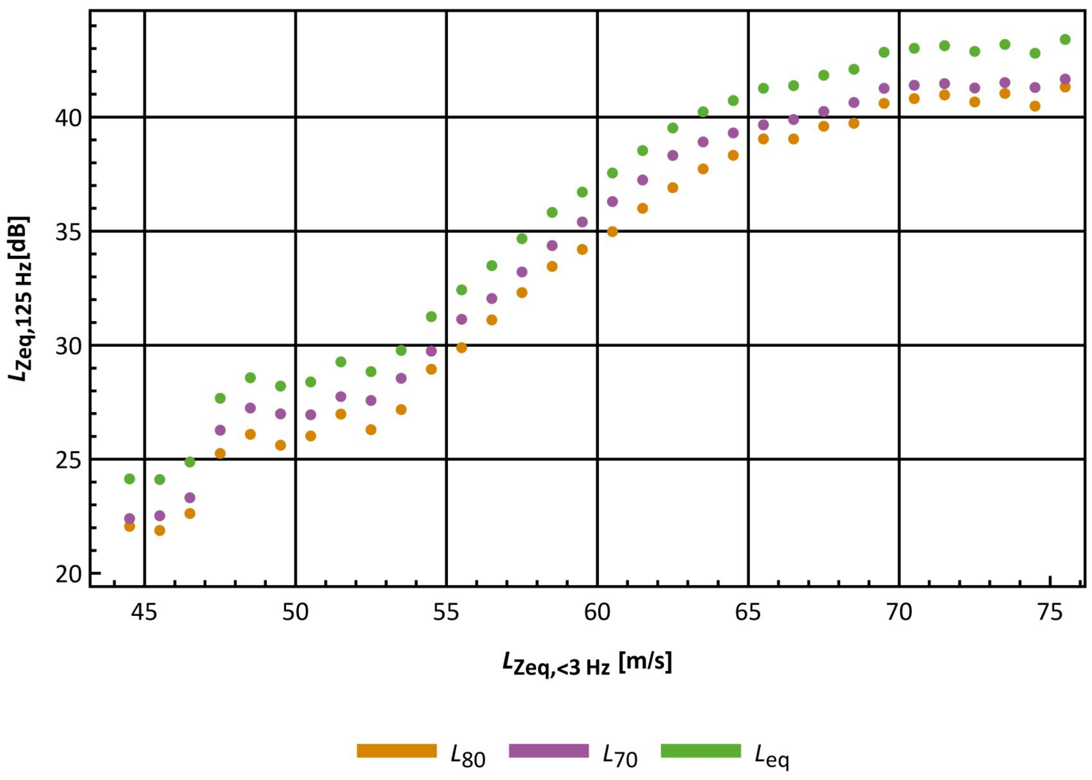
L_{Zeq},Terz[dB] = L_{Zeq}, one-third-octave[dB]

The level at 125 Hz also increases considerably with an increase in $L_{eqZ,<3Hz}$. For simplicity's sake, it is assumed that the level at 125 Hz is representative of immissions of audible sound from the wind turbines. Although this is a vastly simplified assumption, it can be claimed that typical emission data from wind turbines exhibit relatively vast emissions of sound in the audible range of around 125 Hz.

The level within the 125-Hz band is plotted against infrasound level $L_{eqZ,<3Hz}$ in Figure 50. From this it can be seen that the audible sound level also increases at 125 Hz as the level of infrasound increases. At low sound levels, on the other hand, there is presumably interference in the audible-sound range that will change the correlation. The rise in the audible sound flattens out in the upper region. A likely explanation for this is that wind turbines' emissions flatten out as wind speed increases, and do not increase further because the rotors of the wind turbines are controlled accordingly, whereas the disturbance generated through the flow between rotor and mast increases further as wind speed increases.

Figure 50: Level of audible sound against infrasound

$L_{Zeq,125Hz}$ at the tripod-mounted Class-1 microphone as representative of wind turbine noise against $L_{Zeq,<3Hz}$ at the infrasound microphone on the ground plate as representative of the infrasound. The 80% and 70% percentiles and the equivalence level are shown in each case.



Source: own presentation, Dr. Kühner GmbH

5.5 Extending the investigations to SA 1 to 4

5.5.1 Measurements with Class-1 microphone

Measurements in study areas SA 1 to 4 were performed using only a Class-1 microphone mounted on a tripod. The drawback that this poses for infrasound investigations is that the microphone's sensitivity decreases significantly at very low frequencies – hence, the levels the measuring system identifies are lower than they actually are. In addition, the greater altitude exposes the microphone to more wind and turbulence, and this can lead the microphone to record signals not caused by the wind turbines.

5.5.2 Comparison of the measuring systems

To estimate infrasound levels in SA 1 to 4 despite the drawbacks mentioned above, the two measuring systems (infrasound microphone on a ground plate and Class-1 microphone on a tripod) were compared with one another. This was done by way of example in SA 5. Both measuring systems were used simultaneously for the entire measurement period of approx. 8 weeks (photo in Figure 51). The two measuring systems were also compared under laboratory conditions. The procedure for comparing the two measuring systems and determining the confidence intervals is described in Appendix F.

To illustrate the influence of local wind on the measurements performed with the tripod-mounted microphone, Figure 52 shows difference spectra between simultaneous measurements made at microphone level and at different wind speeds using a tripod-mounted Class-1 microphone, on the one hand, and an infrasound microphone on a ground plate on the other. Positive values mean that the level at the microphone on the tripod is higher than at the microphone on the ground plate; negative values for level, accordingly, indicate that higher values were measured at the infrasound microphone on the ground plate.

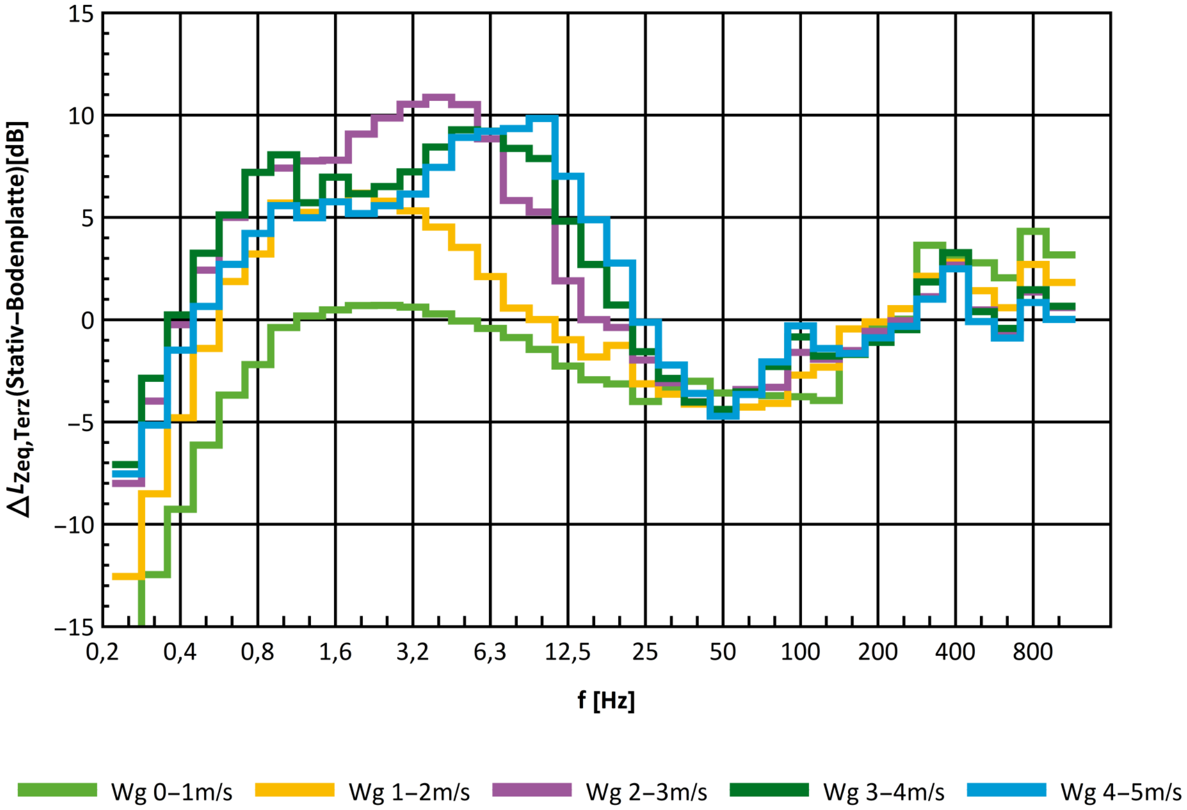
At low frequencies, it appears that the sensitivity of the infrasound microphone is greater than that of the Class-1 microphone. The difference spectrum is negative here. The wind has an additional strong influence on the difference spectrum. Levels in the one-third-octave bands increase considerably, even at low local wind speeds. Hence, local wind conditions must be taken into account before conclusions can be drawn about infrasound immissions at locations SA 1 to SA 4 based on measurements taken with the Class-1 microphones.

Figure 51: Measurement on the ground plate alongside measurement on a tripod

Source: own presentation, deBAKOM GmbH

Figure 52: 80% percentile of the difference spectra (tripod-ground plate) for different wind speeds

For the intervals from 11:00 p.m. until 5:00 a.m., 1-minute spectra were measured for each of the two measuring systems and the difference calculated. This shows 80th percentiles for different wind speed classes at the level of the Class-1 microphone.



Source: own presentation, Dr. Kühner GmbH

$\Delta L_{Zeq,Terz}$(Stativ-Bodenplatten)[dB] = $\Delta L_{Zeq,one\text{-}third\text{-}octave}$(tripod-ground plates)[dB]; Wg 0-1m/s = Wind speed 0-1m/s; Wg 1-2m/s = Wind speed 1-2m/s; Wg 2-3m/s = Wind speed 2-3m/s; Wg 3-4m/s = Wind speed 3-4m/s; Wg 4-5m/s = Wind speed 4-5m/s

5.5.3 Averaging level according to load conditions

According to the measurement on the ground plate, G-weighted sound levels L_{Geq} are formed, as are levels for several frequency bands:

- $L_{Zeq,<3Hz}$ very low frequencies
- $L_{Zeq,4\text{-}7Hz}$ the extended infrasound range
- $L_{Zeq,8\text{-}20Hz}$ the classic infrasound range
- $L_{Zeq,25\text{-}80Hz}$ low frequency above the infrasound range

To take the influence of wind during infrasound measurements using a tripod-mounted Class-1 microphone into account, extrapolations were made to local windless conditions; these are described in Appendix F. The results of these extrapolations for the different study areas are compiled in Table 10 to Table 14.

Table 10: L_{Geq} against wind speed at hub height in dB

The errors indicated are only the statistical errors from the extrapolation to local windless conditions.

Wind speed	SA 1	SA 2	SA 3E	SA 3I	SA 4E	SA 4I
0-2m/s	40.4±0.3	46.2±0.6		44.7±0.3	46.9±2.9	40.1±1.1
2-4m/s	38.9±0.3	48.9±0.6	54.1±0.5	46.6±0.9	50.3±1.1	49.0±0.7
4-6m/s	39.9±0.5	51.5±0.7	56.6±0.2	50.4±0.5	55.6±0.9	51.2±0.5
6-8m/s	43.4±1.0	58.3±0.9	64.1±2.5	51.7±1.1	62.3±0.8	56.0±0.4
8-10m/s	49.2±1.2	56.3±2.5	73.5±0.7	52.3±3.0	64.8±1.0	56.7±0.4
10-12m/s	56.6±2.2		79.5±6.6	51.9±4.8		51.4±6.1

Table 11: $L_{Zeq,<3Hz}$ against wind speed at hub height in dB

The errors indicated are only the statistical errors from the extrapolation to local windless conditions.

Wind speed	SA 1	SA 2	SA 3E	SA 3I	SA 4E	SA 4I
0-2m/s	33.3±0.8	39.3±2.2	41.3±3.1	43.3±0.5	41.0±1.0	32.3±2.9
2-4m/s	32.7±1.8	43.1±1.7	46.7±0.4	41.8±1.7	41.5±1.2	41.6±1.5
4-6m/s	36.0±1.5	54.6±2.2	52.2±0.5	46.0±1.6	49.7±3.0	41.5±2.9
6-8m/s	41.9±2.8	58.5±3.7	60.7±1.0	52.4±2.2	60.3±0.6	49.6±2.0
8-10m/s	48.8±3.7	58.3±5.0	64.8±1.3	54.1±5.4	60.1±2.1	54.9±1.7
10-12m/s	64.0±2.8		68.7±1.8	52.1±8.4	60.3±4.6	50.4±7.8

Table 12: $L_{Zeq,4\text{-}7Hz}$ against wind speed at hub height in dB

The errors indicated are only the statistical errors from the extrapolation to local windless conditions.

Wind speed	SA 1	SA 2	SA 3E	SA 3I	SA 4E	SA 4I
0-2m/s	32.7±0.4	36.1±1.8	37.8±1.9	40.1±0.7	39.3±1.4	33.9±1.3
2-4m/s	31.2±0.8	41.0±1.2	41.8±0.3	40.6±0.8	38.8±1.3	40.8±0.8
4-6m/s	32.2±1.1	48.6±1.6	46.7±0.7	43.4±0.9	46.4±1.7	40.7±1.7
6-8m/s	39.6±1.9	51.4±3.5	57.0±1.1	48.4±1.5	53.6±1.6	48.5±1.4
8-10m/s	48.0±1.7	51.3±4.8	60.3±1.2	49.2±4.4	58.1±1.0	50.2±1.5
10-12m/s	53.7±3.9		67.1±2.3	47.3±7.0	53.1±5.7	48.3±6.6

Table 13: $L_{Zeq,8\text{-}20Hz}$ against wind speed at hub height in dB

The errors indicated are only the statistical errors from the extrapolation to local windless conditions.

Wind speed	SA 1	SA 2	SA 3E	SA 3I	SA 4E	SA 4I
0-2m/s	34.3±0.3	40.5±0.5			42.6±1.5	34.8±1.0
2-4m/s	32.7±0.5	43.4±0.7	46.6±0.6	41.9±0.7	43.9±1.0	43.2±0.5
4-6m/s	33.6±0.6	47.2±0.8	49.1±0.6	45.2±0.5	49.7±0.9	43.7±0.8
6-8m/s	38.1±1.3	53.3±1.3	58.0±2.3	46.8±1.2	55.6±0.8	49.0±0.7
8-10m/s	43.5±1.5	51.3±3.0	64.0±1.0	47.2±3.4	58.8±1.3	49.4±0.6
10-12m/s	51.1±2.9		64.1±2.3	47.1±5.3		

Table 14: $L_{Zeq,25\text{-}80Hz}$ against wind speed at hub height in dB

The errors indicated are only the statistical errors from the extrapolation to local windless conditions.

Wind speed	SA 1	SA 2	SA 3E	SA 3I	SA 4E	SA 4I
0-2m/s	34.4±0.5	32.5±0.3			37.5±1.9	27.5±0.7
2-4m/s	35.2±0.2	36.5±0.3	44.4±0.4	35.5±0.5	44.7±0.3	36.8±0.8
4-6m/s	36.0±0.3	38.2±0.8	47.7±0.7	39.0±0.3	47.1±0.6	39.6±0.5
6-8m/s	37.8±0.2	44.3±0.4	55.7±0.6	40.2±0.6	52.0±0.6	44.2±0.2
8-10m/s	37.3±0.8	41.8±1.7	55.8±1.0	38.8±2.0	54.6±0.9	45.0±1.0
10-12m/s	44.2±1.1	44.2±5.3	60.9±4.1	40.9±2.6	49.0±4.8	40.5±6.1

The errors indicated in each of the tables are the statistical errors that result from the extrapolation. Some statistical uncertainties are considerable at higher wind speeds. This is due to the fact that, if wind speeds are high at hub height, low wind speeds at microphone height occur only rarely. Values if wind speed at hub height is even higher were measured but not included due to the high uncertainties involved.

The same applies to the question of the dependence of the levels on wind direction. Just as levels can be determined for all wind directions, it is also possible to calculate in individual classes of wind direction (i.e. tailwind, headwind, crosswind). The data sets to which this leads are so small, however, that the results are no longer significant.

Table 15: Confidence intervals: Level on tripod

Effect of measurement sensitivity on the bands formed/assessment taking the shape of the spectra into account

Band/assessment	Rel. confidence interval
G	+1.5 to +5.0 dB
<3 Hz	+10 dB to +29 dB
4-7 Hz	+1.5 dB to +7.0 dB
8-20 Hz	+1.5 dB to +4.5 dB
25-80 Hz	+1.5 to +3.5 dB

5.5.3.1 Uncertainties and frequency response

The levels shown in Table 10 through Table 14 are the levels measured for the bands from an extrapolation. The confidence intervals for these bands consist of several parts. The composition of confidence ranges of the individual one-third-octaves (Appendix F.3.4) and confidence intervals due to the distribution ranges in the wind-speed classes are shown in Table 15. Added to this in each case are the errors indicated in the tables due to extrapolation to local windless conditions.

5.5.3.2 Assessing the load-dependent averaging levels

Levels at all measuring locations increase with increasing wind-turbine output. This means that wind turbines' contribution to infrasound can be shown at all measuring locations.

As can be seen from the tables – and as expected – in the study areas in which both emission and immission measurements were carried out, the levels in the emission range are always higher than in the immission range. There is a slight tendency for the decrease in levels to be less pronounced at lower frequencies than at higher frequencies. For example, at a wind speed of 8 to 10 m/s in SA 3, the difference between emission and immission measurement for $L_{\mathrm{Zeq,25\text{-}80Hz}}$ is approx. -15 dB and for $L_{\mathrm{Zeq,<3Hz}}$ approx. -10 dB. This tends to track with expectations based on theoretical considerations (Kühner (2016)).

The infrasound levels measured in the immission areas are below the auditory thresholds for all SA. Even if the upper limits of the confidence intervals are taken into account, the values fall below the auditory thresholds.

If the wind turbines are in operation, low-frequency audible sound in the frequency band of 25 to 80 Hz crosses the auditory threshold.

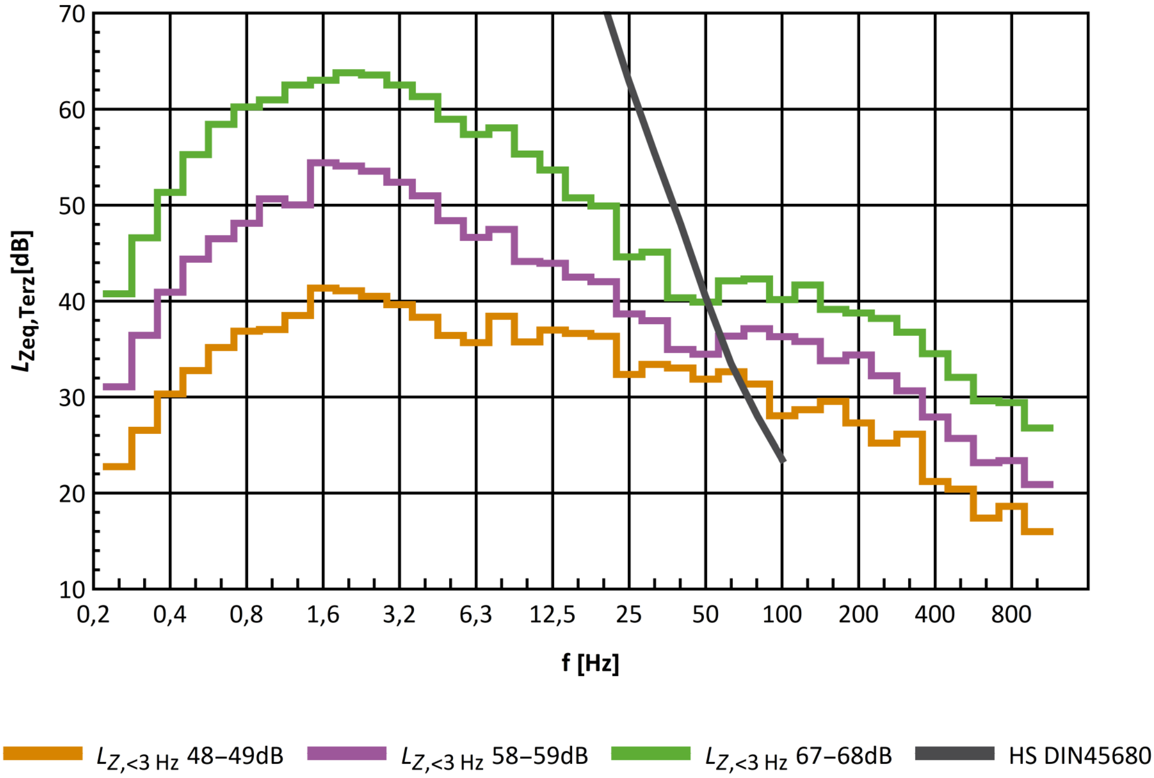
5.6 One-third-octave spectra

5.6.1 One-third-octave spectra in SA 5

One-third-octave spectra were also determined as part of the measurement campaign. For SA 5, it was possible to take readings directly with the infrasound microphone on the ground plate – with little wind influence – over a period of approx. eight weeks. Figure 53 shows the one-third-octave spectra for three different classes of noise level. Since there are no operating data available for these wind turbines, the classification is based on three ranges of $L_{\mathrm{Zeq,<3Hz}}$, representing wind turbines with a small load, medium load and rated load.

Figure 53: One-third-octave spectrum measured for low load, medium and large load, SA 5

Assuming that the infrasound level is representative of wind turbine output, one-third-octave spectra were created for time periods with three different level classes for $L_{Zeq.<3Hz}$.



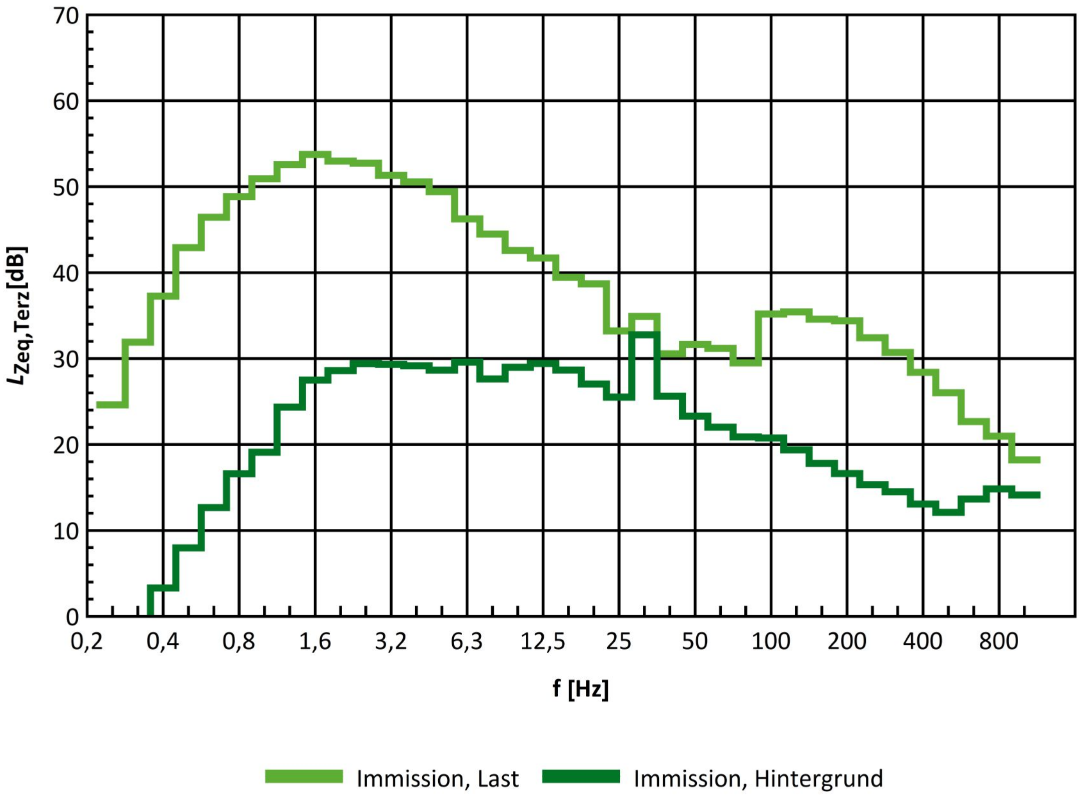
Source: own presentation, Dr. Kühner GmbH

$\Delta L_{Zeq,Terz}$[dB] = $\Delta L_{Zeq,one\text{-}third\text{-}octave}$[dB]

5.6.2 One-third-octave spectra in SA 1 to 4

In the other study areas, the data from the wind turbines can be used. In order to determine one-third-octave spectra with the smallest possible wind influence, times are selected in which local wind speeds are as low as possible. A distinction is made between times when the wind turbines did not supply any energy and times when the wind turbines are operating at rated output, with a wind speed of 8 to 10 m/s at hub height. The measurement results for SA 1 to 4 are presented in Figures 46 to 49.

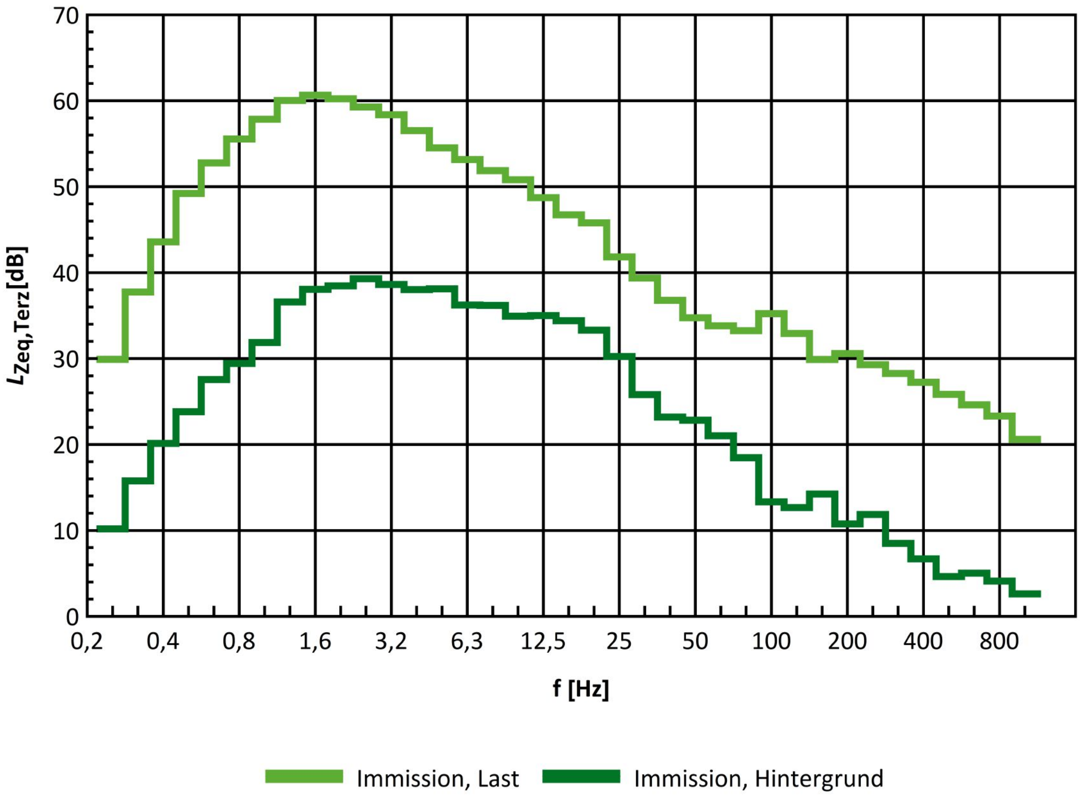
Figure 54: One-third-octave spectrum calculated for background and wind turbines at rated output, SA 1



Source: own presentation, Dr. Kühner GmbH

$\Delta L_{Zeq,Terz}$[dB] = $\Delta L_{Zeq,one\text{-}third\text{-}octave}$[dB]; Immission, Last = Immission, load; Immission, Hintergrund = Immission, background

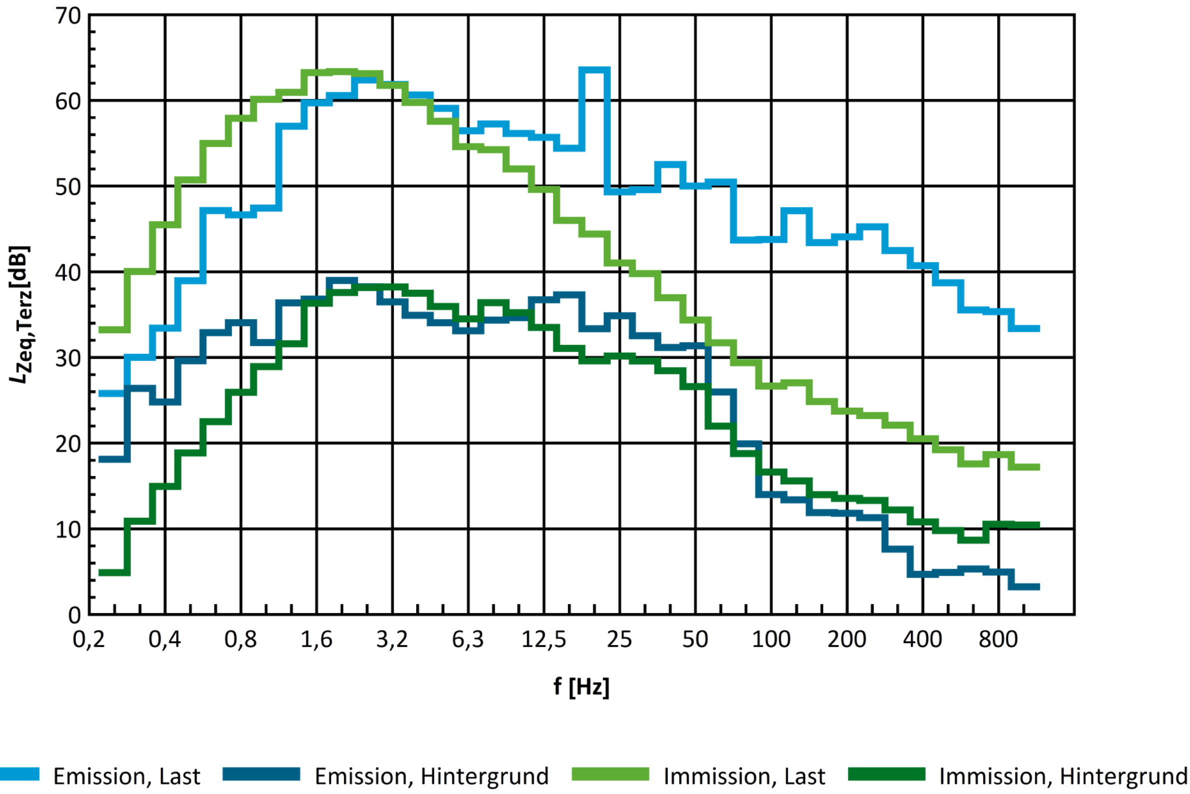
Figure 55: One-third-octave spectrum calculated for background and wind turbines at rated output, SA 2



Source: own presentation, Dr. Kühner GmbH

$\Delta L_{Zeq,Terz}$[dB] = $\Delta L_{Zeq,one\text{-}third\text{-}octave}$[dB]; Immission, Last = Immission, load; Immission, Hintergrund = Immission, background

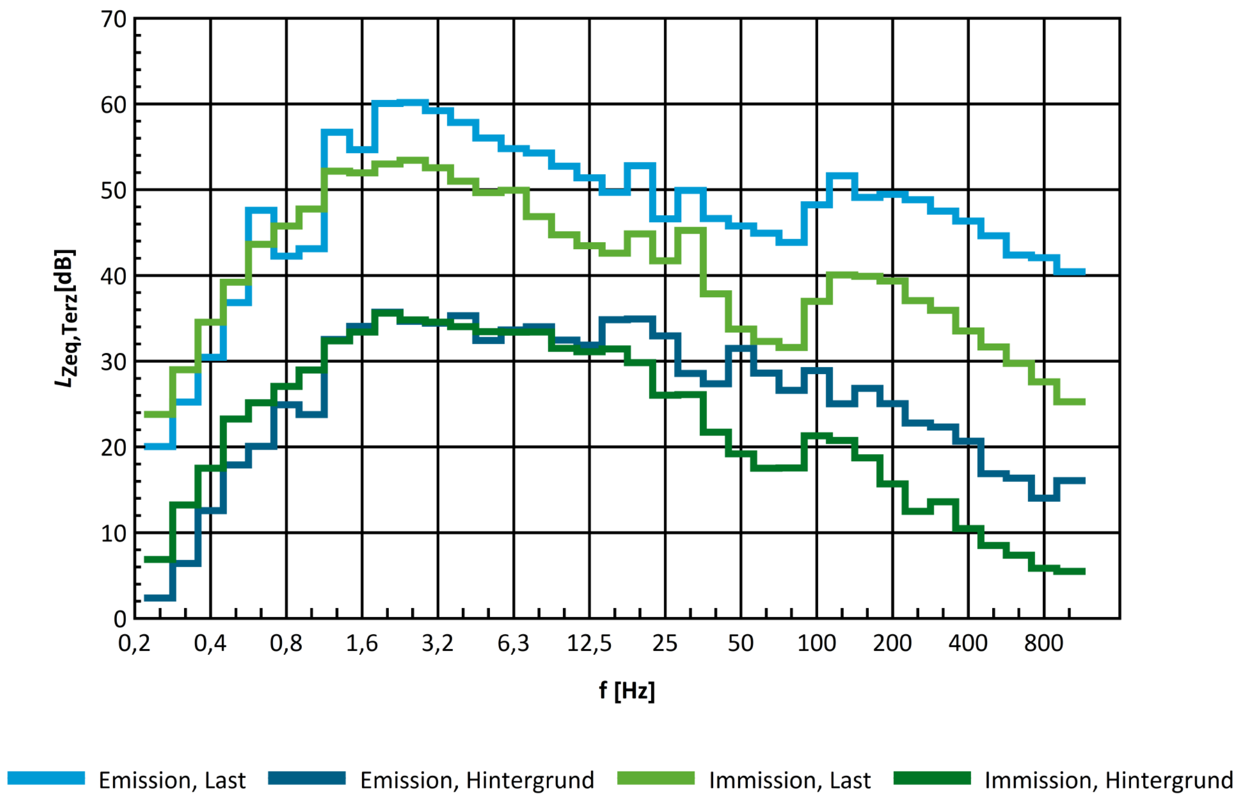
Figure 56: One-third-octave spectrum calculated for background and wind turbines at rated output, SA 3



Source: own presentation, Dr. Kühner GmbH

$\Delta L_{Zeq,Terz}$[dB] = $\Delta L_{Zeq,one\text{-}third\text{-}octave}$[dB]; Emission, Last = Emission, load; Emission, Hintergrund = Emission, background; Immission, Last = Immission, load; Immission, Hintergrund = Immission, background

Figure 57: One-third-octave spectrum calculated for background and turbines at rated output, SA 4



Source: own presentation, Dr. Kühner GmbH

$\Delta L_{Zeq,Terz}$[dB] = $\Delta L_{Zeq,one\text{-}third\text{-}octave}$[dB]; Emission, Last = Emission, load; Emission, Hintergrund = Emission, background; Immission, Last = Immission, load; Immission, Hintergrund = Immission, background

5.6.3 Frequency response and uncertainties

The frequency responses set out in Appendix F concern measurements made using an infrasound microphone on a ground plate and a Class-1 microphone on a tripod. The presentation does not include these data, i.e. at low frequencies, the one-third-octave levels are reduced due to the frequency responses.

For each of the measurements in UG 1 to UG 4, the times with the lowest local wind strengths were taken into account, but the remaining influence due to local wind was not removed (e.g. by extrapolation). Hence, one-third-octave levels may be elevated by 1 to 5 dB at low frequencies.

5.6.4 Assessing the one-third-octave spectra

In all cases, the one-third-octave spectra in the infrasound range are significantly below the auditory threshold.

The auditory threshold is only crossed at frequencies above the infrasound range, i.e. in the range of the audible sound.

5.7 Classification of the results

5.7.1 Technical aspects of measurement

Where audible sound is concerned, how and with which measurement technology an immission measurement must be carried out is quite clear (Technical Instructions on Protection Against Noise (1998), DIN EN 61672-1 (2014)), but where the measurement of infrasound is concerned, there are basic questions that remain to be answered.

It is unclear which technical requirements must be met in terms of the microphone. If the microphone has a known frequency response, then it is unclear whether and how this should be factored in when results are reported.

The influence of the wind is less pronounced for measurements on a ground plate than from a tripod. It makes sense to measure noise from a tripod as this could correspond more closely to the position of a human ear and come closer to meeting the requirements of the Technical Instructions on Protection Against Noise.

In this study, a range of confidence was identified by comparing simultaneous measurements taken with two different microphones – one on the tripod and one on the ground plate.

5.7.2 Audible sound and classification of the results

In Germany, the classification of levels is governed by DIN 45680 (1997), as referenced in the Technical Instructions on Protection Against Noise, and the curve it contains with regard to the auditory threshold. This does not extend down to the low frequencies associated with wind turbines, however.

A summary of scientific publications with curves for perception thresholds can be found in Møller and Pedersen (2004). Müller-BBM (2015) lists not only the results of studies of auditory threshold but also the methods employed in the studies.

Not much work has been done to study perception thresholds, particularly at very low frequencies. This is also because it is no trivial undertaking to generate a signal with a high level and a clean sinusoidal shape at very low frequencies such that the signal can be played back to subjects under controlled conditions.

An example of a study of signals generated at very low frequencies is the study by the German Environment Agency [UBA] entitled 'Noise effect of infrasound immissions' (German Environment Agency (2020)). Here, for example, a signal of 105 dB was generated at 2.5 Hz, and was perceived by a majority of the subjects.

Unless explicitly stated otherwise, the auditory threshold is always the average hearing threshold. This is the level above which half of the people can hear (or perceive) sound. However, there may be people who can perceive the sound even below the average auditory threshold. How many people these might be depends on the distribution of the individual auditory thresholds, and the distance between the noise level and the average auditory threshold.

Kurakata, Mizunami (2008) (see also Müller-BBM (2015)) identify distributions across individual auditory thresholds for 10 Hz and 20 Hz. An attempt can be made to take the distribution across individual auditory thresholds into account in an effort to identify the percentage of people living in the vicinity who might be in a position to perceive infrasound. There are no reliable studies on the distribution of individual hearing thresholds for frequencies in the range of 1 Hz; data for 10 Hz and 20 Hz can be found in Kurakata, Mizunami (2008). Approximately 5% of people can perceive noise at a level of 10 dB below the auditory threshold.

If the distribution assumptions of Kurakata, Mizunami (2008) are transferable to lower frequencies, and if the assumption of a normal distribution is valid even at a remove of 30 dB from the auditory threshold, then people would no longer be expected to perceive the noise at such levels.

In unfavourable situations, the levels measured in this study fall in this range with a confidence interval of between 10 and 30 dB below the auditory thresholds identified in the literature. Depending on how the true sound pressures look, up to 5% of people might perceive infrasound, or practically no one.

In addition to the auditory threshold, there is an unknown limit beyond which infrasound can have a physiological effect. How far this limit lies below the hearing threshold, how it is distributed across individuals, and whether it makes a difference how long a person is exposed to infrasound, are not sufficiently known in order to be able to classify the importance of infrasound immissions that are 10 or 20 dB below the auditory thresholds identified in the literature.

5.8 Summary of the findings

Infrasound caused by wind turbines was demonstrated in all of the study areas. In individual cases, based on the line structure, the infrasound is clearly attributable to the wind turbines. Statistically, it has been demonstrated that the levels increase with wind-turbine load.

The levels caused by the wind turbines for the infrasound range are all below the auditory thresholds identified in the literature. The upper limits of the confidence intervals for the levels also lie below the auditory thresholds.

6 Annoyance survey and evaluation

6.1 Survey concept

The annoyance surveys were conducted in the residential surroundings of all five study areas, where the long-duration measurements were performed, within a radius of up to 3 km from the wind turbines. Each survey was conducted once the measurements had been completed. A total of 468 people were interviewed in the study areas. Of these persons, a total of 150 were interviewed in SA 1, 108 in SA 2, 95 in SA 3, 45 in SA 4 and the remaining 70 in SA 5. It was not possible to determine the rating levels of five persons because their geo-coordinates were not known; hence, acoustic and survey data are available for the evaluations of the impacts of exposure to noise for a total of 463 persons.

Telephone or (optionally) online surveys focussing on the housing and living situation in the vicinity of the wind turbines and on the impact of wind turbine noise at each location ('main survey') were presented, followed by individual in-depth interviews conducted in-person or over the telephone ('in-depth survey') of a subgroup of persons who participated in the main survey, with detailed, open-ended questions asked about the perception of wind turbine noise, and specifically about amplitude modulation.

In the following sections, first the content of the questionnaires used (section) is presented, followed by the survey methodology 6.3 and the results (Sections 6.4 and 6.4.14). The survey results are discussed in Section 6.5.

6.2 Survey content

6.2.1 Main survey questionnaire

A questionnaire with a total of 95 questions was drawn up for the annoyance survey. The complete questionnaire can be found in Appendix D.1D.1. It is broken down into 10 thematically structured blocks (A-J) with the following contents:

Block A: Current residential setting ('Home living situation'), seven questions (Items 1-7)

Block B: Annoyance due to noise in respondent's surroundings in the past 12 months, eight questions (Items 8-15)

Block C: Sensitivity to ambient noise, five questions (Items 16-20)

Block D: Thoughts, feelings during recent weeks, ten questions (Items 21-30)

Block E: Consequences of wind turbine noise, ten questions (Items 31-40)

Block F: Attitude ('Opinion') towards wind turbines, 21 questions (Items 41-61)

of which:

Attitude towards wind turbines generally: Twelve questions (Items 41-52)

Visual and other annoyance: Five questions (Items 53-57)

Activities against wind turbine noise or connection to wind turbines: Four questions (Items 58-61)

Block G: Possibilities for development/change since construction of the wind turbines in your residential area: Six questions (Items 62-67)

Block H: Description of wind turbine noise: Ten questions (Items 68-78)

Block I: Ventilation habits, window type, quiet space: Seven questions (Items 79-85)

Block J: Personal details: Eleven questions (Items 86-96)

In addition to these items, some of the participants who had completed the questionnaire in each location were also asked to take part in an in-depth interview.

Furthermore, in order to take into account a possible change in the overall situation due to the coronavirus pandemic, specifically to include changed exposure to noise in everyday life (e.g. due to working from home, short-time work or additional days off for urgent child care at home), from the third study area onwards, the questionnaire was extended by two further items specifically targeting the psychological effects of the pandemic and its side effects, along with any changes in the noise profile of the residential setting that have occurred since the beginning of the pandemic.

6.2.2 Content of the in-depth survey

The qualitative survey following the main survey served to facilitate in-depth insights into residents' attitudes and perceptions around wind turbines generally and, especially in residential areas, the impact the wind turbines have on their residential area and their everyday lives, along with detailed consideration of the characteristics of the wind turbines and wind noise the residents find disturbing.

A guideline addressing the following topics was developed for the survey:

- Attitudes towards wind turbines (personal reference, points of contact with wind energy)
- Positive and negative impacts of wind turbines located near residential areas
- Changes due to the construction of the wind turbines
- Side effects
- Perception of and disturbance by wind turbine noise
- Description of sound characteristics
- Activity in citizens' initiative/association with regard to wind energy

The guidelines for the qualitative survey can be found in Appendix D.2.

6.3 Methodology

6.3.1 Methodology of the main survey

All residential buildings were selected that surrounded the wind turbines within a radius of up to 3 km (in the case of several interconnected wind turbines, the distance was determined for the nearest wind turbine). On the basis of the residential registration data of all adults living in the selected residential buildings, a random sample was taken, and the persons selected in this manner were contacted with a cover letter informing them of the purpose, content and participants of the survey (consumers of the research, clients), and about data protection, and asking them to participate. The persons contacted had an opportunity to be interviewed over the telephone or online; each person received individual access data for use in responding to the questionnaire online.

The surveys were carried out in
succession in the study areas. The first survey area went through the survey phase in November 2018 and February 2019, the last survey area between January and February 2021. As implementation of the project coincided with several lockdowns of individual economic and social sectors, leading to significant changes in public life, the survey was initially suspended between April 2020 and October 2020 in an effort to produce survey results that would be unaffected by the changed conditions. After it became apparent, no later than in October 2020, that the measures would be of a longer and difficult-to-estimate duration, the surveys continued in spite of sustained and recurring closures. In response to the changed conditions, supplemental questions relating to the coronavirus pandemic were added. Likewise, the interviews conducted in Study Areas 1 and 2 were no longer conducted in person but over the telephone; this meant that the portion of the qualitative, in-depth interviews in which sounds were played to respondents was eliminated in locations 3 to 5.

6.3.2 Methodology of the in-depth survey

Participants in the qualitative interviews were recruited as part of the main study. Participants were asked whether they had any further interest in participating in an in-depth, qualitative survey. If they were, they were requested to provide a telephone number or e-mail address where they could be reached. Interested persons were then contacted at random and asked to participate. In the first two locations, an appointment was made for the listening test and the qualitative interviews on the same day, to make participation as convenient and uncomplicated as possible. In some instances, other persons from the household of the person originally contacted appeared at the appointment and participated in the survey as well.

The qualitative surveys were carried out on site at locations 1 and 2. Due to the coronavirus pandemic and the associated restrictions and measures, at locations 3, 4 and 5, the qualitative survey was carried out by telephone. The surveys were conducted in summer 2019, autumn 2020 and spring 2021.

The interviews were recorded with participants' consent and then transcribed to facilitate the evaluation. The transcription was made according to Kuckartz (2012). One person did not consent to a sound recording, and in this case the interviewer took detailed notes. Mentions of names, streets or places that could permit identification of the participants were removed (e.g. 'Hagen' became '[City]'). Incomprehensible phrases and words were marked with '[inc.]'.

Coding was carried out on the basis of Mayring's qualitative content analysis (2015). The individual questions formed the root categories and were inductively filled with subcategories based on interviewees' statements. Multiple mentions were not recorded, but it was possible to assign a particular statement to multiple categories. MAXQDA software was used for coding and evaluation.

6.3.3 Methodology of the sound exposure assessment

For the analyses of the exposure-response relationships, noise immission forecasts were performed relative to interviewees' residential buildings. The calculations were carried out in the form of a detailed dispersion calculation in keeping with the LAI information of 30 June 2016 LAI (2016) pursuant to the requirements of the 'Documentation on Sound Propagation – Interim Procedures for the Forecast of Noise Immissions from Wind Turbines, Version 2015-05.1' NALS (2015). The octave-band sound power spectra of the respective approval procedure were included in the calculation. If these were not available, survey reports for the respective turbine type were used. The terrain model was digitally replicated for the complex locations; buildings were not taken into account. The calculations were carried out using the Soundplan program (version 8.2).

6.4 Results of the main survey

This section presents the results of the statistical analyses of the annoyance survey in the study areas, together with the principal results. Additional, detailed item statistics on the content queried can be found in Appendices D.3 and D.4.

6.4.1 Results, Block J: Personal details

As the final block of the questionnaire (J: Personal details) queried the usual sociodemographic characteristics and indicators, the results of this block are reported first; the results of the further items are subsequently analysed and discussed chronologically, from Block A to Block I.

A total of 468 people were interviewed in the study areas. Of these persons, a total of 150 were interviewed in Study Area 1, 108 in Study Area 2, 95 in Study Area 3, 45 in Study Area 4 and the remaining 70 in Study Area 5. All individuals participating voluntarily provided information about their gender: The overall sample consists of 243 women and 225 men. As calculated at the time of the survey in the individual study areas, the average age of interviewees was 59.38 years (SD = 13.74 years). The youngest participants were 19 years old, the oldest 91. Extensive corrections of the year specification were required prior to evaluation; further details on this procedure are explained in Section 6.4.2.

A total of 22 people had a hearing aid, 445 indicated that they did not have one. One person did not want to make a statement about this. 325 people indicated that they did not have any hearing difficulties; 109 had only slight difficulties, 25 had considerable difficulty hearing, and five indicated that they could not hear at all. Three indicated that they did not know the answer to this.

6.4.2 Results, Block A: Current residential setting (‘Home living situation")

First, the respondent was asked the year in which he or she moved into his or her current housing. Some of the answers provided here were inconclusive. An answer in ‘YYYY’ format was expected. However, there were also two-digit entries in the fields. Six persons in all were excluded from the analysis as a result. It may sound plausible that, for example, the value ‘16’ refers to the year 2016 as the year a respondent moved in, but this is only a guess. After subtracting for some ‘don't know’ responses, 419 responses remained for analysis.

After a brief plausibility check, the smallest value for the move-in year was set to 1933, with the latest move occurring in 2019. The duration of residence was therefore at least two and not more than 88 years at the time of the evaluation.

Overall satisfaction with the residential buildings and the residential setting was good in all of the study areas. In terms of satisfaction with the residential setting, just 13 (2.78%) people were not satisfied, nine (1.93%) were not very satisfied, and 45 (9.64%) indicated that they were moderately satisfied. All other 403 respondents were fairly or even very satisfied with their residential setting (86.39%). Responses with regard to satisfaction with one’s own home were similar. 292 (62.8%) were very satisfied, 135 (29.03%) fairly satisfied, and a total of just 38 people (8.17%) were either not satisfied or only moderately satisfied with their home or flat.

A total of 397 (85.75%) participants lived in detached single-family homes, one respondent (0.22%) lived in an end-of-terrace house, four (0.86%) lived in mid-terrace houses, and 31 (6.7%) in semi-detached houses. 30 (6.48%) of the respondents lived in flats in multi-storey apartment buildings, ten of them on the first floor, 14 on the second and three on the third; one respondent did not answer this question. The apartment buildings had between one and four habitable floors. 427 participants indicated that they owned the property in which they lived; 31 were renters, and five opted not to provide details on this.

6.4.3 Results, Block B: Annoyance due to noise in respondent's surroundings in the past 12 months

The questions in Block B addressed any annoyance caused by the respondent's surroundings. The degree of noise annoyance was measured on the five-point ICBEN verbal scale with the values 1 = not at all, 2 = slightly, 3 = moderately, 4 = very, 5 = extremely. In addition to targeted querying of annoyance due to wind turbines as a whole, in the house or building and outside the house or building (see Table 16), the survey also asked about annoyance due to road traffic noise. The mean value for annoyance due to road traffic noise in the total sample is 1.78 (standard deviation (SD) = 1.06). It can be seen from Table 16 that the mean value for total annoyance due to wind turbine noise is approximately equal to the mean value for annoyance due to road traffic, at 1.75 (SD = 1.24). The results in Table 16 also show that noise annoyance due to wind turbines overall, whether indoors or outdoors, is higher on average for Study Areas 4 and 5 than in the remaining three areas. The higher noise annoyance in these areas also corresponds to the somewhat higher average noise rating levels in comparison to the other areas studied (cf. Table 28).

Table 16: Annoyance due to wind turbines

Noise annoyance due to wind turbines	Study Area	Number of valid values	M	SD
Total (overall)	Overall	468	1.75	1.24
	1	150	1.37	0.93
	2	108	1.62	1.12
	3	95	1.37	0.8
	4	45	2.29	1.5
	5	70	2.91	1.48
In the house/in the flat (indoors)	Overall	466	1.39	0.88
	1	148	1.17	0.56
	2	108	1.35	0.87
	3	95	1.2	0.56
	4	45	1.69	1.24
	5	70	2.01	1.15

Noise annoyance due to wind turbines	Study Area	Number of valid values	M	SD
Outside the house (garden, terrace, balcony) (outdoors)	Overall	467	1.75	1.23
	1	149	1.32	0.85
	2	108	1.6	1.08
	3	95	1.53	0.89
	4	45	2.22	1.51
	5	70	2.91	1.50

Annoyance scale: 1 = not at all; 2 = slightly; 3 = moderately; 4 = very; 5 = extremely
M = Mean value; SD = Standard deviation

The interviewees were also free to name other sources of noise. 92 people made mention of a total of 172 references to various sources of noise. 92 people gave at least one indication of another source of noise; 60 of them offered two, and 20 of the 92 identified three. As a detailed qualitative content analysis would exceed the scope of this report, semantically similar words (e.g. 'aeroplane' and 'helicopter') were combined and the frequencies of mention counted (Table 17).

Here, too, the mean values for annoyance at other sources of noise clearly exceed those for wind turbines and for road traffic as well, with mean values between 3.15 (M = 0.98) and 3.44 (M = 1.13). By way of example, Table 17 summarises the ten most common mentions in semantically similar categories. From this it emerges that most participants feel annoyed by aircraft and helicopters. Noise from agricultural equipment, traffic and work also seems to be relevant as a factor of disturbance to some residents of the study areas, all of which are very rural.

Table 17: Most frequent mentions of other sources of noise

Other source of noise	Number of mentions
Agricultural source	16
Vehicles	9
Aircraft, aircraft noise, helicopters	20
Lawn mowers	6
Vehicle traffic	5
Neighbours	5
Traffic	5

6.4.4 Results, Block C: Sensitivity to ambient noise

The five-point ICBEN scale described in Section 6.4.3 was also used to query respondents about their sensitivity to ambient noise (noise sensitivity particularly with regard to low frequencies). This block queried sensitivity to five different kinds of ambient noise: Low-frequency noise, rumbling noise (e.g. washing machines), music with bass, monotonous humming, noise generally.

The analysis showed that participants' self-assessments about sensitivity to the forms of noise queried were quite uniform. This was lowest for rumbling noise, with an average value of 1.73 (SD = 1.73), and highest for monotonous humming, with an average value of 2.16 (SD = 1.18).

The averages for this series of items yield a score for 'noise sensitivity'. The mean value across the total sample is 2.04 (SD = 0.82). There are statistically significant differences in noise sensitivity across study areas ($F[4;440] = 3.19$; $p = 0.013$), but in terms of absolute values the differences are only marginal, with a low effect size (η^2part = 0.03): The mean values for noise sensitivity fall between M = 1.9 (SD = 0.72; SA 2) and M = 2.2, SD = 0.85; SA 1).

6.4.5 Results, Block D: Thoughts, feelings during the past weeks (*Perceived Stress Scale, PSS-10)*

In Block D, perceived psychological stress was measured using the Perceived Stress Scale (PSS-10; Cohen & Williamson, 1988) in the German version by Klein et al. (2016). The scale contains a total of ten items querying 'thoughts and feelings' around stressful situations during the four weeks prior to the survey. A basic starting point for assuming the health effects of environmental noise is that it causes acute disturbance and stress, which can have further physical and mental health effects during many years of exposure. The feeling of annoyance due to noise is understood as a psychological stress reaction. This study included questions on perceived stress that, even in their wording, do not contain any reference to wind turbines or noise. The purpose of this approach was to determine whether perceived (general) stress is more pronounced where exposure to wind turbine noise is greater. The minimum assumption was that, even if generally perceived stress bears no relation to levels of wind turbine noise, it nevertheless moderates the relationship between exposure to wind turbine noise and noise annoyance, i.e. those persons reporting a higher degree of psychological stress based on their answers respond more sensitively to wind turbine noise and report a higher level of annoyance due to noise.

During the course of the study, the measures taken to contain the infection caused by the COVID-19 pandemic had serious repercussions on the everyday life and experience of all citizens living in Germany. For this reason, another question was included in this block following the PSS-10 items, which was asked directly following what originally had been the final question. The item reads: 'How strongly have your feelings and thoughts related to the coronavirus pandemic during the past month?'

This question was additionally asked from SA 3 onwards; accordingly, the number of responses is lower than for the remaining items in this block (N = 205).

The response options offered also included a five-point rating scale participants were asked to use to estimate the frequency of the feelings and thoughts they experienced in the previous four weeks (1 = never, 2 = almost never, 3 = sometimes, 4 = quite often, 5 = very often).

Table 18: Mean values and standard deviations of the items of the Perceived Stress Scale PSS-10 from Block D

Question: In the last month, how often …	N	M	SD
1. … have you been upset because of something that happened unexpectedly?	454	2.31	1.07
2. … have you felt you that you were unable to control the important things in your life?	454	2.10	1.03
3. … have you felt nervous or ‘stressed’?	457	2.58	1.22
4. … have you felt confident about your ability to handle your personal problems?	452	3.88	0.98
5. … have you felt that things were going your way?	447	3.45	0.97
6. … have you found that you could not cope with all the things that you had to do?	455	2.09	0.98
7. … have you been able to control irritations in your life?	446	3.81	1.00
8. … you felt that you were on top of things?	449	4.07	0.79
9. … you been angered because of things that were outside your control?	452	2.93	1.07
10. … have you felt difficulties were piling up so high that you could not overcome them?	454	1.96	0.94
Additional question from Study Area 3 (not a part of PSS-10)			
How strongly have your feelings and thoughts related to the coronavirus pandemic during the past month?	205	3.20	1.16

PSS-10 rating scale: 1 = never, 2 = almost never, 3 = sometimes, 4 = quite often, 5 = very often; Coronavirus question rating scale: 1 = not, 2 = little, 3 = moderately, 4 = rather, 5 = very; M = mean; SD = standard deviation

The correlation of the ‘feelings and thoughts about the coronavirus pandemic’ in Study Areas three to five is quite strong and, with a mean value of 3.20 (SD = 1.16), clearly exceeds the theoretical mean value of the scale, which is 2.5. Considered overall, the respondents’ assessments are rather positive. Most of the responses to positively formulated items are situated in the upper areas of the scales, while affirmative responses to questions with negative connotations are more rare. The PSS scale does not consider the degree of perceived psychological stress as a one-dimensional concept, and instead records psychological stress as subdivided into two subdimensions or two factors: The factor of ‘helplessness’ (PSS questions 1, 2, 3, 6, 9 and 10) and the factor of ‘self-efficacy’ (PSS questions 4, 5, 7 and 8). To quantify these two PSS factors, mean value scores were formed for the ratings, meaning each PSS factor can also be interpreted based on the rating scale used. In this context, any high values signify a high level of the two factors, i.e. high helplessness or high self-efficacy. The mean value for helplessness across the total sample is 2.33 (SD = 0.71). Overall, the factor values for helplessness are clustered closely together in the individual study areas: the lowest value was calculated for SA 4 (M = 2.17, SD = 0.84), while the highest is only slightly higher, with a mean value of 2.51 (SD = 0.66) in Study Area 5.

The situation with regard to the score for self-efficacy is different: here, a mean value of 3.8 (SD = 0.72) for the total sample clearly exceeds the mean scale value. The individual areas are similarly close together as before: the lowest value is achieved by the SA 3 with 3.41 (SD = 0.68), and the highest again in SA 4 (MW = 3.94, SD = 0.59).

The two scales can be used to determine whether participants with higher exposure have a greater sense of stress than those with lower exposure, which would have been the expected outcome based on the results from Hübner et al. (2019). This could not be demonstrated in this study, however; the correlations between noise levels L_{rT} and the two PSS mean scores are close to zero ($r_{\text{self-efficacy, LrT}}$ = -0.09, $r_{\text{helplessness, LrT}}$ = 0.04).

However, helplessness slightly correlates with annoyance due to wind turbine noise (overall *r* = 0.171; outdoors *r* = 0.184; indoors: *r* = 178). This might be an indication that helplessness, like noise sensitivity, is a kind of vulnerability measure ('measure of susceptibility') and a moderator for noise annoyance. This hypothesis will be examined in greater detail later by correlation analyses in section 6.4.13.

6.4.6 Results, Block E: Consequences of wind turbine noise (activity disturbance)

In the following block of questions, participants were asked in detail about the consequences of wind turbine noise. This question addresses activities that are disturbed by wind turbine noise. This block consists of a total of ten questions that can be combined into three scores. The descriptive results (mean, standard deviation, number of mentions) for the summary scores and the associated items are shown in Table 19.

The score for disturbances in communication indoors results from items one, two and five: disturbances during telephone calls, listening to the radio/watching TV and when socialising indoors. With a mean value of 1.17 (SD = 0.49), this score is quite low. The score is highest in SA 5, where it stands at 1.36 (SD = 0.61); it is lowest in Study Area 2, at 1.1 (SD = 0.35). Scores for the other study areas are located close together between these end points.

Items three and four form the score for disturbed rest and concentration (disturbances when reading, thinking, etc., and disturbances in relaxing). This score is also low overall (M = 1.23, SD = 0.62). Here, too, the value peaks in SA 5 (M = 1.48, SD = 0.77); the lowest mean value (1.17) was measured in SA 1 (SD = 0.61).

Items six and seven together constitute the score for the 'outdoor disturbances' (disturbances when spending time and relaxing outdoors, as well as socialising outdoors), which asked about annoyance due to wind turbine noise outside of participants' homes and flats. This score, too, is at a fairly low level overall, but in spite of all of this it is the highest of all scores in this block and reaches an overall mean value of 1.7 (SD = 1.1). Here, too, participants in SA 5 report by far the highest value (M = 2.66, SD = 1.29); as with the analysis of disturbances to concentration, the score for outdoor disturbances is the lowest in SA 1.

Table 19: Mean values and standard deviations of the items addressing disturbances in activity from Block E

Question	N	M	SD
During the past 12 months, how disturbed were you by noise from wind turbines altogether in the following situations?			
Disturbance of communication indoors (mean score)	*461*	*1.17*	*0.49*
During conversations or when talking on the telephone in the flat/in the house	462	1.21	0.60
When listening to radio/music or watching television	463	1.15	0.48
When socialising indoors or when there are visitors in the flat/house	462	1.17	0.52
Disturbance indoors (mean score)	*461*	*1.23*	*0.62*
When relaxing and after work in the flat/house	462	1.24	0.67
When reading, thinking or concentrating in the flat/house	462	1.21	0.61
Outdoor disturbances (mean score)	*463*	*1.69*	*1.09*
When spending time and relaxing outdoors (on the terrace, the balcony, in the garden)	463	1.76	1.17
When talking/during conversations outdoors	463	1.62	1.07
Sleep disturbance (mean score)	*460*	*1.28*	*0.74*
When falling asleep	462	1.34	0.83
At night, while sleeping (or *for night shifts*: at the usual bedtime)	462	1.27	0.77
When sleeping in at the end of sleeping time	461	1.27	0.74

Rating scale (ICBEN Scale): 1 = not at all, 2 = slightly, 3 = moderately, 4 = very, 5 = extremely; M = mean; SD = standard deviation; N = quantity

The final score combines three questions about sleep difficulties (when falling asleep, at night, during sleep and when sleeping in). With an overall mean value of 1.29 (SD = 0.75), this is again a lower level than the score for outdoor disturbances. As with all other scores, the highest annoyance was measured in Study Area 5 (M = 1.71, SD = 1.01); sleep disturbances were the least pronounced in Study Area 3 (M = 1.14, SD = 0.52).

Perceived disturbances in activity due to noise are regarded as the direct consequences of the influence of noise and as mediators of the effect of noise levels on noise annoyance. They thus constitute an element of the process of forming judgements on noise annoyance (cf., among others, Guski et al., 2017). Correspondingly, in this study, the disturbances in activity correlate with the noise annoyance due to wind turbine noise as well as with noise rating level L_r.

The effort to interpret the magnitude of the correlation can refer back to the rough classification of the correlation coefficients relative to effect size according to Cohen (1988). A product-moment correlation of less than r = 0.1 means no effect (no relationship); if the correlation is $0.1 \leqq r < 0.3$, the coefficients mean a small effect. Coefficients in the range of $0.3 \leqq r < 0.5$ signify a medium or moderate effect, and coefficients of $r > 0.5$ denote a large effect or a strong link. This rough classification of correlation values as a measure of linkages also applies to the following representations of correlations.

The correlation coefficients of disturbances in activity with the noise rating level are of an order of magnitude of $0.130 \leqq r \leqq 0.280$. Particularly the outdoor disturbances reported ($r = 0.280$), such as annoyance due to wind turbine noise, correlated with a small effect size with the noise rating level L_r (cf. also Section 6.4.13 on the level-annoyance correlation). Higher correlations with a moderate to high effect size can be seen with coefficients of $0.436 \leqq r \leqq 0.865$ between disturbances in activity and annoyance due to wind turbine noise. As expected, the highest correlation is seen for the reported outdoor disturbances and annoyance due to wind turbine noise with $r = 0.865$ (Table 20).

Table 20: Correlation between noise rating level, annoyance due to wind turbine noise and disturbances in activity

	Noise rating level L_r	Wind turbine noise annoyance overall	Wind turbine noise annoyance indoors	Wind turbine noise annoyance outdoors
Noise rating level L_r	1.000	0.263**	0.219**	0.272**
Disturbance of communication indoors[1]	0.137**	0.436**	0.547**	0.492**
Disturbance of calm and concentration indoors[1]	0.130**	0.467**	0.619**	0.535**
Outdoor disturbances [1]	0.280**	0.834**	0.676**	0.865**
Difficulty sleeping[1]	0.181**	0.631**	0.722**	0.673**

[1] Summary score of multiple items (individual questions); * = $p < .05$; ** = $p < .01$; p = significance level

6.4.7 Results, Block F: Opinions on and annoyance by wind turbines

Block F breaks down into a total of three smaller sections with the following content:

- Respondents' attitudes towards wind turbines generally and to the wind turbines in their vicinity
- Annoyance due to visual impacts of wind turbines
- Engagement in connection with wind energy generally, wind turbines and any employment and/or income relationships in connection with wind energy.

The three sections of Block F are analysed and described separately below.

6.4.7.1 Results, Block F: Attitudes towards wind energy generally and at respondents' location

The respondent's attitude to different aspects of wind energy and wind turbines was first queried on the basis of twelve individual questions (items). The first ten of these items were answered on a five-point verbal scale with levels 1 = 'agree not', 2 = 'agree a little', 3 = 'agree moderately', 4 = 'agree quite a bit' and 5 = 'agree very'. The remaining two questions concerned the visibility of wind turbines (cf. Table 21). First, a simple 'yes/no' query was used to determine whether participants could see wind turbines from their home. The second question asked participants to estimate the number of wind turbines visible from their home. 369 participants indicated that they could see at least one wind turbine from their property. The mean value for participants' reports of visible turbines is 10.22 (SD = 20.24); the values range from one visible turbine to a maximum of 180. This study cannot determine whether or not this claim is plausible.

A statistical method of data reduction, factor analysis6, was used to locate aspects of attitudes (known as 'attitudinal dimensions') on which answers to the individual items were based. Factor analysis is a multivariate statistical method that summarises responses to individual items (questions) to create a factor based on the homogeneity of the responses. This leads to a 'dimension reduction'. This turns many individual questions into a manageable number of factors expressing the same content as the individual items. The factors thus obtained must be interpreted substantively, i.e. there are no fixed rules governing how the factors are to be named. For example, the method of factor analysis can be used to make it possible to deduce and quantify the underlying, even unobservable dimension of 'intelligence' from the solution of computational problems or knowledge questions.

Applying factor analysis to attitudinal questions about wind energy resulted in a possible pooling of responses to the ten items into three attitude scores.

The substance of the three scores identified can be described as follows:

1. Lack of rest/relaxation

2. Negative significance of wind turbines for the residential area

3. Positive significance of wind turbines for the residential area.

The item querying participants' agreement with the statement 'Wind turbines are good for environmental protection' was excluded from scoring as it failed to meet the requirements in factor analysis that permit assignment to one of the three attitudinal scores. This means that none of the three attitudinal scores (factors) was sufficiently in a position to explain variance in the response to this question.7 In terms of content, this could be justified by the fact that the criterion of environmental friendliness is too global for the content queried here, and there is no direct reference to this question for the participants where they reside, but this is rather a presumption than a result and cannot be justified or rejected statistically.

Table 21 describes factor loadings of the individual items (questions) relative to the three extracted factors. Loading values fall between -1 and +1 and indicate how strongly an item (a question) is explained by the respective factor; values close to -1/+1 reflect a high explanatory role.

Table 21: Factor loadings for the items about attitudes towards wind turbines

	Factor loadings		
Item	Factor 1 Lack of rest	Factor 2 Negative consequences of wind turbines for the residential area	Factor 3 Positive consequences of wind turbines for the residential area

[6] Principal axis factor analysis with promax rotation and Kaiser normalisation

[7] None of the factors met the minimum criterion of a factor loading (parameter for a factor's role in explaining a response to an item) of at least 0.4.

	Factor loadings		
Avoidance of spending time outdoors of residential buildings due to wind turbines	**0.836**		
Difficulty of local recreation due to wind turbines	**0.695**		
Neighbourhood dispute over wind turbines	**0.669**		
Disturbances caused by shadow casting inside the home	**0.552**		
Land depreciation due to wind turbine operations		**0.678**	
Promoting further regional development through wind turbines		**0.703**	
Disfigurement of the landscape by wind turbines		**0.556**	
Creation of jobs in the region			**0.691**
Reduction in electricity costs			**0.635**
Wind turbines are good for environmental protection*	-	-	-

Explanation of total variance: 47%; * Not contained in the scores

In keeping with the results of the factor analysis, the items were added together to form mean scores. For all of the items that were combined into scores, the scale homogeneity was determined in advance by calculating Cronbach's alpha. This means that there was a quantification of the degree to which the individual items together represent a common concept (a content-consistent, homogeneous score). Individual items together produce a common concept if a clear trend can be identified when individual persons answer the individual questions. The Cronbach's alpha value calculated for this purpose lies between 0 and 1, where values close to 1 reflect high internal consistency.

The first score thus obtained, for the lack of rest, has an average value of 2.08 (SD = 1.01), and the scale homogeneity is acceptable with $\alpha = 0.76$. According to the orientation of the variables included in the score, high values mean a high degree of lack of rest; high values thus reflect a negative influence of wind turbines on participants' experience of getting rest. As the score in this case is rather low, there is no reason to assume that the operation and/or presence of wind turbines would have a negative effect on rest, or the perceived opportunity for interviewees living in the vicinity of the wind turbines to relax. In terms of study areas, the lowest value is found in the Study Area 1 (1.84, SD = 0.97). The highest value is measured in Study Area 5 (M = 2.76, SD = 1.01).

The second score summarised here is composed of three items: depreciation in property value, promotion of the region and disfigurement of the landscape. The higher the value for this score, the higher the negative consequences expected from survey participants. Here, too, a mean value score was formed, the scale homogeneity of which, with $\alpha = 0.66$, is somewhat lower than the score for the lack of rest, but nevertheless still seems acceptable. The 95% confidence interval for Cronbach's alpha is correspondingly acceptable, with values of 0.61 (lower) and 0.72

(upper). The score has a mean value of 3.42 (SD = 1.07), and this suggests a rather negative influence of the wind turbines on the living environment of the persons surveyed. The negative consequences considered here clearly constitute important content for the survey participants. Here, Study Area 3 has the lowest mean value for negative consequences (3.07, SD = 1.14); the highest approval of negative impacts was measured in Study Area 2, with a value of 4.03 (SD = 0.49).

Finally, the score was calculated in the same way with regard to the positive consequences of wind turbine operation for the residential area. This involves one question that asks whether wind turbine operation cuts electricity costs, and another that considers whether wind turbine operations create jobs in the region. With an α = 0.64, the scale homogeneity test (test of the internal consistency of the scale) also yields a value still in the acceptable range. The 95% confidence interval spans the gap between 0.58 (lower limit) and 0.71 (upper limit). In all, 355 valid values were collected here. With an overall mean value of 1.85 (SD = 0.99), the score is rather low. The highest approval is measured in SA 3, where the mean for the 60 valid answers is 2.26 (SD = 0.88); the lowest approval came from the 60 participants in UG 5, with an average of 1.54 (SD = 0.83).

As the scoring and its evaluation make clear, the opinion on wind turbines is more negative than positive. The opinion is determined by the negative content and local impacts of the wind turbines. The three items explained by the 'negative consequences' – on landscape disfigurement, real estate depreciation and promotion of further regional development (this item was rated very negatively) – have significantly higher weightings than the positive consequences. This is expressed in a low value for the 'positive consequences' factor, with mean agreement of M_{total} = 1.85 and the overall mean value, which is almost twice as high, for negative consequences (M_{total} = 3.42); this is true not just of the total sample but of each individual study area as well.

However, reference should also be made here once again to the magnitude of the values for Cronbach's α as a measure of the homogeneity of the scores formed. Specifically, the scores for negative and positive consequences, with Cronbach's α values of 0.66 for positive consequences and 0.64 for negative consequences, have homogeneity values at the lower limit of what constitutes satisfactory homogeneity (based on the convention for Cronbach's α values from 0.7; Bland & Altman, 1997).

6.4.7.2 Results, Block F: Visual annoyance due to wind turbines

This part of the questionnaire asked respondents how annoyed they felt with the different visual characteristics of the wind turbines. Specifically, the items asked about the visual annoyance caused by wind turbines based on their visibility in the residential environment, shadow casting, the aviation-obstruction lighting, the rotations of the rotors and the sight they create in the landscape.

All five items from the 'visual annoyance' sub-section of Block F: Opinions on wind turbines can be summarised to a score correspondingly referred to as 'visual annoyance due to wind turbines'. The factor analysis was calculated using the same default settings as described in Section 6.4.7.1 and explains an overall proportion of variance of 62%. Scale homogeneity is nearly perfect here, with a Cronbach's α of 0.93. Viewed in detail, the least annoyance is seen as coming from shadow casting by the turbines (M = 1.38, SD = 0.9) and the highest annoyance from the impact in the landscape (M = 2.38, SD = 1.43). The score has a comparatively low significance with an overall mean value of 1.78, but it should be pointed out that this varies significantly in some areas: There is more than an entire valuation unit separating the lowest mean value, in Study Area 3 (1.4, SD = 0.58), from the highest, in Study Area 5 (M = 2.49, SD = 1.12).

6.4.7.3 Results, Block F: Activities against wind turbine noise or connection to wind turbines

This block concluded with four multiple-choice questions designed to explore three different contents of the respondents' financial dependence on wind turbines and discussing whether the participant had ever campaigned for or against wind turbines in an initiative or the like. Over the total sample, there were 12 persons (2.59%) employed in jobs linked to wind turbines; 452 (97.41%) were not. Still, 22 participants (4.76%) reported having a financial interest in the turbines; this was not the case for the remaining 440 (95.24%). Just nine respondents (2.12% of the sample) indicated that they saved on electricity costs through wind turbines, while the remaining 416 (97.88%) reported that they did not.

The last question in Block F asked respondents whether they had ever been involved in a citizens' initiative or an association that was either in favour or against wind turbines. In response, six people (1.29%) reported having worked for wind turbines in such an association, 20 (4.3%) had worked against them, and the remaining 439 (94.41%) had done neither.

6.4.8 Results, Block G: Possible developments/changes since construction of the wind turbines in your residential area

Block G contained a total of six questions aimed at exploring perceived changes associated with wind turbines. The first question asked whether there had been a change in wind turbine noise levels since their construction. Participants could choose whether noise had increased or decreased, or whether there had been no change. 101 (23.01%) stated that the noise had increased, just five (1.14%) that it had decreased, and the remaining 333 (75.85%) stated that the noise had neither decreased nor increased.

The second item queried whether the type of noise produced by the wind turbines had changed over time. 68 (16.87%) people said that it had changed, and 335 (83.13%) indicated that there had been no change. The participants who had said they noticed a change were asked to describe how the noise had changed. This was done in the form of an open question, with 61 participants offering further details on the subject. The scope and precision of the answers provided varied significantly. Most described various types of additional noise, and many others reported that the impacts of noise exposure had increased over time. Most of the 61 responses consisted of complete sentences, making a short analysis based on keywords difficult; this did not change much even with the deletion of 'stop words' ('the most common words in a language'). Even tracing words to their original form ('stemming') with the help of the Porter algorithm (Feinerer, Hornik and Meyer, 2008) had no effect here. 16 responses included the word 'louder', which was the word mentioned most frequently in this open item; the word 'loud' was mentioned another five times. 'Quieter' occurred seven times in the responses, and people also identified 'rushing' (four times), 'humming' 'whistling' and 'screeching' (three times each) as further characteristics of the noise. All of the other words mentioned occurred fewer than three times. 309 of the respondents also indicated that there had been further changes since the construction of the wind turbines, but only 13 people provided further information on this. Two reported that there had been a dispute about wind turbines in the neighbourhood or with the landowners. Statements were also occasionally made about various changes in local infrastructure, although these probably have little connection to the wind turbines; and one person indicated seeing fewer wild animals.

Finally, respondents were asked to offer an assessment of how annoyed they will feel about the noise of the wind turbines over the next twelve months. The response format corresponds to the verbal five-point scale already used in Section 6.4.3. 52 (11.98%) of the respondents indicated that they were likely to feel strongly or extremely annoyed, while the remaining 382 people expected no, or at most moderate, annoyance (88.02%).

6.4.9 Results, Block H: Description of wind turbine noise

As the results presented in Block G suggest, the types of noise emitted by wind turbines vary depending on the turbine and/or study area involved. To explore how different noise emissions from wind turbines can be, and how participants perceived them, a total of eleven different questions were asked in Block H.

For the first eight questions in this block, respondents were asked to provide greater detail about their agreement with eight different sound characteristics of the local wind turbines. Survey participants were instructed to indicate their agreement to the eight indicated sound characteristics on a seven-point scale with verbal extremes of '1 = disagree' and '7 = agree completely'. The results can be found in Table 22.

In the overall sample, wind turbine noise is perceived most often as rushing ($M = 3.85$, $SD = 2.2$) and whooshing (approval: $M = 4.23$, $SD = 2.4$), especially in Study Area 5, followed by Study Area 4 and Study Area 2, in descending order. Wind turbine noise is perceived least frequently as a rushing and whooshing sound in Study Area 1 and Study Area 3 (Table 22). Whooshing is often understood as the subjective counterpart of amplitude modulation, as is possibly rushing where it is perceived as pulsating or in intervals, as mentioned in the in-depth interviews. A slight correspondence can be seen between the degree of perception of the wind turbine noise as whooshing and rushing and the percentage frequency of occurrence of detected, stable (periodic) AM (Table 22). In other words, in SA 2 and SA 4, in which the AM occurs at a significantly higher percentage rate than in the other SAs (47.4% in SA 2 and 42% in SA 4), agreement with descriptions of wind turbine noise as whooshing or rushing is the strongest in SA 5. The highest correspondence of the percentage rates of the AM with characterisations of the noise as whooshing or rushing, however, can be found in SA 5; there, however, the frequency of occurrence of AM and its modulation depth do not represent the highest values for the regions studied. Whether the area differences shown here in the frequency of occurrence of detected periodic AM and the subjectively perceived features of wind turbine noise correspond to area differences in the annoyance due to wind turbine noise was investigated in the context of a covariance analysis; this is addressed in the following section.

6.4.9.1 Covariance analysis of area differences in noise annoyance due to wind turbine noise

A covariance analysis was carried out to investigate whether and to what extent the values for annoyance due to wind turbine noise vary across the study areas. In a further step, the area-related differences in annoyance due to noise were compared with the parameters of the AM (cf. also Table 4, p. 61) and subjective perceptions of sound characteristics with a view to possible correspondence. The area differences in noise annoyance considered in the covariance analysis were adjusted as covariates based on rating level L_{r}, i.e. area differences were investigated assuming a constant rating level. The first line in Table 22 lists the judgements of wind turbine noise in the five study areas, holding constant for noise level. The covariance analysis reveals highly significant differences across the study areas in terms of noise annoyance due to wind turbines $F(4.457) = 24.53$, $p < 0.001$. Post-hoc tests to analyse individual differences between areas showed that the degree of wind turbine noise annoyance judgements in areas SA 1 and SA 3 is significantly lower, statistically, than in the other areas, whereas there are no statistically significant differences in adjusted assessments of wind turbine noise annoyance in areas SA 2, 4 and 5.

6.4.9.2 Correspondence between area differences in noise annoyance, assessed sound characteristics and parameters of stable, periodic AM

The differences in annoyance levels between areas, corrected for the effect of different rating levels in the study areas, appear to correspond both to the differences in noise perception as whooshing or rushing, and also, in part, to the parameters of the AM from Table 4, section 3.4.3, which were included again in Table 22. This is because both the perception of wind turbine noise as 'whooshing' or 'rushing' and the frequency of occurrence of detected, stable (periodic) AM are lower in SA 1 and SA 3 than in the other study areas. However, the differences in annoyance do not correspond to the measured modulation depth of the wind turbines in the various study areas.

Table 22: Descriptive statistics on annoyance due to wind turbine noise, on the parameters of AM and the sound characteristics queried

	SA 1	SA 2	SA 3	SA 4	SA 5	Overall
Wind turbine noise annoyance overall *	1.32	2.06	1.24	2.12	2.59	--
Parameters of AM (from Table 4)						
Frequency of occurrence of detected, stable (periodic) AM in %	10.8	47.4	1.7	42.0	22.3	--
ΔL_{AM95} in dB	1.1	1.3	0.6	0.9	0.8	--
ΔL_{AM50} in dB	2.0	2.4	1.4	1.5	1.6	--
ΔL_{AM05} in dB	4.2	4.7	5.5	3.3	2.9	--
I would describe the wind turbine noise as … 'Disagree' (1) to 'Agree completely' (7) Mean value (standard deviation)						
Rumbling	1.47 (1.16)	1.45 (1.26)	1.29 (0.77)	1.35 (0.98)	2.13 (1.79)	1.53 (1.26)
Droning	1.57 (1.33)	2.00 (1.83)	1.44 (0.98)	1.68 (1.36)	2.44 (1.94)	1.80 (1.56)
Rushing	3.11 (2.12)	4.18 (2.46)	3.14 (1.59)	5.08 (2.14)	5.00 (1.72)	3.85 (2.20)
Humming	1.87 (1.60)	2.33 (1.96)	1.76 (1.18)	2.00 (1.80)	3.24 (2.08)	2.20 (1.80)
Pulsating	2.22 (1.93)	2.38 (2.00)	2.15 (1.37)	2.26 (1.94)	2.42 (1.84)	2.30 (1.85)
Whistling	1.68 (1.49)	2.04 (1.92)	1.65 (1.25)	2.03 (1.80)	2.81 (2.00)	1.98 (1.72)
Whooshing	3.79 (2.43)	4.10 (2.54)	3.61 (2.05)	4.95 (2.49)	5.81 (1.71)	4.23 (2.40)
Constant fluctuation	2.53 (2.05)	3.33 (2.58)	2.28 (1.71)	2.81 (2.40)	2.81 (2.11)	2.74 (2.19)

N = 396 – 420; * mean value adjusted according to rating level L_r

The next item asked which of the sound characteristics mentioned was the most annoying. Absolute and relative frequencies of responses can be found in Table 23.

Table 23: Frequency table of the most annoying characteristics of wind turbine noise

Noise characteristic								
	Rumbling	Droning	Rushing	Humming	Pulsating	Whistling	Whooshing	Constant fluctuation
N	11	8	45	23	13	21	127	7
%	4.31	3.14	17.65	9.02	5.1	8.24	49.8	2.75

The significance of perceiving wind turbine noise as whooshing is confirmed here, too. ‘Whooshing’ is not only the sound characteristic with the highest level of agreement relative to the sound characteristics emitted, but it also causes the highest level of annoyance by far.

This is consistent with the results of the correlation analyses between the perceived sound characteristics and annoyance with wind turbine noise (Table 24); this is addressed in the following section.

6.4.9.3 Correlation between noise annoyance due to wind turbine noise and perceived sound characteristics

Three of the sound characteristics examined here in particular would come close to describing amplitude-modulated noise: Pulsating, Whooshing, Fluctuation. The table of correlations (Table 24) suggests that a relationship exists between these sound characteristics and annoyance due to wind turbine noise. The highest correlations emerge between the wind turbine noise annoyance overall and outdoors, and the characteristic of ‘whooshing’ ($r_{\text{whooshing, noise annoyance overall}} = 0.455$, $r_{\text{whooshing, noise annoyance outdoors}} = 0.446$). The stronger the agreement that wind turbine noise is characterised by ‘whooshing’, the stronger the reported annoyance due to wind turbine noise. Taken together, these findings give an indication that subjectively perceived amplitude-modulated noise is actually assessed as more annoying than continuous noise.

Table 24: Table of correlations of perceived sound characteristics and wind turbine noise annoyance

	Rumbling	Droning	Rushing	Humming	Pulsating	Whistling	Whooshing	Fluctuation
Noise annoyance overall	0.358	0.414	0.393	0.424	0.266	0.363	0.455	0.358
Noise annoyance indoors	0.295	0.346	0.338	0.354	0.265	0.381	0.356	0.386
Noise annoyance outdoors	0.332	0.378	0.409	0.408	0.236	0.380	0.446	0.336

Range of correlation values: -1 to +1. The closer the value comes to 1.0 or -1.0, the stronger the positive or opposite relationship.

Participants were also asked if there are any other terms that describe wind turbine noise; 56 answered in the affirmative. Many terms mentioned in this connection had already been queried beforehand. Many other comments referred to noise with parallels to wing flapping (e.g. ‘flap

flap'); many others also describe continuous noise and/or draw parallels to various kinds of air traffic noise.

6.4.10 Results, Block I: Ventilation habits, window type, quiet space

In the last block, participants were queried in detail about the orientation of their living quarters and their ventilation habits. A total of seven items were queried in multiple-choice format, with only one answer permitted for each question.

With regard of the window type, most living rooms and bedrooms are double glazed (more than 80% of cases). This is followed by triple glazing in the bedroom and living room, with 12 and 13%, respectively. Not many people have single-glazed windows at home; none of the interviewees has soundproof windows used in conjunction with ventilation fans (Table 25).

Table 25: Absolute and relative frequencies of glazing and window types

		Window or glazing type			
Room		Single glazing	Double glazing	Soundproof windows or triple glazing	Soundproof windows in connection with fans
Bedroom	N	13	392	56	-
	%	2.82	85.03	12.15	-
Living room	N	7	393	61	-
	%	1.52	85.25	13.23	-

128 (27.83%) participants indicated that they keep the window in their living rooms closed for the most part by day in warm weather; 332 (72.17%) indicated that they opened or tilted the windows. 396 of respondents kept the windows in the bedroom open at night during warm weather (85.34%), while only 68 indicated that they kept the windows closed (14.66%). 336 (77.42%) also indicated that they had a quiet room at home where they could retreat to shield themselves from ambient noise.

Table 26: Absolute and relative frequencies of room orientation towards wind turbines

	Room orientation towards wind turbines			
Room		Leeward	To the side	Facing
Bedroom	N	182	122	151
	%	40	26.81	33.19
Living room	N	168	106	180
	%	37	23.35	39.65

To check whether it can be a successful noise-management strategy to set the bedroom up in a room facing away from the wind turbine, a covariance analysis was carried out to ascertain whether annoyance due to wind turbine noise differs with bedroom orientation. As in the previous block, the questions controlled for the effect of the noise level. The model was additionally supplemented with the interaction of room orientation and noise level. It turned out that wind turbine noise annoyance, both overall and indoors, differs depending on the bedroom orientation towards the wind turbines: The annoyance is highest if the bedroom faces the wind turbines and lowest if it faces away from the wind turbines (Table 27). The effect of room orientation is statistically significant (for wind turbine noise annoyance overall: Wald chi square = 7.76, df = 2, $p = 0.021$; for wind turbine noise annoyance indoors: Wald chi square = 6.47, df = 2, $p = 0.039$). This effect is independent of the rating level, i.e. there is no interaction between the rating level and room orientation in terms of their effect on wind turbine noise annoyance indoors and overall ($p > 0.05$).

Table 27: Wind turbine noise annoyance as a function of bedroom orientation towards the wind turbine

Room orientation in the bedroom	Wind turbine noise annoyance overall	Wind turbine noise annoyance indoors
	Mean (marginal mean) and standard error, adjusted according to rating level L_r	
Facing away from the wind turbine	1.61 (0.083)	1.23 (0.062)
Aligned sidewards to the wind turbine	1.68 (0.102)	1.35 (0.075)
Facing the wind turbine	1.90 (0.113)	1.49 (0.079)

6.4.11 Descriptive statistics of the noise level data

The calculated continuous sound levels L_{Aeq} for day and night were combined with address data so that noise levels could be calculated for the residential building of each respondent in the sample. Because the forecast assumed continuous, 24-hour wind turbine operation, the rating level for daytime operation ($L_{r,day}$) corresponds to that for the night time ($L_{r,night}$). Table 28 shows mean values, the standard deviation and the calculated minimum and maximum rating levels based on the respondents' respective residential addresses, both for the total sample and per study area.

Table 28: Rating level L_r in dB in the total sample of respondents and per survey area

L_r in dB	N	M	SD	Min	Max
Total	463	31.29	5.53	17.0	43.0
SA 1	149	31.97	2.89	24.0	42.0
SA 2	108	23.92	5.08	17.0	36.0
SA 3	94	33.02	1.92	30.0	37.0
SA 4	43	35.20	4.32	26.0	43.0
SA 5	69	36.52	1.94	30.0	42.0

M = mean value across rating levels based on the respondents' respective residential addresses, in dB; SD = standard deviation in dB; Min = minimum; Max = maximum. The rating level L_r applies to the day and night period.

6.4.12 Annoyance due to wind turbine noise per assessment-level class

Table 29 shows the noise annoyance per class of noise rating level L_r for the total sample of interviewees. It becomes clear that noise annoyance overall, as well as inside and outside the home, in the two top level classes of 35.1 – 40.0 dB and ≥ 40.1 dB, on occasion significantly exceeds the level classes below. In the level classes up to L_r = 35 dB, i.e. the level classes of ≦ 20 dB up to the level class of 30.1 – 35.0 dB, there is no clear discernible relationship between rating level and the judgement of annoyance. The noise rating levels below 35 dB are probably too low to lead to systematic differences in annoyance among local residents.

Table 29: Noise annoyance per class of noise rating level

Level class L_r	N	Noise annoyance due to wind turbines, overall	Noise annoyance in the home due to wind turbines, indoors	Noise annoyance outside the home due to wind turbines, outdoors
		M (SD)	M (SD)	M (SD)
≤ 20 dB	23	1.04 (0.21)	1.00 (0.0)	1.04 (0.21)
20.1 - 25.0 dB	56	1.79 (1.09)	1.39 (0.80)	1.77 (1.10)
25.1 - 30.0 dB	57	1.46 (1.09)	1.30 (0.76)	1.46 (1.07)
30.1 - 35.0 dB	206	1.37 (0.89)	1.17 (0.57)	1.38 (0.81)
35.1 - 40.0 dB	109	2.53 (1.46)	1.78 (1.11)	2.55 (1.50)
≥ 40.1 dB	12	3.33 (1.24)	2.67 (1.72)	3.17 (1.80)

N = number; M = mean value; SD = standard deviation in dB(A)

Across the entire survey sample, the highest average report of noise annoyance is seen in SA 5, where noise annoyance due to wind turbine noise also exceeds that of other areas (cf. Table 29).

6.4.13 Correlations with rating level and noise annoyance

A correlation calculation demonstrates the strength of bilateral correlations between two variables, thus providing initial indications for the following analyses of exposure impact with regard to the relationships between the variables of rating level, wind turbine noise annoyance overall, indoors and outdoors, and other possible influencing variables involved in annoyance due to wind turbines. Values close to 1 indicate a high concurrent correlation ('the more, the more'), whereas correlation values close to -1 indicate an opposite correlation ('the more, the less'). Zero values indicate the absence of a relationship. The results are presented in Table 30.

First of all, the results presented in Table 30 show that the rating level L_r correlates, with a small effect size (Cohen, 1988), with judgements of annoyance due to wind turbine noise. At $0.219 \leqq r \leqq 0.272$, the correlation coefficients fall in a range familiar from the literature on wind turbine noise annoyance. For instance, in their systematic review of annoyance with ambient noise, for wind turbine noise annoyance Guski et al. (2017) identify an average correlation between noise annoyance and noise level equal to $r = 0.278$, with a range of $0.130 \leq r \leq 0.464$.

Judgements of wind turbine noise annoyance correlate highly with each other, whereby overall wind turbine noise annoyance correlates more strongly with outdoor wind turbine noise annoyance (r = 0.801) than with the indoor wind turbine noise annoyance (r = 0.646).

Table 30: Correlations between noise annoyance, rating level and other potential influencing factors of wind turbine noise annoyance

	Noise rating level L_r	Wind turbine noise annoyance overall	Wind turbine noise annoyance indoors	Wind turbine noise annoyance outdoors
Noise rating level L_r	1.000	0.263**	0.219**	0.272**
Wind turbine noise annoyance indoors	0.219**	0.672**	1.000	0.646**
Wind turbine noise annoyance outdoors	0.272**	0.801**	0.646**	1.000
Noise sensitivity	0.027	0.174**	0.177**	0.163**
PSS1_Stress mean score on helplessness	0.039	0.171**	0.178**	0.184**
PSS2_Stress mean score on self-efficacy	-0.093*	-0.007	-0.084	-0.069
Lack of rest[1]	0.148**	0.681**	0.582**	0.687**
Negative consequences[1]	-0.198**	0.442**	0.313**	0.446**
Positive consequences[1]	0.010	-0.307**	-0.258**	-0.298**
Visual impact[1]	0.085	0.744**	0.591**	0.726**
Rumbling	0.105*	0.366**	0.317**	0.343**
Droning	0.045	0.380**	0.327**	0.354**
Rushing	0.039	0.368**	0.317**	0.388**
Humming	0.048	0.411**	0.341**	0.403**
Pulsating	-0.016	0.279**	0.274**	0.251**
Whistling	0.088	0.359**	0.373**	0.378**
Whooshing	0.128**	0.414**	0.330**	0.418**
Fluctuation	-0.085	0.353**	0.368**	0.321**

[1] Summary score of multiple items (individual questions); * = $p < .05$; ** = $p < .01$; p = significance level

In addition to the noise level, there are other factors related to wind turbine noise annoyance. It turns out that nearly all of the other potential influencing variables significantly correlate with wind turbine noise annoyance. An exception is the stress self-efficacy score, which does not correlate with any of the judgements of annoyance.

Visual impact, for example, bears a strong relation to the wind turbine noise annoyance overall (r = .744) and outdoors (r = .726); this finding is also known from other studies (including

Michaud et al., 2018a,b; Hübner et al., 2019). This means that the more pronounced the perceived visual impact due to wind turbines, the greater the annoyance due to wind turbine noise. Visual impact does not correlate with the rating level, however. Similarly, as Table 30 shows, there are clear correlations between wind turbine noise annoyance and attitudes to wind turbines. Thus, the perceived lack of options for rest correlates with coefficients of $0.582 \leq r \leq 0.687$, and the fear of negative consequences of operation of local wind turbines correlates with wind turbine noise annoyance indoors, overall and outdoors, with coefficients of $0.313 \leq r \leq 0.446$. At a slightly lower level, with correlation coefficients of $-0.307 \leqq r \leqq -0.258$, wind turbine noise annoyance is associated with perceived positive consequences of local wind turbine operation, where the more positively the consequences of the wind turbines are assessed, the lower the wind turbine noise annoyance. The attitude score for 'Lack of rest' also correlates slightly yet statistically significantly – with $r = 0.148$ – with the rating level, according to which the lack of options for rest is assessed more severely with higher levels of noise annoyance. Interestingly, this is the reverse for fears of negative consequences: they are somewhat more pronounced in areas with less noise annoyance than they are in areas with more noise annoyance. In this connection, it is necessary to recall the individual aspects of this attitudinal score: the economic aspects (diminishing property value, failure to promote regional development) and the visual aspect of landscape disfigurement. The assessments relating to economic consequences can be more due to fears than a result of specific experiences: the way the question is formulated, they do not concern one's own personal situation but rather the expected impacts for the region. The assessment of wind turbines as a disfigurement to the landscape relates to wind turbine visibility; this visibility is a given fact even at a greater distance from the wind turbines (perhaps even better), which may be why it is mentioned even at lower noise rating levels. Other authors have already pointed out that the visibility of wind turbines and the visible number of local turbines can have an effect on noise annoyance (summary: Freiberg et al. 2019, Van Kamp & van den Berg, 2017, 2020). To a lesser yet still statistically significant extent, individual noise sensitivity correlates with wind turbine noise annoyance ($0.163 \leq r \leq 0.177$), but not with the rating level. This was to be expected as noise sensitivity is an individual, stable personality trait that does not depend on a specific noise situation to which a person is exposed (among others, Job, 1999). The stress score of 'helplessness' correlates with wind turbine noise annoyance in the same way and to the same extent as noise sensitivity and bears no relationship to the rating level. It can be assumed that the stress factor of 'helplessness' as well as noise sensitivity reflect a person's general vulnerability (susceptibility) to ambient noise exposure (see also Section 6.4.5).

All of the variables that describe the sound characteristics of wind turbines, such as rumbling, rushing and whooshing, significantly correlate with the annoyance variables (see Table 30), the most pronounced of which are the sound characteristics of 'whooshing' and 'humming', whereby 'whooshing' correlates more strongly with wind turbine noise annoyance overall ($r = 0.414$) and outdoors ($r = 0.418$), and 'humming' correlates more with wind turbine noise annoyance overall ($r = 0.411$) and indoors ($r = 0.403$). The correlations mean that wind turbine noise annoyance is all the more pronounced the more the wind turbine sound characteristics are perceived as 'whooshing' or 'humming'. The correlation between the perceived sound characteristics and the rating level is less pronounced. Thus, for example, only rumbling ($r = .105$) and whooshing ($r = .128$) have a significant correlation to the rating level, i.e. perception of these sound characteristics is slightly stronger at higher rating levels.

6.4.14 Exposure-response relationships with regard to wind turbine noise

6.4.14.1 Exposure-response analyses for wind turbine noise annoyance

Simple and multiple logistic regression models were calculated to illustrate the relationship between the percentage of highly annoyed persons (%HA) and the rating level L_r.

The highly annoyed persons are those who indicated one of the top two levels, 4 and 5 (strongly and extremely) in their response to the five-point annoyance scale. Annoyed persons are those who chose one of the top three levels (fairly, strongly, extremely). The simple models (basic models) have only the rating level as a predictor (influencing factor). The multiple models (extended models) also contain other influencing variables associated with the judgement of annoyance, as identified using the correlation calculations (see Section 6.4.13). Of the variables examined in the correlation analyses, only the attitudinal score for 'self-efficacy' was removed from further model analyses, as this score bears no statistically significant relationship to wind turbine noise annoyance. Accordingly, the following remaining potential influencing variables were included in the modelling:

- noise sensitivity,
- perceived stress-related factor of 'helplessness',
- attitudinal factors around wind turbines: 'lack of rest', 'negative consequences', 'positive consequences',
- the sound characteristics of rumbling, droning, rushing, humming, pulsating, whistling, whooshing, fluctuation.

The results of the regression analyses (coefficients) are presented in tabular form in Appendix D.5.

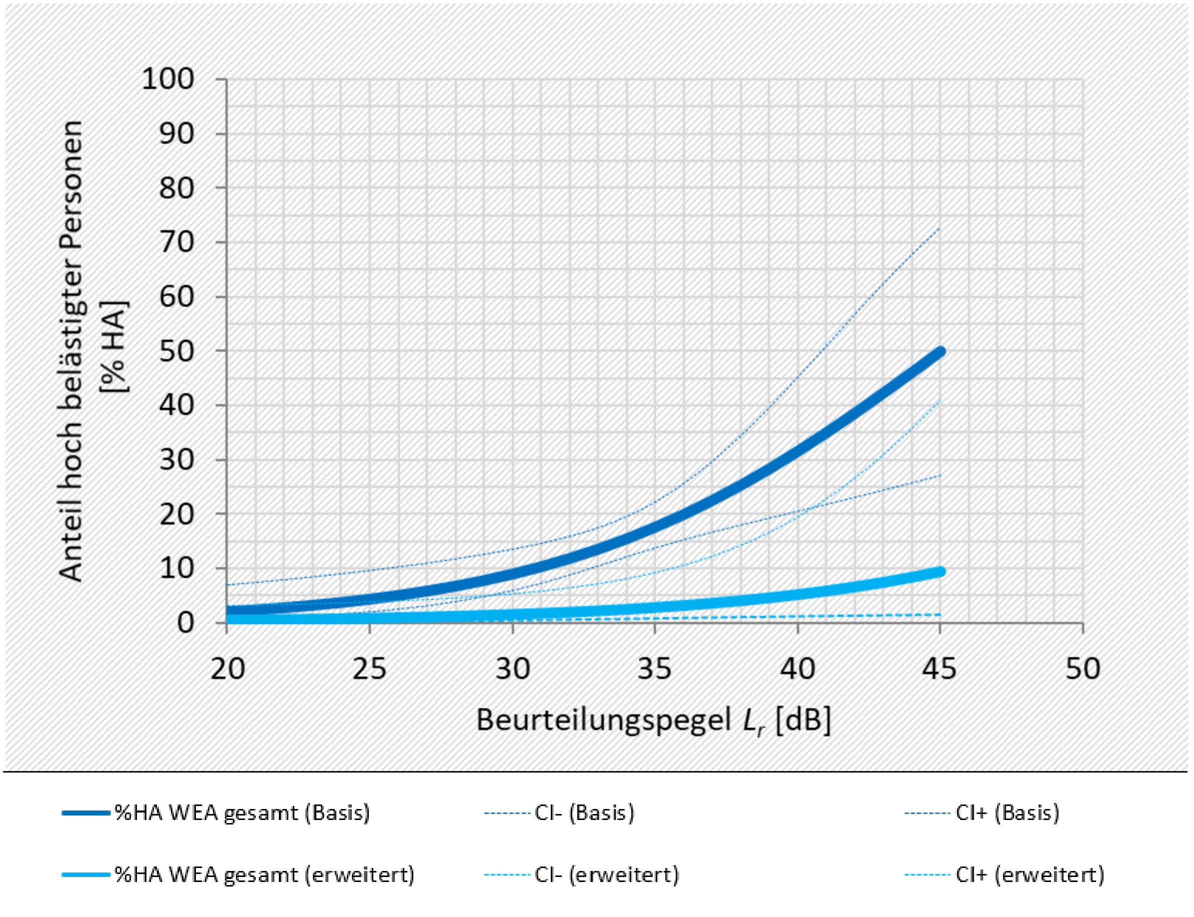
6.4.14.2 Regression models for the proportion of highly annoyed persons

Figure 58 to Figure 60 show the exposure-response curves for %HA due to wind turbines overall, outdoors and indoors. The depicted %HA curves (solid curves) indicate the percentages of people highly annoyed at given rating levels. The dashed lines (CI- and CI+) indicate the lower and upper limits of the confidence interval (95% confidence interval) for the respective %HA curve. While the basic model stems from a prediction model with only the rating level as the influencing variable, the extended model additionally takes into account the further influencing variables mentioned in Section 6.4.14.1, i.e. the %HA curve is 'adjusted' based on these further influencing variables. The further influencing variables 'flatten' the %HA curve relative to the rating level, i.e. the variance in the %HA component elucidated by the rating level decreases. For wind turbine noise annoyance indoors, the %HA component is hardly predictable based on rating level once the other influencing variables are added. For the %HA component overall and outdoors, it can be seen that, if further influencing variables are taken into account, the %HA share over the assessed rating level range is lower than in the basic models without taking into account the further influencing variables.

Among the influencing factors related to attitudes, it is mainly the sense of limited use of the outdoors and a lack of opportunities to relax (lack of rest), together with the visual impact of the wind turbines, that influences respondents' judgement of noise annoyance (see also Figure 61). Among the perceived sound characteristics, it is mainly the whooshing, together with the rushing sound and perceived fluctuations, that account for the share of high annoyance. It can be assumed that these are characteristics that reflect the subjective perception of amplitude modulations.

The regression models identified are compared and assessed in detail in Sections 6.6 and 6.7.

Figure 58: Percentage of persons who are highly annoyed (% HA) by wind turbine noise, overall

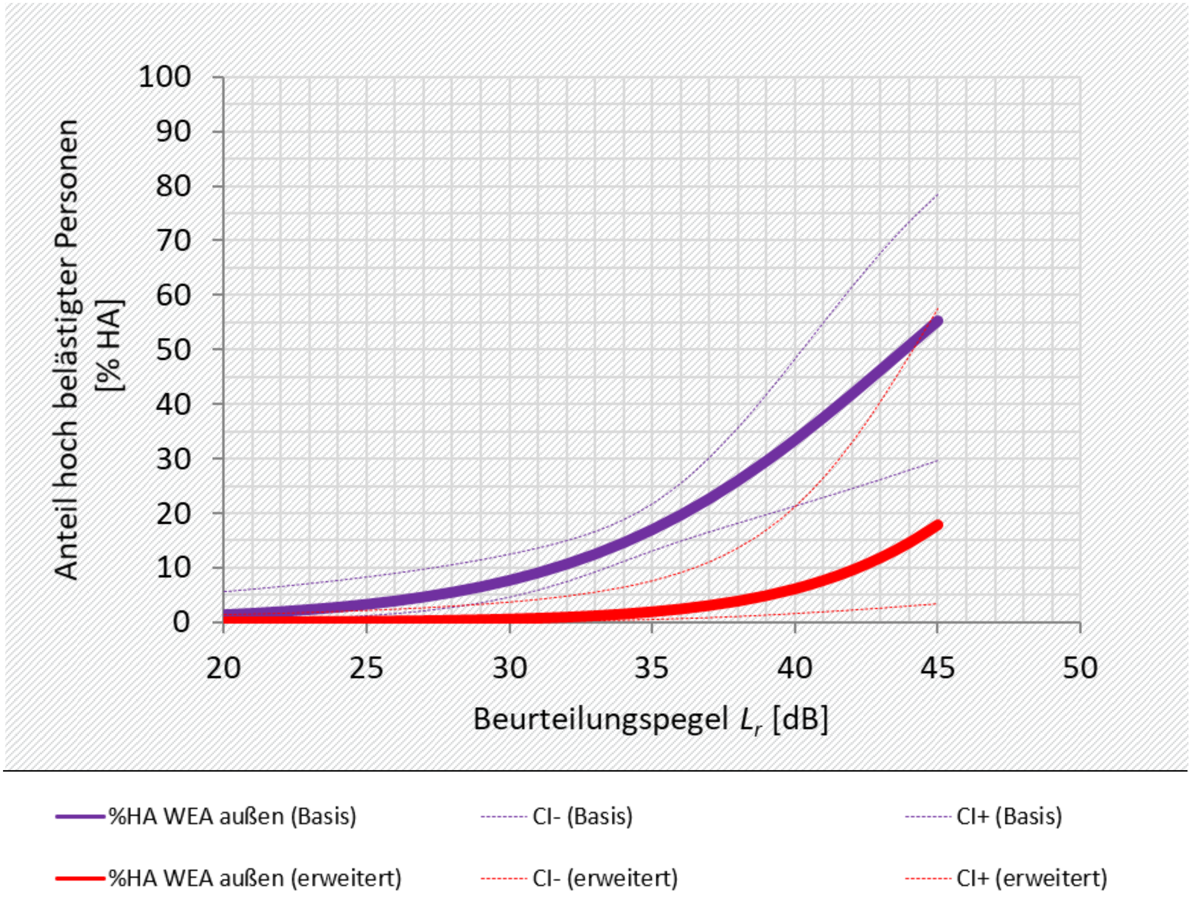


Quelle: eigene Darstellung, ZEUS GmbH

% HA = % highly annoyed; WT = wind turbine; CI-/+ = lower/upper limit of the confidence interval of the exposure-response curve; Basis: Influencing factor noise rating level L_r unadjusted; Extended: Influencing factors noise rating level L_r, noise sensitivity, attitude towards wind turbines, perceived stress, visual impact of wind turbines, sound characteristics

Anteil hoch belästigter Personen = Percentage of highly annoyed persons; Beurteilungspegel L_r[dB] = Noise rating level L_r[dB]; %HA WEA gesamt (Basis) = %HA wind turbine overall (basic); %HA WEA gesamt (erweitert) = %HA wind turbine overall (extended); CL- (Basis) = CI- (basic); CL- (Basis) = CI- (basic); CL+ (Basis) = CI+ (basic); CL+ (Basis) = CI+ (basic); Quelle: eigene Darstellung, ZEUS GmbH = Source: own presentation, ZEUS GmbH

Figure 59: Percentage of persons highly annoyed (% HA) by the outdoor impact of wind turbines

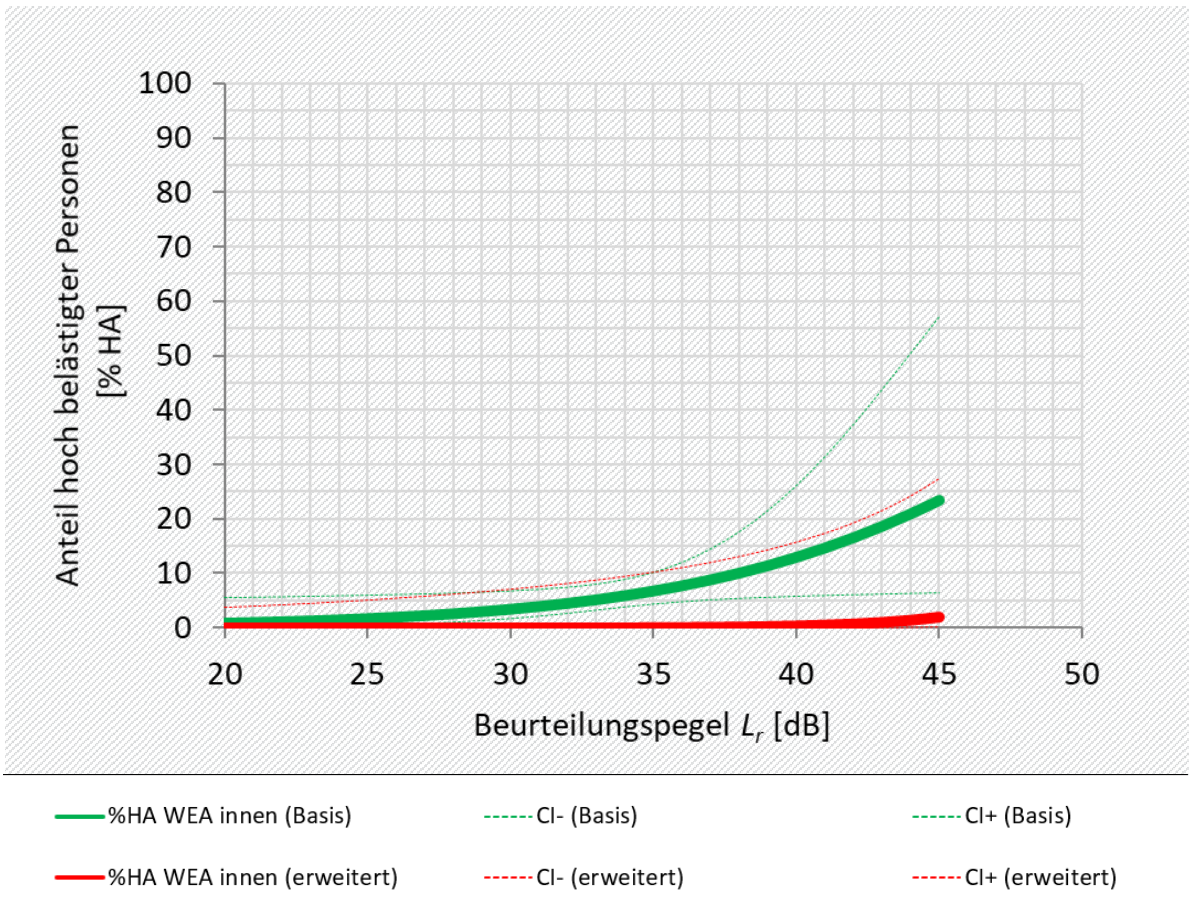


Quelle: eigene Darstellung, ZEUS GmbH

% HA = % highly annoyed; WT = wind turbine; CI-/+ = lower/upper limit of the confidence interval of the exposure-response curve; Basis: Influencing factor noise rating level L_r unadjusted; Extended: Influencing factors noise rating level, noise sensitivity, attitude towards wind turbines, perceived stress, visual impact of wind turbines, sound characteristics

Anteil hoch belästigter Personen = Percentage of highly annoyed persons; Beurteilungspegel L_r[dB] = Noise rating level L_r[dB]; %HA WEA außen (Basis) = %HA wind turbine outdoors (basic) ; %HA WEA außen (erweitert) = %HA wind turbine outdoors (extended); CL- (Basis) = CI- (basic); CL- (erweitert) = CI- (extended); CL+ (Basis) = CI+ (basic); CL+ (erweitert) = CI+ (extended); Quelle: eigene Darstellung, ZEUS GmbH = Source: own presentation, ZEUS GmbH

Figure 60: Percentage of persons highly annoyed (% HA) by the indoor impact of wind turbines



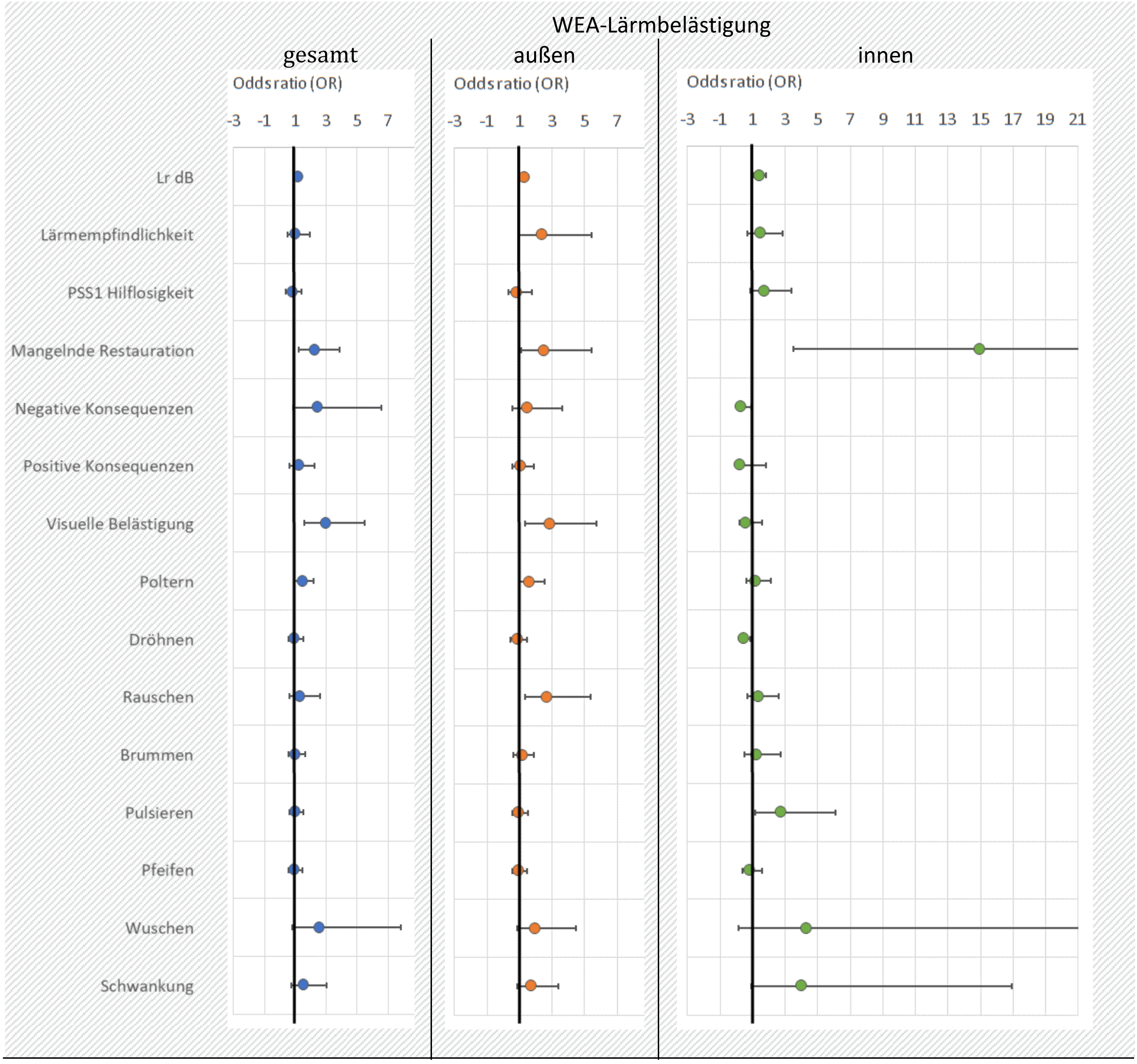
Quelle: eigene Darstellung, ZEUS GmbH

% HA = % highly annoyed; WT = wind turbine; CI-/+ = lower/upper limit of the confidence interval of the exposure-response curve; Basis: Influencing factor noise rating level L_r unadjusted; Extended: Influencing factors noise rating level L_r, noise sensitivity, attitude towards wind turbines, perceived stress, visual impact of wind turbines, sound characteristics

Anteil hoch belästigter Personen = Percentage of highly annoyed persons; Beurteilungspegel L_r[dB] = Noise rating level L_r[dB]; %HA WEA innen (Basis) = %HA wind turbine indoors (basic) ; %HA WEA innen (erweitert) = %HA wind turbine indoors (extended); CL- (Basis) = CI- (basic); CL- (erweitert) = CI- (extended); CL+ (Basis) = CI+ (basic); CL+ (erweitert) = CI+ (extended); Quelle: eigene Darstellung, ZEUS GmbH = Source: own presentation, ZEUS GmbH

Figure 61 shows the strength of the various influencing factors on overall annoyance due to wind turbine noise, outdoors and indoors, with the odds ratio (OR) as a measure of how strong the effect is. The reference value is the value 1. If the odds ratio (shown as points in the diagrams), with its confidence interval included (black lines above/below the point) is completely below or above the reference value of 1, then the influence considered is statistically significant. The more the odds ratio, including its confidence interval, deviates from the value of 1, the stronger the effect. In contrast to the case with the correlation coefficients presented in Section 6.4.13, each of the odds ratios of the respective influencing variables presented here reflects the strength of the influence above and beyond the influence of the other factors.

Figure 61: Effect size (odds ratio) of the influencing variables of annoyance due to wind turbine noise



Quelle: eigene Darstellung, ZEUS GmbH

The points shown depict the odds ratio (OR) as a measure of the strength of effect of the respective influencing factor on wind turbine noise annoyance overall (blue dots), both outside (orange dots) and inside the home (green dots). The horizontal lines through the dots represent the 95% confidence interval of the OR. The reference is an OR = 1. If an OR value including its confidence interval is greater than 1 (shown at the right in the figure), then the impact of the influencing factor adds to the annoyance. If an OR value is less than 1 (shown at the left in the figure), then this influencing factor diminishes the annoyance.

Lärmempfindlichkeit = Noise sensitivity; Mangelnde Restauration = Lack of rest; Negative Konsequenzen = Negative consequences; Visuelle Belästigung = Visual nuisance; Poltern = Rumbling; Dröhnen = Droning; Rauschen = Rushing; Brummen = Humming; Pulsieren = Pulsating; Pfeifen = Whistling; Wuschen = Whooshing; Schwankung = Fluctuating; WEA-Lärmbelästigung = WT noise annoyance; Gesamt = Overall; Odds ratio (OR) = Odds ratio (OR); Außen = Outdoors; Innen = Indoors; Quelle: eigene Darstellung, ZEUS GmbH = Source: own presentation, ZEUS GmbH

6.5 Results of the in-depth interviews

A total of 25 people took part in the qualitative survey. These participants were selected at random. The breakdown across the different study areas was as follows: five persons from SA 1, SA 2 and SA 5, four persons from SA 3 and six from SA 4.

What follows is a presentation of the results of the qualitative survey in the order in which the questions were presented in the guideline. For each topic, first an overall consideration of interviewees' statements is performed across all study areas. Any differences identified between study areas are highlighted and discussed. The figure in parentheses indicates the number of persons making the statement in question.

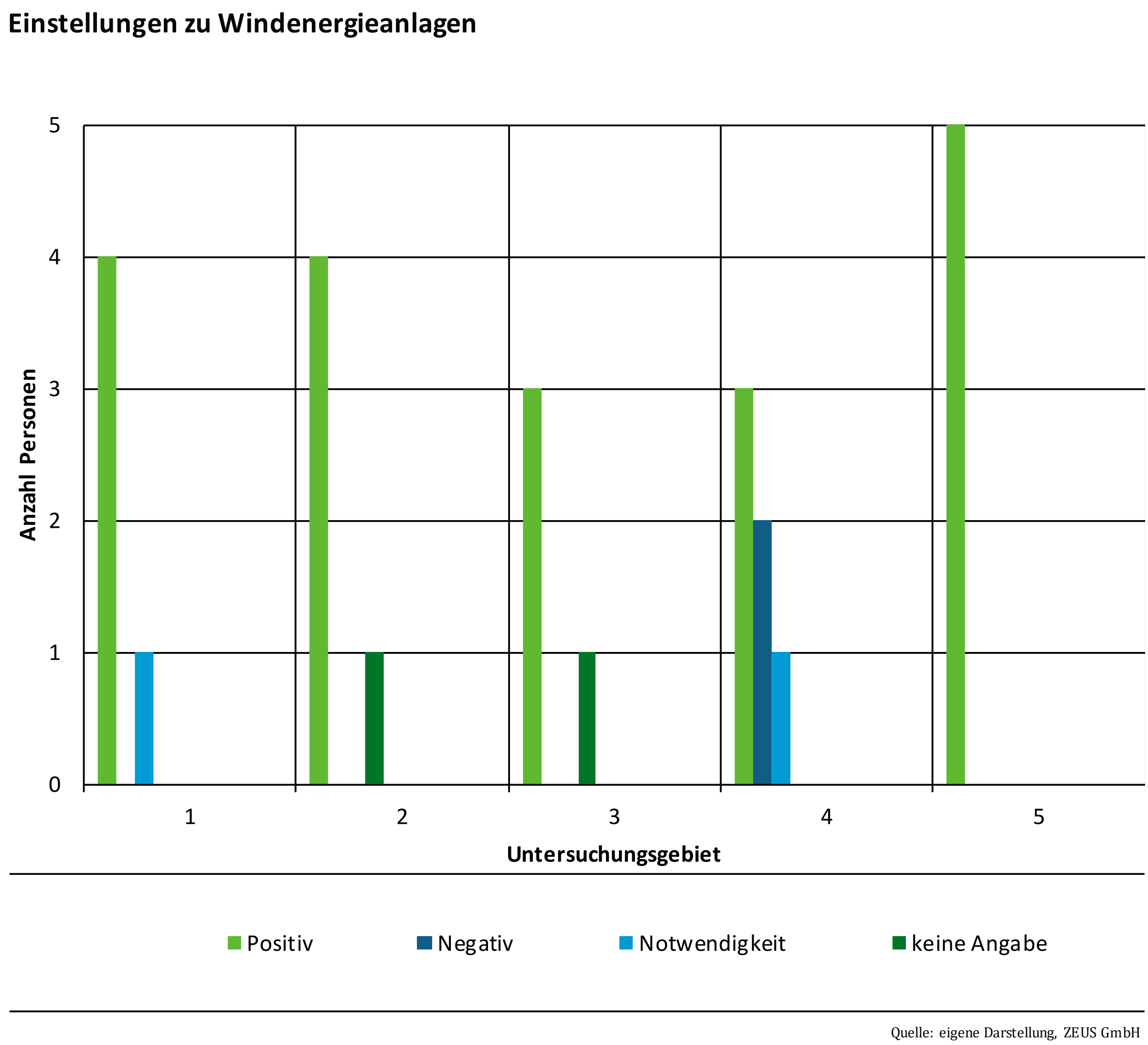
6.5.1 Attitudes towards wind turbines

Most participants have a positive attitude towards wind turbines (N = 19); four respondents pointed out that turbines should be built and used in environmentally-compatible ways and should not have an impact on either nature or people. Two other people do not speak about wind turbines directly but view them as absolutely necessary. Two people, both from SA 4, take a negative attitude towards wind turbines. A graphical representation of the attitudes towards wind turbines can be found in Figure 62.

11 respondents indicated that they have no personal connection or point of contact with wind turbines. Others mention the visual (N = 5) and acoustic impacts (3) of the turbines. Three people have a professional connection or point of contact with wind turbines. One respondent worries that the turbines could have a negative impact on their business, as guests have already complained about the wind turbines. Three other people find the topic of wind energy relevant in and of itself.

Many people consider the energy that wind turbines generate to be sustainable, clean and a necessary alternative to other methods of energy production (19). Two persons point out that wind energy cannot be stored.

Figure 62: Comparison of attitudes towards wind turbines across study areas (n=25)



Anzahl Personen = Number of people; Anzahl Personen = Number of people; Untersuchungsgebiet = Study Area; Positiv = Positive; Negativ = Negative; Notwendigkeit = Necessity; Keine Angabe = Not specified

6.5.2 Impacts of wind turbines located near residential areas

All in all, participants cited significantly more negative than positive impacts of wind turbines near residential areas. Participants were free to mention several aspects in response to this question. It should be noted that participants mentioned perceptible effects for themselves as well as effects that they can generally imagine or have heard of from others.

17 people cite the turbine noise as negative impacts. Other negative impacts mentioned are shadow casting (N = 9), landscape disfigurement (N = 6) and the lighting of the wind turbines (N = 5), which can be particularly bothersome at night. Three people criticise the fact that the electricity generated cannot be used locally. Two respondents from SA5 also reported local deforestation as a negative impact.

6.5.3 Changes due to the construction of the wind turbines

All participants stated that they had already lived in the study area before the wind turbines were built and were able to compare life with and without wind turbines. Particularly the noise now perceptible (N = 8) and the visual impacts (N = 4) were important in this connection. Six persons cannot see any difference or changes in their everyday life relative to the wind turbines.

6.5.4 Side effects

Participants were also asked whether they noticed or suspect other side effects in addition to noticing wind turbine noise. Most respondents did not experience any other physical or psychological side effects apart from the noise. A total of four people indicated that they sensed other physical and/or psychological side effects in addition to wind turbine noise. Three of these people come from SA 3. Two of the three people state that they have already experienced an uncomfortable feeling due to the wind turbines, and the third person from SA 3 indicates that they have already experienced a sense of pressure when standing directly next to a wind turbine. One person from SA 2 noticed vibrations.

6.5.5 Perception of and disturbance by wind-turbine noise

16 people are able to hear wind turbine noise at home, and nine people cannot. People who can hear the noise at home were asked to assess the loudness of these noises based on a scale. The results are very wide-ranging and are presented, both overall and for the individual study areas, in Table 31.

Table 31: Perceived loudness of wind turbine noise (n=16)

Scale	SA 1	SA 2	SA 3	SA 4	SA 5	Overall
Very loud					1	**1**
Loud			1		1	**2**
More loud than quiet		1		1		**2**
Neither loud nor quiet		1		1	1	**3**
More quiet than loud	1	1	1	1		**4**
Quiet	1			1		**2**
Very quiet		1	1			**2**
Overall	**2**	**4**	**3**	**4**	**3**	**16**

Roughly one respondent in three reported having already felt annoyed by wind turbine noise (8). As a countermeasure, three participants indicated that they would avoid the noise by keeping a distance from the turbines outside or changing rooms inside the house. One person stated that the bedroom had been installed in a room facing away from the wind turbines due to the noise pollution. Many respondents do not take any direct steps if they are annoyed by the noise from the turbines.

6.5.6 Description of sound characteristics

The next set of questions concerned the characteristics of the noise and the frequency and timing of its occurrence. At times, the noise emanating from wind turbines is described in very different terms. The word used most commonly to describe the noise emitted by wind turbines was ‘rushing’ (7). Others described it as a kind of ‘whooshing noise’ (3), a ‘whizzing’ (1) or as a ‘flop’ noise (1). The noises were compared to an aircraft flying overhead (2), a passing train (2), but they were also considered similar to the noise of a running washing machine (1) or the sound of sea surf (1). Two people also noticed gear noises when they were near the wind turbines. Two other people found the sounds pleasant. Some describe wind turbine noise as interval-like rushing (3), or interval-like whizzing (1), while others describe it as steady (2). The incidence of noise depends on the wind direction (3). Three people report that it is rare and two people report hearing it on a regular basis. According to six participants, the noise occurs mainly in the evenings, particularly if other noise sources such as traffic are eliminated or greatly reduced. The noise is particularly disturbing when outdoors (4) and during periods of relaxation (3).

Results for the nine comparisons of word pairs are presented only for the first two study areas (SA 2 and SA 1), as it was only possible to play the sound sample (amplitude modulation) to in-person interviewees. A precise overview of the comparison of word pairs can be found in Appendix D.6. It is striking that respondents from SA 1 perceive the noise as considerably more pleasant, calm, static, harmonious and complex than people from SA 2. All in all, persons from SA 2 use the answer category ‘neither nor’ (22) much more often than persons from SA 1 (7 mentions of ‘neither nor’). One word pair in which both groups responded ‘neither nor’ particularly often is ‘warm or cold’ (3 each).

None of the persons interviewed is a member of a citizens' initiative or other association involved in the topic of wind energy. By way of other concluding remarks, two people indicated that wind turbines represent a good compromise to previous methods of energy production. Two people also felt that profit-sharing for a municipality/residents could boost the acceptance of wind turbines. Another person criticised that holding a share in wind turbines was too expensive for the citizenry. Others expressed disappointment with politics (1), concern about a planned expansion and the effects this will have (1) and the disturbing lighting of the wind turbines (1).

6.6 Conclusion based on the survey results

6.6.1.1 Conclusion with regard to the results of the main survey

463 residents were asked about annoyance and disturbances caused by wind turbine noise, their feelings of stress, and about their attitudes towards wind turbines and various aspects of living conditions; rating levels were calculated for their residential addresses.

The results of the main survey show that judgements around annoyance due to wind turbine noise at the five locations studies are low. In other words, on average, the overall degree of annoyance caused by wind turbines is 1.75 on a scale of 1 (not bothered or annoyed at all) to 5 (extremely bothered or annoyed). This roughly matches up with the average degree of annoyance (1.78) expressed in the survey sample with regard to road traffic noise in the study areas, which had a rather rural overall structure and comparatively low road traffic volume. The rating level Lr for day and night falls in the range of 16 dB to 43 dB in the study areas. It was not possible to measure or calculate noise levels from other types of source, e.g. road traffic, that could serve as a reference value for the five study areas considered. A comparison of sources with regard to annoyance in this study is limited. For the interpretation of similarities (e.g. in annoyance due to wind turbine and road traffic noise) and differences in source-specific noise annoyance information on the underlying noise exposure would have to be known for all to be compared sources. The results of this study on annoyance due to wind turbines can, however, be compared with generalised results from noise-effect research. One possibility is the 2018 World Health Organisation (WHO) Environmental Noise Guidelines for the European Region (WHO, 2018), as well as the systematic review of environmental noise annoyance that underlies the guidelines on the health effects of environmental noise (Guski et al., 2017). This will be discussed in greater detail in the following Section 6.7.

As for the role of amplitude-modulated noise emitted by wind turbines for explaining residents' noise annoyance, the following picture emerges:

- Among the sound characteristics, respondents are most likely to agree to a description of the noise as a ‘whooshing’ that has an influence on the wind turbine noise annoyance, followed by the description (presumably meant periodically) as ‘rushing’ but also ‘pulsating’. ‘Whooshing’ is the sound characteristic cited more frequently by respondents as the most annoying characteristic in comparison to other sound characteristics. These descriptions of the noise as a ‘whooshing’ (periodic) ‘rushing’ and ‘pulsating’ can be understood as characteristics of subjective descriptions of amplitude modulations.
- Wind turbine noise annoyance differs across study areas inasmuch as the annoyance experienced in SA 1 and SA 3 is lower than in the other study areas. These areas are characterized by the fact that the respondents describe the wind turbine noise as ‘whooshing’ to a lesser extent, and these are the areas with lower occurrence frequencies of detected, stable AM than seen in the other areas. In this respect, there appears to be a correspondence between area-based differences in noise annoyance, subjectively perceived AM and the different frequencies of occurrence of the AM detected during measurements in the areas. By contrast, there seems to be no correspondence with the modulation depth of the AM.
- Hence, a deduction from the findings is that the frequency of occurrence of detected, stable periodic AM and its subjective perception has an increasing effect on annoyance due to wind turbine noise. The information provided by interviewees in the in-depth study on the disruptive nature of wind turbine noise confirms this impression as well. As presented in detail in Section 7, the listening tests also exhibit a clear influence of AM on short-term annoyance.

In addition to the rating level, there are non-acoustic factors that also influence levels of annoyance over noise: one’s individual noise sensitivity, the attitude towards wind energy and local wind turbines, the general psychological feeling of stress, particularly the stress-promoting factor of ‘helplessness’ (in stressful situations) and the visual impacts (the mere sight, shadow casting, the aviation-obstruction lighting, the rotational movements, and the impact on the landscape). Among these factors, the views on noise annoyance were influenced most by the attitude towards limitations on use of the outdoors and the impediments to opportunities for relaxation, along with visual impacts.

Regarding the %HA due to wind turbine noise overall and outdoors, the non-acoustic factors that affect the expression of high noise annoyance specifically include the attitude that wind turbine noise impedes enjoyment of time outdoors, and that the turbines create a visual nuisance. In terms of wind turbine noise annoyance indoors, perceptions of impaired conditions for relaxation and activities outdoors have a very clear influence on %HA. It is assumed that interviewees experience the lack of outdoor relaxation, 'including around the house' or feel all the more annoyed by wind turbine noise in the flat/house if they feel they cannot spend time outdoors in peace or relax in their surroundings.

The statistical correlation between the rating level and annoyance due to wind turbine noise is lower than the usual strength of the correlation between noise levels and judgements of annoyance due to traffic noise (Guski et al., 2017). Although the rating levels in simple and extended models are significant, i.e. wind turbine noise annoyance also increases as rating levels increase, the analyses in this study show that there are other factors, specifically the non-acoustic factors mentioned above, that contribute to wind turbine noise annoyance, and that in some cases these factors are stronger predictors of the share of annoyed or highly annoyed persons. These additional factors modify the exposure-response relationship between noise rating levels and wind turbine noise annoyance. This is evident through the fact that when further non-acoustic factors and perceived sound characteristics in the exposure-response models are statistically controlled for, the exposure-response curves shift in magnitude and in slope (downwards). In this case, the %HA elucidated by the rating level decreases. In the case of wind turbine noise annoyance indoors, the rating level hardly contributes to prediction of the %HA component if the further influencing variables are added to the prediction model.

6.6.1.2 Conclusion with regard to the results of the in-depth survey

As the in-depth survey shows, those surveyed generally take a positive view of wind energy overall, and of the wind turbines in their local vicinity as well. Even if most respondents do not feel directly annoyed by the wind turbines, they can imagine that other people might be annoyed by noise, for example, and by shadow casting, as well as by interference with the landscape and the lighting. For the most part, the noise the wind turbines produce is described as noise that is particularly noticeable in the evenings. This is an indication of the disturbing nature of amplitude modulation. In principle, in contrast to the results of the main survey, there are apparently very few differences across the study areas in terms of the statements made about wind turbine sound characteristics. As was revealed through the in-depth survey, visual impacts also seem to play a role in addition to noise. Given that with 25 individuals the sample of participants in the in-depth survey was small, no concrete conclusions can be drawn from the differences identified. They do, however, tend to support the findings of the main survey.

6.7 Discussion and classification of the survey results

The rating level L_r used in this study is based on 24-hour wind turbine operations. In other words, broken down into the daytime level from 6:00 a.m. until 10:00 p.m. $L_{r,day}$ and the night-time level for the time from 10:00 p.m. 6:00 a.m. $L_{r,night}$ the same levels for $L_{r,day}$ and $L_{r,night}$ emerge for the respective residential building of the individuals surveyed. All in all, the level calculated for many of the residential buildings was low and ranged between 20 and 43 dB. This is accompanied by a low level of noise annoyance of the survey participants. On the five-point verbal scale of annoyance, then, the average judgement of annoyance by the persons interviewed lies between the verbal categories of 'not at all disturbed or annoyed' (1) and 'slightly disturbed or annoyed' (2). This result must be understood to mean that, since the persons interviewed are exposed to low levels, their annoyance over wind turbine noise across the entire sample also presents a low mean value over the entire annoyance scale from 1 (not annoyed at all) to 5 (extremely annoyed). On the other hand, an exposure-response curve shows an if-then situation for highly annoyed persons, i.e. this indicates how high the percentage of highly annoyed individuals will be at a certain level, even if this level occurs only rarely in the sample.

In this study, such exposure-response curves have been estimated in regression analyses to identify the percentage of highly annoyed persons regarding the wind turbine noise annoyance overall, and separately for situations indoors or outdoors at home related to the rating level. Below, they are compared to findings of the Environmental Noise Guidelines for the European Region issued by the World Health Organisation (WHO) in 2018. However, this comparison is subject to the limitation that the rating level in this study (L_r), calculated according to the interim procedure, differs from the yearly averaged day-evening-night level L_{den} used by the WHO in the Guidelines. L_{den} is composed of an averaging level for the daytime from 6:00 a.m. to 6:00 p.m. (L_{day}), an averaging level for the evening time from 6:00 p.m. to 10:00 p.m. ($L_{evening}$) and an averaging level for the night-time from 10:00 p.m. to 6:00 a.m.(L_{night}). Before these three averaging levels are summed up energetically, the evening level is provided with a penalty of 5 dB and the night level with a penalty of 10 dB in order to take account of the special need for rest at these times of day.

Piorr (2019) provides a proposal for use in converting the rating level, calculated according to the interim procedure, into the day-evening-night level. Given the lack of information about year-round wind conditions (speed, direction) and operating times, this study does not undertake a direct conversion of rating level and only makes a rough comparison instead.

The WHO Environmental Noise Guidelines (WHO, 2018) set the threshold for health relevance of noise annoyance at a value for the day-evening-night level L_{den} at which the proportion of *highly annoyed* people (%HA) exceeds 10% of those exposed to the given noise level. The levels at which this is the case result from generalised, source-specific exposure-response functions. The review by Guski et al. (2017) on environmental noise annoyance contains such exposure-response functions, which the WHO relies on in its environmental noise guideline recommendations regarding noise annoyance. There are other systematic reviews that address other health impacts; these reviews were drawn up in the course of developing the WHO Environmental Noise Guidelines. For various critical health impacts – along with noise annoyance, these include sleep disorders, cardio-vascular diseases, cognitive impairment and hearing damage – the WHO stated thresholds in its Guidelines (2018) at which, according to the WHO Guideline Development Group, health relevance is reached, i.e. beyond which health-relevant impacts occur. The Guidelines define the relevance thresholds per health impact due to environmental noise, broken down by the type of noise source. Although the WHO took different health impacts into account, the recommendations for the day-evening-night sound level (L_{den}) for all noise sources are based on long-term noise annoyance, as the relevance threshold of 10% HA was exceeded at the lowest level of continuous sound in comparison to the other relevance thresholds. The WHO set the following guideline values for various sources of noise:

- Noise due to air traffic at L_{den} = 45 dB(A),
- Noise due to road traffic at L_{den} = 53 dB(A),
- Noise due to rail traffic at L_{den} = 54 dB(A),
- Wind turbine noise at L_{den} = 45 dB(A)

The value of L_{den} = 45 dB for noise due to wind energy is based exclusively on the results of the systematic review of evidence on environmental noise annoyance carried out by Guski et al. (2017). In the review, the results of the meta-analysis by Janssen et al. (2011) and a Japanese study by Kuwano et al. (2014) were presented, and the stated guideline values were determined based on meta-analyses using basic models, i.e. taking only the rating level L_{den} as predictor of %HA into account. These WHO analyses do not contain non-acoustic factors or other predictors of sound characteristics. The reason for this is that the various international studies (a) analysed different influencing variables that (b) were measured in different ways, thus making comparisons of %HA as predicted by extended models including multiple predictors considerably more difficult.

In the present study, based on the basic models with the noise rating level as single predictor, the values of L_r at which the threshold of 10% of highly annoyed persons is exceeded (%HA = 10%) are

- around L_r = 31 dB for wind turbine noise annoyance overall,
- around L_r = 32 dB for wind turbine noise annoyance outdoors,
- around L_r = 38 dB for indoor wind turbine noise annoyance at an outdoor rating level

Given the simplifying assumption of year-round tailwinds and a uniform daily distribution of wind turbine noise over 24 hours, a value of 6.4 dB would have to be added to the rating level L_r in order to reach the corresponding value for L_{den}. Even then, however, in this study, 10% of people who are highly annoyed by wind turbine noise would be reached at L_{den} levels at least 1 to 8 dB lower than the WHO indicates for 10% HA. This study as well as the recommendations of the WHO (2018) on wind turbine noise both show that wind turbine noise leads to higher %HA than transportation noise for the same rating level L_{den}. This applies in particular to noise due to road and rail traffic.

Several reviews (Freiberg et al., 2019; van den Berg & van Kamp, 2017; van Kamp & van den Berg, 2020, among others) have also showed that, at a given level, there is higher annoyance due to wind turbine noise than due to other sources of environmental noise. Michaud et al. (2016b) assume that 'that communities are between 11 and 26 dB [A-weighed SPL] less tolerant of WTN than of other transportation noise sources' (p. 1455). A comparison of the basic model used in this study with other noise sources, and with road traffic noise in particular, also concludes on the basis of the 10% HA relevance threshold that wind turbine noise at the same level of noise exposure is perceived as more annoying.

The analyses of the extended models demonstrated that, among the non-acoustic predictors, it was the attitudes towards local wind turbines, the general stress factor of 'helplessness' (as an indicator of greater vulnerability), the visual impact and the sound characteristic of 'whooshing' that in some cases largely influence the percentage of highly annoyed people. In other words, the other influencing variables moderate the relationship between exposure to wind turbine noise and the impact of this exposure; these other variables play a stronger role for the wind turbine noise annoyance than the noise rating level itself.

The results of this study show that visual impact (including shadow casting, blinking aviation-obstruction lighting, the fact that the wind turbines are visible at all, the destruction of the landscape) contributes to wind turbine noise annoyance. This is in line, for example, with the study on wind turbine noise conducted in the USA by Haac et al. (2019), which showed that the visual impact went the furthest towards explaining noise annoyance. Hübner and colleagues (2019) compared the results obtained by Haac et al. (2019) with their own data based on surveys conducted in Germany and Switzerland. This re-analysis found no connection between wind turbine noise annoyance and the rating noise level. This is in line with the low correlations between wind turbine noise annoyance and the rating level in this study. Furthermore, the results obtained by Haac et al. (2019) and Hübner et al. (2019) showed that wind turbine visibility increases the noise annoyance; this is also in line with the results of this research project, where the visual impact also helps explain the noise annoyance. Hübner et al. (ibid.) also identified high significance in the attitudinal factors towards local wind turbines for the prediction of wind turbine noise annoyance; in the present research project, it is particularly the lack of opportunities to relax outdoors that exerts a high influence. A large-scale study conducted in Canada on the health effects of wind turbine noise also concludes from its findings that attitudinal factors contribute to the noise annoyance (Michaud et al., 2016a, b).

Both Hübner et al. (2019) and Michaud et al. (2018a, b) propose not to consider noise annoyance separately, but rather to speak of general annoyance due to wind turbines and to form a 'composite annoyance score' (Michaud et al., 2018a, b) that aggregates into a single value various characteristics of wind turbines including wind turbine noise and visual annoyance (Michaud et al., 2018a, b), as well as at least one self-reported stress symptom (Hübner et al., 2019). According to the results of Hübner et al. (2019), this value can explain the differences between the results of the US study and the German/Swiss studies on the impacts of wind turbine noise. It turns out that average annoyance over noise hardly differs between the studies, but that annoyance due to wind turbines overall is higher in Europe; this is due to a more negative general attitude towards wind turbines as well as less perceived fairness. The composite annoyance score proposed by Michaud et al. (2018a, b) using factor analysis correlates well with distance to the wind turbines and with self-reported health. The present study also shows the high importance of attitudes towards wind turbines and the correlation between noise annoyance and the visual impact; accordingly, the findings of this study would not contradict a combination of noise and visual annoyance.

In their field study conducted in Lower Saxony in Germany on the effects and causes of wind turbine noise, Pohl et al. (2018) found that AM is a major cause of the noise complaints voiced. In a laboratory experiment, Schäffer et al. (2018) show that amplitude modulation – here in addition to the noise level – is an important acoustic predictor of noise annoyance. In their laboratory experiments, Bradley (1994) and Hafke-Dys (2016) also show that amplitude-modulated wind turbine noise is more annoying than unmodulated noise. These results align with the findings of the present study, in which, among all sound characteristics, 'whooshing' has the highest explaining effect on %HA. 'Whooshing' is often understood as a subjective perception of amplitude modulation. Correspondingly, the differences in annoyance levels across study areas largely coincide with the differences in the frequency of occurrence of detected, stable amplitude modulations at the various locations.

7 Listening tests

The annoyance of sound events generated by wind turbines is largely a function of the immission level at the listener's location. Other influencing variables, however, such as the spectrum of the signal or its structure over time, also have an effect on the sensation of annoyance. There are additional influencing variables involved, however, that cannot be derived directly from the signal. Consequently, in this study, AM was analysed not only based on a signal analysis and a survey of annoyance, but rather the annoyance of AM was investigated in the context of listening tests conducted in laboratory conditions situation in three study areas. In addition, comparative experiments were conducted at another location with test subjects who were typically not affected by wind turbine noise emissions. The investigations aim to identify a relationship between the immission level and the strength of the AM. The investigations described in detail below were divided into two sub-experiments. The first investigates the influence of constant AM over time, while the second considers the influence of AM that increases or decreases with time.

7.1 Stimuli

Consideration was given to using recorded stimuli as well as synthetically produced stimuli in the listening tests. It is especially the free parameterisation of individual influencing variables, in particular the strength, the progression over time and the duration of the AM, that argue in favour of synthetic stimuli. But the drawback of synthetic stimuli is that, because they are not exact replicas of the signals produced by wind turbines, this fact could influence the annoyance rating by an unknown value. In order to determine whether annoyance depends on the exact noise situation at the point of immission (turbine type, number of turbines, distance and, consequently, the spectrum of the recorded signals), stimuli from two different recording locations were used. For the listening tests, audio recordings of the measurement campaigns (Section 2) were used; these had been carried out at two measurement locations in 2018.

- Recording location 1: Distance of approx. 1 km to a wind farm with three wind turbines of the 2-MW to 3-MW class, with a rotor diameter of between 80 m and 100 m
- Recording location 2: Distance of approx. 750 m to a stand-alone wind turbine of the 2-MW to 3-MW class, with a rotor diameter of approximately 130 m

The characteristics of the stimuli used in the course of the listening tests thus vary with the different types, sizes and number of wind turbines, as well as the distance between the recording location and the turbines. The recordings were made using a B&K 4189 microphone set up at a height of 7 m. The pre-amplifier was a B&K 2669C, and the AD converter was an RME HDSPe AIO. For both installations, stimuli were extracted from the recordings of the turbines with different AMs.

The parameters $L_{\mathrm{HP,05}}$-$L_{\mathrm{HP,95}}$ and ΔL_{AM} as presented in Section 3.4 were used as a measure for the occurrence of AM. $L_{\mathrm{HP,05}}$-$L_{\mathrm{HP,95}}$ is the difference between the percentile frequencies of 5 and 95 of the high-pass-filtered signal when considering a single AM. This measure for AM was also used in a comparable form in (Schäffer et al., 2016; Schäffer et al., 2017).

The duration of each stimulus was limited to 25 seconds. The choice of stimulus duration was based on the study by Schäffer et al. (2016) in which necessary and sufficient lengths were identified for an annoyance assessment for the execution of listening tests. As all of the stimuli used in this study originate from turbines measured in real operation, fluctuations in level, and hence AM as well, are not entirely constant over a recording period of 25 s; they fluctuate slightly instead. In order to generate the nominal values of AM of 0 dB, 2 dB, 4 dB, 6 dB and 8 dB used in the listening test, corresponding ranges were manually extracted from the long-duration audio recordings. Sequences from 15 May 2018 were selected for the stimuli of recording location 1; at recording location 2 the sequences used had been recorded on 28 November 2018 (dynamic stimuli and 4 dB AM), 6 December 2018 (6 dB AM and 8 dB AM) and 15 December 2018 (2 dB AM). All stimuli come from measurements taken at night between 12:00 a.m. and 3:00 a.m.

From the stimuli preselected from this, sequences were then selected that, to the extent possible, presented AMs of 2 dB, 4 dB, 6 dB and 8 dB in the signal. Because the segments with constant AM were often significantly shorter than 25 s, and because easily perceptually discernible sequences are produced when segments are stitched together, in each case only a single period was selected and then set in succession until the stimulus had reached the desired length of 25 s. The individual audio parts were lined up using cross-fades in such a way as not to create any audible transitions. Because the period duration can also affect perception, AM were used with a period duration of 1.2 ± 0.1 s that were as identical as possible (exception: recording location 2, 8 dB AM: period duration of 1.6 s). These period durations are customary for wind turbines operating under customary power states.

For the second part of the listening experiments, stimuli were extracted that exhibit fluctuations in level that swell or fade over time. In what follows, this is referred to as 'dynamic'. For this purpose, stimuli that also had a duration of 25 s were created for both facilities in accordance with the following procedure. Stimuli were selected in which a maximally-uniform swelling or fading in AM occurs over short periods of 5 s to 8 s. This dynamic part, i.e. this part with changing amplitude modulation, is inserted into the middle of the synthesised stimulus, with matching periods from this short segment again supplemented for the earlier and the later time periods. In this case, the same procedure is chosen as for the synthesis of the static stimuli, with the segments for a period stitched together a number of times in each case. For recording location 2, there were sequences in which AM changes from 4 dB to 5 dB, and from 6.5 dB to 5 dB. For recording location 1, the selected sequences exhibited markedly greater changes in AM, going from 3.5 dB to 7.5 dB and from 8 dB to 4 dB. For these stimuli, the period duration was in the range of 1.6 ± 0.3 s and thus fluctuated somewhat more than in the case of the static stimuli.

Finally, for the presentations in the listening experiments, stimuli were also synthesised from the recordings that do not exhibit AM. Such stimuli were not found in the measurement intervals examined, however. Hence, these signals were also created by assembling different audio recordings; the following procedure was chosen for this purpose: The signal with the AM of 2 dB is randomly overlapped with itself multiple times over in a cyclically, time-shifted manner. 125 temporally random overlaps were selected. Finally, the original mean energy in the signal was reconstructed through standardisation. This resulted in a signal with a virtually unchanged frequency spectrum and the same average energy, but in which AM is no longer perceptible. As a computational measure $L_{HP,05}$–$L_{HP,95}$ for AM, the AM for these stimuli still stood at approx. 1.4 dB. Nevertheless, these stimuli are identified below as 0 dB AM. Further information on $L_{HP,05}$-$L_{HP,95}$ for each stimulus, as well as the ΔL_{AM} determined using the method explained in Section 4.4, can be found in Appendix E.

For both parts of the test, stimuli with different AM and average playback levels of -3 dB, 0 dB +3 dB and +6 dB were produced relative to an immission level L_{eq} of 35 dB(A), which is typical for wind turbines. In the first part of the test, 20 stimuli were presented for each of the turbines, resulting in a listening test design consisting of 4 immission levels × 5 AM × 2 recording locations. For the second part of the test, 12 stimuli were used for each turbine measured. Hence, the second part of the listening test had a design of 4 immission levels × 3 dynamic variants of the AM × 2 recording locations.

7.2 Set-up

Both loudspeakers and headphones were considered for making playback of the stimuli audible. The decision was made in favour of headphones-based playback of the stimuli, as in this case playback levels can be controlled more effectively and, for example, do not depend on the exact distance between listener and loudspeaker. Moreover, the space in which the audio is played back plays only a subordinate role in the case of a headphones-based experiment. Room-acoustical properties such as room reflections or reverberation do not influence the way the test is performed. Only the background noise in the playback room must either be taken into account or be negligible relative to the sound played through the headphones. This influence was reduced through the use of closed headphones (AKG K 271). The stimuli were presented through an external sound card (Focusrite Scarlet 2i2) connected to a Lenovo V130 notebook computer.

A laboratory measurement was performed beforehand to calibrate playback levels. A Neumann KU 100-type dummy head was used for this purpose. It was thus possible to set a defined sound-pressure level at the ear of the dummy head that corresponds to a defined sound-pressure level in an open field without headphones. Overall, the listening tests were carried out with three completely identical systems consisting of headphones and an external sound card. Each of the headphones sound cards used was calibrated to the specified playback level. The differences between the identical headphones and the identical sound cards were less than 1 dB, however.

7.3 Procedure

Perceived short term noise annoyance was assessed using the 11-point scale of ISO/TS 15666 (2003). This scale comprises 11 values ranging from 0 to 10. Here, the value 0 corresponds to 'not annoying at all' and the value 10 corresponds to maximum annoyance. The scale was tested and evaluated for the annoyance of wind turbine noise in Schäffer (2016). Based on ISO/TS 15666 (2003), the subjects assessed annoyance levels by answering the following question [in German, modified from ISO/TS 15666]: 'If you imagine that this is the sound situation in your garden, which number, from 0 to 10, best represents how much you would feel annoyed, disturbed or bothered by it?'

The psychoacoustic listening tests were conducted in the form of 'focus tests', i.e. participants were asked to consciously listen to the stimuli offered and evaluate them during or immediately after playback. Before the start of the actual test, five stimuli were presented in an introduction and were not included in the evaluation. These stimuli were selected to include examples that were potentially very annoying and examples that were not very annoying at all. This gave subjects an opportunity to acclimatise themselves to the procedure and the variety of the stimuli offered.

In the listening test, playback of the next stimulus was launched immediately following assessment of the preceding stimulus; subjects could not shorten or interrupt playback. The subjects assessed each stimulus just once. More frequent assessment would have given participants an opportunity to assess variances across assessments, but this would have prolonged the tests considerably. Participants performed the listening tests either individually or with two test subjects simultaneously listening to two completely separate systems in the same room. In this case, there was no interaction between the subjects. The procedure used in the listening tests was controlled using PsychoPy software (Peirce, 2019). This provided randomised playback of the stimuli while also recording the assessments, which subjects entered with the help of the mouse using a graphical user interface.

7.3.1 Locations for listening tests

The tests were carried out at the four different listening-test locations.

- SA 1: Gymnasium in the town hall. Background noise level of 25 dB(A)
- SA 2: Commons room in the town hall. Background noise level of 25 dB(A)
- SA 3: Community centre, background noise level of 20 dB(A)
- Cologne University of Applied Sciences: Seminar room (ZW8-3), Deutz Campus, background noise level < 25 dB(A).

This ensured a sufficient distance between the immission levels of the quietest stimuli presented, with an L_{eq} of 32 dB(A), and the background noise of the room. In addition, the insertion loss of the closed headphones, which was not defined in greater detail, also had a supporting effect here.

7.3.2 Test participants

Of the four series of listening tests, three were held in locations with wind turbines in the immediate vicinity. In these locations, test subjects had been made aware of the listening tests in the context of previous surveys (see Section 4) on the subject of annoyance due to wind turbine noise. Participation in the listening tests was unpaid and voluntary. It can be assumed that only persons familiar with the noise effects of wind turbines, or who are at least informed about the issue of noise, took part in the tests at the three locations with wind turbines nearby. In addition, a control experiment was carried out at the Cologne University of Applied Sciences with participants who for the most part are neither affected by wind turbine noise nor have detailed knowledge of this issue. For the most part, these were students or academic staff of the Cologne University of Applied Sciences who had been asked via an e-mail distribution list to participate in the tests in a voluntary and unpaid capacity. None of these participants had a direct connection to the research project.

In SA 1, 16 participants took part in the experiments (11 male, 5 female, mean age of 60 years); in SA 2, there were 25 participants (18 male, 7 female, mean age of 56 years); in SA 3, there were 20 participants (7 male, 13 female, mean age of 49 years). 18 individuals (4 female, 14 male, mean age of 29 years) participated in the control experiment conducted at the Cologne University of Applied Sciences.

7.4 Results

The representations below are based on $L_{HP,05}$-$L_{HP,95}$. The results relative to ΔL_{AM} are documented in Appendix E. Generally speaking, different computational determinations of modulation depth for selected stimuli lead to only slight changes in study results.

The statistical evaluation was conducted using the SPSS software and with MATLAB. The aim of statistical analysis is to determine the influence of the various within-subject factors (such as the influence of the strength of the AM or the influence of the playback level). It is not of particular interest here how the absolute values fluctuate between subjects due, for example, to different scale anchoring. Between-subject variance was thus reduced first by normalising raw data for each participant with the respective mean value over all values per subject (mean value exemption). This makes it unimportant for further evaluation, for example, to know the value range in which the respective subjects used the annoyance scale. The normalised data were analysed using a multi-factor ANOVA with repeated measurements in order to identify significant main and interaction effects of the individual within-subject factors. Finally, a regression analysis was established with the aim of comparing the impact of the playback levels presented in the test and the AM.

7.4.1 Evaluations for constant amplitude modulation

The first part of the experiment considers assessments of amplitude modulations that do not vary over time.

7.4.1.1 Variance analysis

In a first step, a three-factorial ANOVA with repeated measurements was conducted. This was corrected according to Greenhouse-Geisser (1959) to compensate for a violation of sphericity and carried out based on the within-subject factors of AM, signal level, and recording location. As the results show, the greatest proportion of differences across assessments stems from the signal level and the strength of the AM.[8] The recording location influences results as well, albeit to a much lesser extent. The cause could lie in the different characteristics of the stimuli recorded at the different locations (e.g. number of turbines, differences in distance, differences in turbine type). These influences are small compared to the other two main effects, however.

7.4.1.2 Mean values and confidence intervals

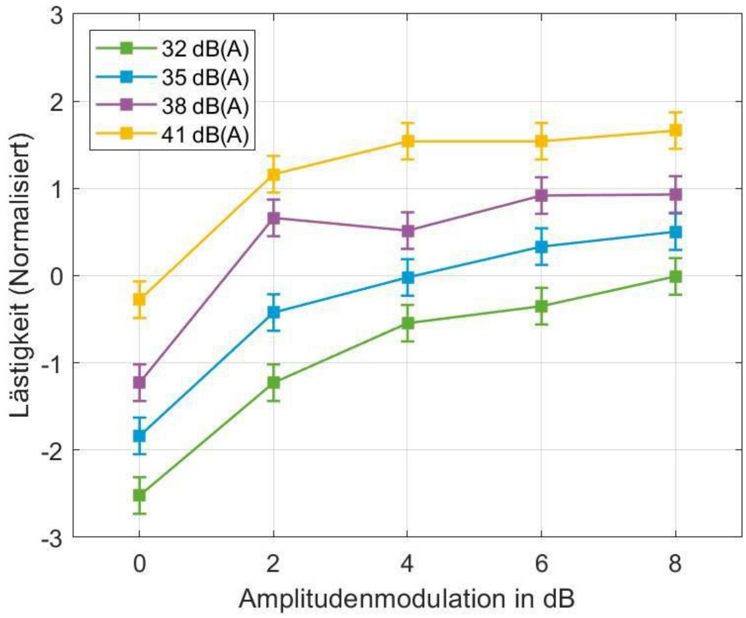
Figure 63 presents the normalised annoyance scores as a function of AM and the immission levels presented in the listening test. It can be clearly seen that annoyance increases not only with increasing AM but with increasing immission level as well. It can also be seen from the figures that the greatest increase in annoyance occurs between 0 dB[9] and 2 dB AM, i.e. when AM is on the verge of becoming perceptible.

[8] The analysis showed a significant main effect for AM [$F(4.324) = 80.08$, $p < .001$, $\eta p2 = .50$, $\varepsilon = .37$] and level [$F(3.243) = 181.11$, $p < .001$, $\eta p2 = .69$, $\varepsilon = .49$], and for recording location [$F(1.81) = 7.53$, $p = .007$, $\eta p2 = .09$, $\varepsilon = 1$]. The ANOVA also showed significant interaction effects with comparatively low effect strength between AM and level [$F(12.972) = 2.66$, $p = 0.002$, $\eta p2 = 0.003$, $\varepsilon = 0.78$] and between AM and recording location [$F(4.324) = 12.43$, $p < 0.001$, $\eta p2 = 13$, $\varepsilon = 0.94$]. The Greenhouse-Geiser-corrected p-values and Greenhouse-Geiser-corrected ε values are given.

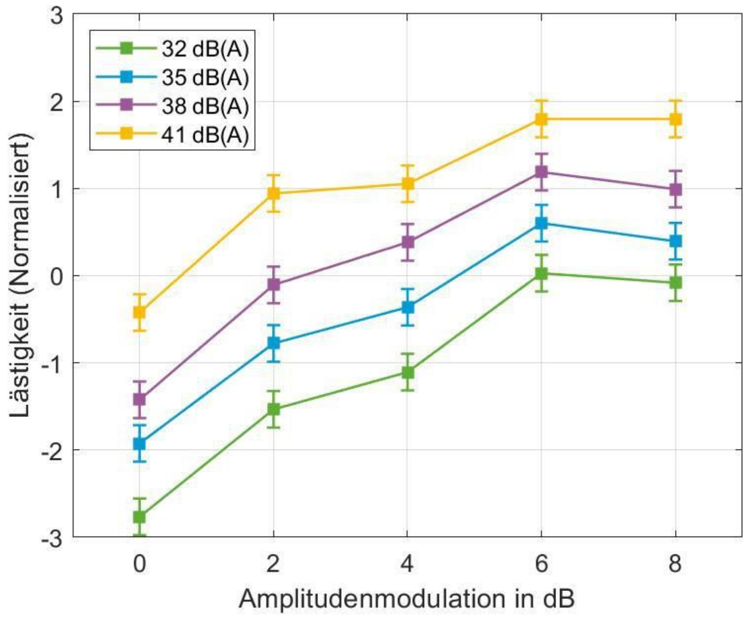
[9] The stimuli marked with 0 dB exhibited no perceptible AM. However, the $L_{HP,05}$-$L_{HP,95}$ used to determine AM yielded values in the range of 1.4 dB.

Figure 63: Annoyance of time-invariant amplitude modulations

Perceived (normalised) annoyance as a function of AM (x axis), the immission level presented (colour) and the recording location (a: Recording location 1, b: Recording location 2). Shown here are the normalized annoyance ratings averaged across listening test participants with 95% intra-subjective confidence intervals of the main effect for the factor of AM.



(a) Recording location 1



(b) Recording location 2

Source: own presentation, TH Köln

Lästigkeit (Normalisiert) = Annoyance (Normalised); Amplitudenmodulation in dB = Amplitude modulation in dB

Interestingly, the results for the control group at the Cologne University of Applied Sciences listening test location do not differ significantly from the results obtained at the wind turbine locations. Here, for example, the results at SA 2 deviate more from the other results than is the case for the hearing tests conducted with the control group at the Cologne University of Applied Sciences who are potentially free from wind turbine-based annoyance. The diagrams in Appendix E illustrate this in detail.

7.4.1.3 Regression analysis

As described above, the ANOVA showed significant main effects for level and AM. Above and beyond this, however, the statistical analysis showed influences resulting from the combination of level and AM (known as a 'significant interaction effect'). In a next step, these relationships are quantified in greater detail as part of a regression analysis. The regression analysis was carried out separately for low AM in the range from 0 to 2 dB and, for stronger AM in the range from 2 to 8 dB, as clearly different slopes were observable, as shown in Figure 63.

Detailed results of the regression analysis are presented in Table 32 and Table 33. A fundamentally similar relationship emerged for both recording locations: For low AM in the range of 0 dB – 2 dB, an increase in AM (regression factor AM) has a much stronger effect than an increase in level (regression factor level). These differences in regression factors are significantly smaller between 2 dB and 8 dB AM. As presented in detail in Table 32 and Table 33, while regression factors differ across recording locations, the trend is nonetheless similar. It is significant that the influence of increasing AM is greater for low AM than for higher AM.

Table 32: Regression analysis, recording location 1

AM range observed	Regression factor, AM	Regression factor, level
0 – 8 dB	0.26 ± 0.02 / dB	0.24 ± 0.02 / dB
0 – 2 dB	0.78 ± 0.12 / dB	0.27 ± 0.03 / dB
2 – 8 dB	0.13 ± 0.03 / dB	0.23 ± 0.02 / dB

Results of the regression analysis for recording location 1. Mean values and standard deviations are indicated.

Table 33: Regression analysis, recording location 2

AM range observed	Regression factor, AM	Regression factor, level
0 – 8 dB	0.32 ± 0.03 / dB	0.24 ± 0.02 / dB
0 – 2 dB	0.66 ± 0.13 / dB	0.27 ± 0.04 / dB
2 – 8 dB	0.23 ± 0.03 / dB	0.24 ± 0.02 / dB

Results of the regression analysis for recording location 2. Mean values and standard deviations are indicated.

Regression factors for AM and for level are correlated below. Based on the regression factors for listening test results averaged across all subjects and all recording location, it turns out that an increase in AM from 0 dB to 2 dB influences annoyance to the same degree as a 5.3-dB increase in sound-pressure level. This results in 5.8 dB for recording location 1 and 4.9 dB for recording location 2. The influence of increasing AM on annoyance is less pronounced in the range of 2 dB – 8 dB. An increase in AM by 1 dB influences annoyance to the same extent as an increase in average sound-pressure level of between 0.6 dB (recording location 1) and 1 dB (recording location 2).

As analysis of the regression data shows, the influence of AM strength on annoyance decreases significantly once AM becomes perceptible. The strength of AM thus has a significantly lower effect on annoyance than the presence of AM. On the other hand, the slope of the regression line for level, on the other hand, is hardly a function of the strength of AM for both listening-test locations.

7.4.2 Evaluations for amplitude modulations that vary with time

The second part of the experiment considered the influence of swelling or fading AM. As already explained above, comparison stimuli consisted of wind turbine noise without AM.

7.4.2.1 Variance analysis

To analyse (mean value-exempt) data, a Greenhouse-Geisser-corrected, three-factorial ANOVA was carried out with repeated measurement of the level of within-subject factors, increase in AM and recording location. It was found that results are influenced by the level as well as the increase and the recording location. [10] The main effect for increase identified through ANOVA shows that stimuli with variable AM were rated as significantly more annoying than the stimuli without AM. Another interlaced ANOVA only for conditions with swelling and fading AM showed no significant differences for the type of change in AM (swelling or fading). For the stimuli investigated here, then, it can be assumed that it is not significant for annoyance whether the stimuli become stronger or weaker in AM over the duration of the presentation.

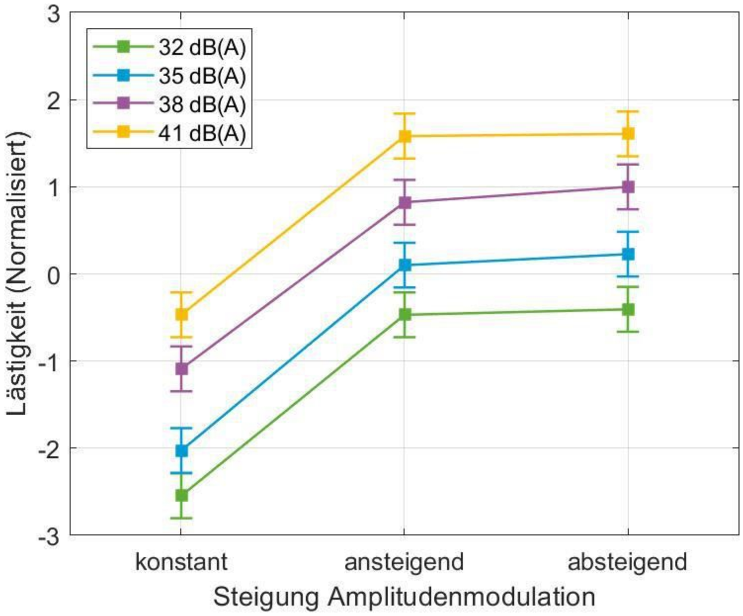
7.4.2.2 Mean values and confidence intervals

Figure 64 presents the normalised annoyances as a factor of the type of course of AM (swelling vs. fading) and the immission level presented in the listening test. It can be clearly seen that annoyance depends only very marginally on the type of change in AM. Annoyance results were significantly lower for stimuli without AM.

[10] The ANOVA showed a significant main effect for level [F (3.234) = 153.6, $p < .001$, $\eta p2 = .66$, $\varepsilon = .56$], for increase [F (2.156) = 86.35, $p < .001$, $\eta p2 = .52$, $\varepsilon = .57$], and for recording location [F (1.78) = 18.71, $p = .001$, $\eta p2 = .19$, $\varepsilon = 1$]. There were no other interaction effects of significance.

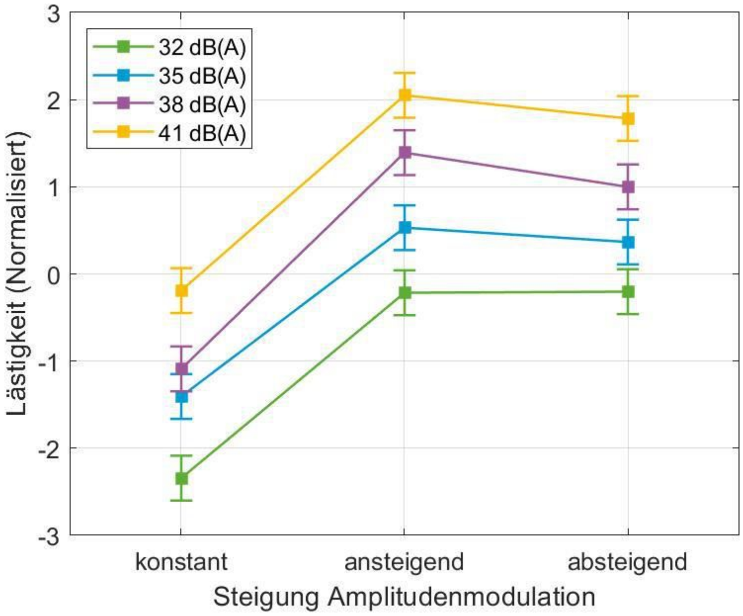
Figure 64: Annoyance of amplitude modulations that vary with time

Perceived (normalised) annoyance as a function of the slope of AM (no AM, swelling AM, fading AM) and of the immission level (colour) offered for both recording locations (a) 1 and (b) 2. Shown here are the normalized annoyance ratings averaged over subjects and recording locations with 95% intra-subjective confidence intervals of the main effect for the factor of increase.



(a) Recording location 1

Source: own presentation, TH Köln



(b) Recording location 2

Source: own presentation, TH Köln

(a) Aufnahmeort 1 = (a) Recording location 1; (a) Aufnahmeort 1 = (a) Recording location 1; konstant = Constant; ansteigend = Swelling; absteigend = Fading; Steigung Amplitudenmodulation = Slope amplitude modulation ; (b) Aufnahmeort 2 = (b) Recording location 2

7.4.2.3 Regression analysis

In contrast to Experiment 1, the information value of the regression analysis is low here. It can only show the extent to which annoyance changes with level. This resulted in 0.19 ± 0.08/dB for recording location 1 and 0.18 ± 0.09/dB for recording location 2. Averaging across both recording locations produced a value of 0.19 ± 0.06/dB. This is slightly below the values for the influence of level in the consideration of static stimuli. It is difficult to verify the significance of these differences, since these differences can also be based on economies of scale, since the stimuli were assessed in the context of different listening tests.

7.4.3 Comparison with other studies

The results of this study confirm results obtained by Hünerbein et al. (2013) [Figure 9.4, p. 201]. Those results also found a steeper increase in annoyance for low modulation depths. For the test stimuli of 35 dB(A) and 40 dB(A) presented there – which also fall within the range of the immission levels investigated in the present study – the strongest increase in annoyance was seen between modulation depths of 0 dB and 2 dB, followed by further flattening of the curve. Here, an increase of 2 dB in modulation depth corresponded to a change in level of around 4 dB. However, it was not possible to demonstrate statistical significance in von Hünerbein et al. (2013), due, among other things, to the low number of subjects in this portion of the test. Our results are also consistent with Schäffer et al. (2016) [Fig. 8], where it was also shown that annoyance increased along with AM. The dynamic course of AM over time did not play a significant role in this study, either.

7.5 Summary

Analysis of the studies of static stimuli revealed significant main effects for parameters of level and AM; although its strength was less pronounced, the recording location also constituted a main effect. The listening tests confirm that the perceived annoyance is clearly a function of AM, and that, as expected, annoyance increases with an increase in AM. The perceptibility of the AM alone seems to be a considerably more decisive factor in terms of annoyance impact, however, than the strength of the AM. It therefore seems appropriate to assume that annoyance will increase wherever AM is perceptible. A more detailed examination should also consider the dependency relationship in terms of the strength of the AM. The effects of AM and level on perceived annoyance are very stable across the individual study areas and groups. The results of the listening tests with the control group at the Cologne University of Applied Sciences differed only slightly from the listening tests conducted in the vicinity of wind turbines. When investigating dynamic stimuli that vary with time, there were no significant differences found between stimuli with swelling AM and stimuli with fading AM.

The impact of AM over time would require further investigation in subsequent studies. Moreover, the listening tests carried out in this study are based only on stimuli from two different recording locations. Follow-up studies would need to consider the extent to which these can be generalised to different types of wind turbines with varying acoustic properties. Various aspects of AM, such as temporal variations in AM, would also need to be investigated in greater detail. This requires further studies that also compare synthetic and natural sound signals at a higher level of abstraction and investigate the influence of AM on annoyance for different forms of noise. Finally, it is of particular importance for follow-up studies to extend the laboratory experiments carried out in this study to include experiments that consider annoyance in a natural listening environment and over a longer period of time.

8 Concluding discussion

The present study examined numerous aspects of the impacts of noise generated through use of land-based wind turbines.

The noise produced by wind turbines has special characteristics. Respondents living in the vicinity of the areas examined specifically described these characteristics as 'rushing' (meaning not just continuous rushing but also 'rushing in intervals') or 'whooshing'. In acoustic metrology, this periodically recurrent noise from wind turbines is known as 'amplitude modulation' (AM). Amplitude-modulated noise was investigated at five locations on the basis of long-term sonic measurements. The selected turbine locations had different wind-farm constellations of 1 to 21 wind turbines and differed in terms of their respective installations and topographical conditions. The measuring locations were at a distance of approx. 800 m to 1500 m from the wind turbines. The following relationships were analysed with regard to the occurrence of AM:

- Topographical structure of the areas
- Turbines' current output
- Wind direction
- Wind speed, as well as
- Thermal stratification of the atmosphere

A clear connection could not be established.

AM was detected at both low and high immission levels. In the study areas, it was particularly the distance to the turbine and the number of turbines that influenced how often amplitude-modulated noise occurred, as well as the modulation depth. The more turbines there are, the less pronounced the AM. The greater the distance, the less pronounced the AM. Given the above-mentioned differences across study areas, this statement can describe other locations only up to a point.

As part of the project, an algorithm was developed that can automatically detect and quantify the periodic AM of wind turbines. The conventional methods used to describe pronounced sound characteristics, such as impulsiveness as defined under the Technical Instructions on Protection Against Noise (1998), have only limited suitability for describing the 'whoosh' noise of wind turbines, since periodically modulated noise cannot be distinguished from other modulated noise. If, for a particular period of time, it can be ensured that noise is essentially periodically amplitude-modulated noise, for the areas studied here it turns out that the modulation depth can be estimated using the maximum cyclical noise level method proposed in the Technical Instructions on Protection Against Noise (1998).

Furthermore, infrasound measurements were conducted at one location over a period of eight weeks. For the remaining four locations, infrasound levels were determined based on measurements of audible sound. Infrasound caused by wind turbines was detected in all of the measurement locations. The infrasound levels measured are below the thresholds of perceptibility.

In the listening tests, amplitude-modulated noise gleaned from the measurements was presented and evaluated under laboratory-like conditions. Participants rated amplitude-modulated noise as significantly more annoying than non-amplitude-modulated noise.

Strikingly, annoyance increases significantly the moment AM becomes perceptible. Follow-up studies should further investigate the extent to which short-term annoyance identified in listening tests conducted under laboratory conditions can be compared to an increase in mean sound-pressure level. At a minimum, however, the results of the listening tests correspond to the results of the survey study. Accordingly, AM has identifying sound characteristics, such as 'whooshing' or the 'rushing' (meant to describe pulsation), with a clear effect on noise annoyance; differences across study areas in terms of the noise annoyance correspond to the frequency of occurrence of the periodic AM detected.

Residents in the study areas were surveyed about the annoyance caused by wind turbine noise. They were exposed to a calculated noise-immission level with an average rating level L_r of 31 dB(A), with levels ranging from less than 20 dB(A) to 43 dB(A). The surveys showed that wind turbine noise leads to a higher proportion of highly annoyed persons among respondents than is known from other sources of environmental noise with the same noise level, e.g. road traffic.

The convention used in noise-effect research is to identify exposure-response relationships by relating the percentage of highly annoyed persons to levels of noise exposure expressed in dB. On the basis of such exposure-response functions the World Health Organisation (WHO) cites a percentage of 10% of highly annoyed individuals as a threshold with health relevance (WHO, 2018). The WHO states that the percentage of 10% highly annoyed persons is exceeded if wind turbine noise reaches a night-time level of L_{den} = 45 dB(A). In comparison to this, the corresponding L_{den} value for road traffic noise according to the WHO is around 53 dB(A).

This study found that 10% of the people were already highly annoyed by wind turbine noise at a rating level of L_r = 31 dB(A). At L_r = 32 dB(A), 10% are highly annoyed with wind turbine noise heard outdoors, and with 38 dB(A) of wind turbine noise heard indoors. Even with a highly simplifying assumption of extreme conditions such as year-round tailwind and a uniform distribution of wind turbine noise over 24 hours a day, these rating levels of 31 dB(A) to 38 dB(A) would convert to (overestimated) L_{den} values below L_{den} = 45 dB(A) – the value given by the WHO (2018) as a guideline exposure level for wind turbine noise. Hence, at a minimum, the results of this study confirm the approach taken by the WHO of setting a lower guideline exposure level for wind turbine noise than for noise due to road and rail traffic.

The survey study shows that other contextual factors are at least as important as rating levels for predicting noise annoyance. This aligns with the findings of international noise-effect research (including Freiberg et al., 2019; Hübner et al., 2019; van Kamp & van den Berg, 2020). Accordingly, mitigating the annoyance caused by wind turbine noise in a residential area located in the vicinity of wind turbines will require a holistic noise management approach that considers comprehensive solutions taking into account the acoustic aspects as well as the contextual factors and, in the best case, also involves the residents.

The present study reaches the conclusion that AM is an important sound characteristic that can increase nearby residents' annoyance due to noise. This is evident in subjective perception of the particularly annoying characteristic of noise ('whooshing'), the apparently extensive correspondence between wind turbine noise annoyance and the frequency of occurrence of periodic amplitude modulations detected in the study results, and in the results of the listening tests.

Nevertheless, more than the noise levels themselves, it was visual perception of the wind turbines and the perceived or expected negative impacts of local turbines for respondents' own region that seem to have an effect on assessments of noise annoyance. Accordingly, as Schick (1997) put it generally when discussing the concept of annoyance, wind turbine noise is not the sole cause but rather an occasion for annoyance. The noise annoyance may be fed by a variety of acoustic and visual characteristics of wind turbines, and by the context around the planning, implementation and operation of these turbines. It is also for this reason that various authors, such as Michaud et al. (2018a, b) and Hübner et al. (2019), propose the compilation of a combined concept of annoyance. This summarises the various acoustic and visual characteristics of wind turbines that have the potential to be viewed as annoying.

In order to understand why noise exposure alone cannot explain judgements of noise annoyance, the definition of noise annoyance must be kept in mind. Noise annoyance is not purely a reaction to sound. It includes (1) the repeated experience of disturbances caused by noise and the adoption of behaviour to avoid these disturbances. It also includes (2) an emotional response to the noise and the disturbance it causes and (3) a perceived loss of control over the noise situation (Guski et al., 2017). A perceived loss of control can arise if changes occur in the living environment; this might include a shift in noise levels over which residents themselves do not feel they have any influence. What matters is not whether people actually have no influence or no way to cope with or control the situation, but rather how residents perceive the situation (Glas & Singer, 1972). The foundation for these perceptions is already laid during the planning and construction of wind turbines. Thus, it is all the more important to take into account, very early on in the planning process, the impact of the broader context of wind turbines and wind turbine noise on noise annoyance. To increase acceptance of wind turbines and give residents a way to experience control over their own living situation, as the survey participants pointed out, the emphasis should be on the benefits to residents. They should be involved from an early stage in wind turbine construction planning. This does not mean that the situation should be whitewashed; possible negative changes should be made transparent as well. Generally speaking, trust in authorities in charge is one of the most important factors affecting noise annoyance. This applies to annoyance due to wind turbine noise (Hübner et al., 2019) and to other noise sources as well, e.g. aircraft noise (Schreckenberg et al., 2017). Squandering this trust through an absence or shortage of information will not solve the problem of noise annoyance. Even better than merely providing information is involving residents as much as possible in decision-making processes concerning the construction of wind turbines in order to foster an experience of control and coping capability (self-efficacy).

9 Need for further research

Evaluating the measured levels of amplitude modulation revealed indications of a variety of relationships. The meteorological conditions observed during the measurement period were not complete, or occurred too rarely to derive statistically significant results. The trends discernible nonetheless should be investigated further using a larger sample of measurements.

Measurements made within residential buildings could help establish a possible relationship between the occurrence of and concomitant annoyance with amplitude modulation in rooms in relation to the existing results, additionally facilitating an assessment of this situation.

In the context of follow-up studies, systematic listening tests should be carried out to identify the influence of AM for a broader bandwidth of source signals. Only through such further psychoacoustic studies will make it possible to set the AM that usually occurs during wind turbine operation in relation to AM of other noise sources (e.g. road traffic). These listening tests should also be supplemented with systematic surveys to ensure that the experiments conducted under abstract laboratory conditions reflect the perceptions of potentially annoyed persons. In doing so, parameters should be determined for AM relative to immission location (residences of affected residents) and relative to the impacts of noise on affected individuals. Like AM, the noise effects should be assessed close to the event – for example through brief surveys repeated several times a day over several days. In an interim study, using the extensive acoustic data collected through long-duration measurements within this project, suitable acoustic parameters beyond the rating levels can be related to the immission locations (residential addresses of the survey participants) by means of propagation calculations and then investigated in more detail in exposure-response analyses. A major advantage of this study is the extensive record of acoustic data; greater use of this record – rarely available to this extent for noise-impact analyses – can and should be made in future re-analyses than was possible in this study.

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A Wind turbines as a source of noise

A.1 Basic information

From a physical point of view, wind turbines can be regarded as enormous, slow-turning fans. The same processes cause sound-pressure waves, whether found in PC cooling fans, industrial-strength axial fans or wind turbines.

Two aerodynamic processes constitute the main sources of fan noise:[11] Turbulence that occurs directly on the rotor blades and pressure fluctuations that occur when a rotor blade moves past a flow obstruction.

These two processes are discussed below.

A.2 Interaction between rotor blade and mast

A.2.1 Lines in the spectrum

A fan with rotating rotor blades causes a fluctuation in pressure each time a rotor blade passes an object standing firmly in the flow.[12] In the case of a computer fan, this might be a plastic peg holding the hub; in the case of an axial fan, it might be a stator – a non-rotating blade designed to boost the flow – and, in the case of a wind turbine, the mast. How the flow is disturbed in this region, and what form the pressure fluctuation takes, can very much depend on details such as the geometry involved, and specifically the distance between the rotor blade and the obstruction to the flow. But a similar fluctuation in pressure occurs over and over again, each time a rotor blade passes the obstruction. In other words, pressure fluctuations occur exactly as often as the rotor blades pass the obstruction.

A typical fan runs at speeds of several hundred or even more than a thousand revolutions per minute, but a wind turbine typically rotates fewer than twenty times per minute. As wind turbines (almost always) have three rotor blades, a rotor blade passes the turbine mast three times in the course of each revolution. Each such passage creates a pressure fluctuation, i.e. there is a noise with a fundamental frequency of

$$f_{BP} = UPM \frac{3}{60\ min^{-1}} Hz$$

This frequency is referred to as the 'blade passage frequency'.

In the ideal case in which the turbine rotates at a constant rotational speed and the flow is constant, the same pressure fluctuation will be generated each time a rotor blade passes the mast. In this case, the resulting noise consists of sharp, pure tones lying at integral multiples of

[11] Presentations can be found in numerous textbooks and reports, e.g. as DLR Internal Report 22314-94/B5, scientific publications from the 1960s onwards, e.g. Sharland, I.J. (1964). Specifically for wind turbines in Hubbar and Shepherd (1991)

[12] Example of an early study of the effect of rotor tilt relative to the fixed element in Němec, J. (1967)

the blade passing frequency.[13] These multiples of the basic frequency are also known as 'harmonics'.[14]

Typical values for blade passing frequencies in wind turbines lie in the range of 0.3 to not more than 1 Hz.

A.2.2 Level of the lines

For a source to emit a strong signal at very low frequencies, it is not sufficient for it to have, for example, a very low rotational speed; the dimensioning of the source must also be sufficiently large. In principle, wind turbines can generate levels at very low frequencies due to the considerable lengths of their rotor blades and masts.

If the pressure fluctuations that occur between the rotor blades and the mast do not look very impulsive in character, then the contributions of the harmonics can be expected to drop relatively quickly as frequencies increase.

With most fans, a comb-like pattern is created in the spectrum, with lines occurring at constant distances, but only rarely will many more than 10 lines be discernible. Accordingly, only at very low frequencies can lines like these be expected to be observable in the spectrum of a wind turbine.

A.2.3 Contributions to audible sound

A wind turbine rotating at 15 rpm has a blade passing frequency of 0.75 Hz. As the lowest note on a piano keyboard is around 27.5 Hz[15], the 36th harmonic would have to make a significant contribution for interactions between rotor and mast to be audible in this area.

A.2.4 Broadening of the lines

In contrast to typical fans, the flow conditions of wind turbines are less constant. As wind is overlaid by gusts and turbulence, the pressure fluctuations that occur between the rotor blades and the mast vary from one passage to the next. The resulting sound signal is not strictly periodic, and a broadening of the individual lines in the spectrum can occur.

A.3 Rotor blade flow noise

A.3.1 Rotor blade aerodynamics

One begins with the trivial statement that a wind turbine is propelled by the wind, but the actual function is much more impressive than might appear at first glance.

[13] For purposes of mathematical analysis, for example, a Fourier series can be formed. A continuous signal is produced consisting only of frequencies that are integral multiples of the fundamental frequency.

[14] Physicists like to use the term *harmonic* as it refers exclusively to integral multiples of the fundamental frequency. The term *overtone* means almost the same thing to musicians, but as it can also refer to fractional multiples under certain circumstances, the term *harmonic* is somewhat safer to use.

[15] When considering the auditory impression of deep tones on a piano, it should be noted that harmonics are heard there, too, and the fundamental tone only to a very small extent.

At each point, the cross section of the rotor blade has the shape of a wing profile. Because the rotor moves faster on the outside than on the inside, the rotor blade profile changes from the inside to the outside to keep it optimally adapted to the speeds expected at the respective radius.

Air generates force when it flows over a wing. The portion transverse to the direction of flow is referred to as 'dynamic lift', and the portion of the force in the flow direction is known as 'drag'.[16] The best-known image for this is the motor-propelled aircraft in horizontal flight, where the air flows over the wing, in the process generating lift precisely upwards to keep it airborne. The second component of flow force is the drag that brakes the aircraft. The higher the speed, the greater the drag; this is why a fixed engine power always corresponds to a certain speed.

As with drag, lift also increases with increasing flow velocity. And it is precisely this lift on the wing profile of the rotor blades that causes wind turbines to rotate. 'Lift' as used here refers not specifically to the share of upwards force but to the share of force transverse to the flow, or the share of force propelling the rotor in its rotation.

The rotation of a wind turbine may look tranquil if viewed from a distance, but appearances can be deceiving. The flow of air over the rotors is not that of the approx. 10 m/s of wind speed but is mainly caused by the rotation itself. If the turbine is rotating at 15 rpm, then the flow the turbine itself has caused, at a radius of 50 m, is approx. 80 m/s, and the wind makes only a small contribution towards the total flow over the rotor.

The great art involved in the design of wing profiles is to have as much of the flow force as possible 'forward', in the direction of movement. The force component that only bends the rotor blade in a tailwind direction cannot be harnessed for energy production.

Of relevance to what follows is that the cross-sections of wind turbine rotor blades are essentially wing profiles, and that high speeds at the rotor blades are required to generate a high power output.

A.3.2 Flow noise

A flow over a wing profile causes noise, particularly if the flow has the speed mentioned above. This results in a broadband rushing sound with a frequency range that depends on the width of the wing (the chord), the angle of incidence and the velocity of flow. As all three of these factors change from the inside to the outside of the rotor blade, the noise generated is a very broadband rushing sound that begins at less than 100 Hz and reaches up to several hundred or even a thousand Hertz.

While the exact shape of the wings also naturally plays a role, for simplicity's sake technical studies still use a NASA study from 1989 (NASA 1218) that examined flow noise over standard profiles. In addition to the shape of the spectra of the noise, the study also includes statements about wind turbines' directional characteristics. As the noise direction is relatively pronounced, noise from the wing does not emanate equally in all directions.

[16] The terms 'lift' and 'drag' are sometimes used somewhat differently for different applications, e.g. relative to the direction of movement rather than the direction of flow. This distinction does not play a decisive role in the following text.

A.3.3 Amplitude modulations

Due to the directional characteristics of wind turbines as a noise source, the noise an observer perceives changes depending on where the rotor happens to be at any point in time. It grows louder and quieter with the rhythm of wind turbine's rotation – amplitude modulations occur.

Outdoors, wind speed increases with height, i.e. a rotor blade is exposed to greater wind speeds in the upper part of its movement than in the lower part. And because higher wind speeds lead to higher noise emissions, this effect also results in a swelling and fading in level that contributes to the amplitude modulations as directional characteristics do.

If the immission measuring point is not exactly in front of or behind the turbine, then the rotor blades also move towards and then away from the observer. Because the rotor blades move very quickly, there is a clear Doppler effect. This creates the familiar shift in frequency between movement towards the observer and away from the observer. This frequency shift is not very noticeable in the case of extremely broadband noise. However, the Doppler effect also leads to an amplification of the level when the source moves toward the observer. If the rotor blade approaches the observer, it becomes louder by up to several dB as a result of the Doppler effect; when moving away, it becomes correspondingly quieter. Since a wind turbine typically has three rotor blades, this effect is offset in part between the rotor blades, but an audible effect can remain.

In addition to the formation of AM directly at the source, AM can also arise or be amplified along the path of propagation. The height of the source changes constantly due to the rotation of the rotors, and propagation conditions from the source to the immission location can depend on the height of the source. A possibility exists that more pronounced AMs will be observed at a greater distance from the wind turbines than in their vicinity.

In summary, a broadband rushing noise is generated at the wind turbine. And, for various reasons, this noise can swell and fade in level with the rhythm of the turbine's rotation – an effect referred to as 'amplitude modulation'.

A.4 Other noise

Wind turbines are large pieces of technical equipment. There may be transmission noise or generator noise, and the rotation of the nacelles can be audible nearby as well. From an immission-protection standpoint, however, this other noise does not play a role.

B Measurement results for all study areas

This appendix compiles measurement data for the five study areas. Measurement data recorded in the immission range and spanning the entire measurement period are presented in each case. Only mean values (averaging time of 10 min. in SA 2 to SA 5 and 60 min. in SA 1) for which the following meteorological conditions are met were used for this purpose:

- Maximum 20% chance of rain,
- Relative humidity < 95%.
- Temperature > 0 °C
- Wind speed < 5 m/s at the microphone

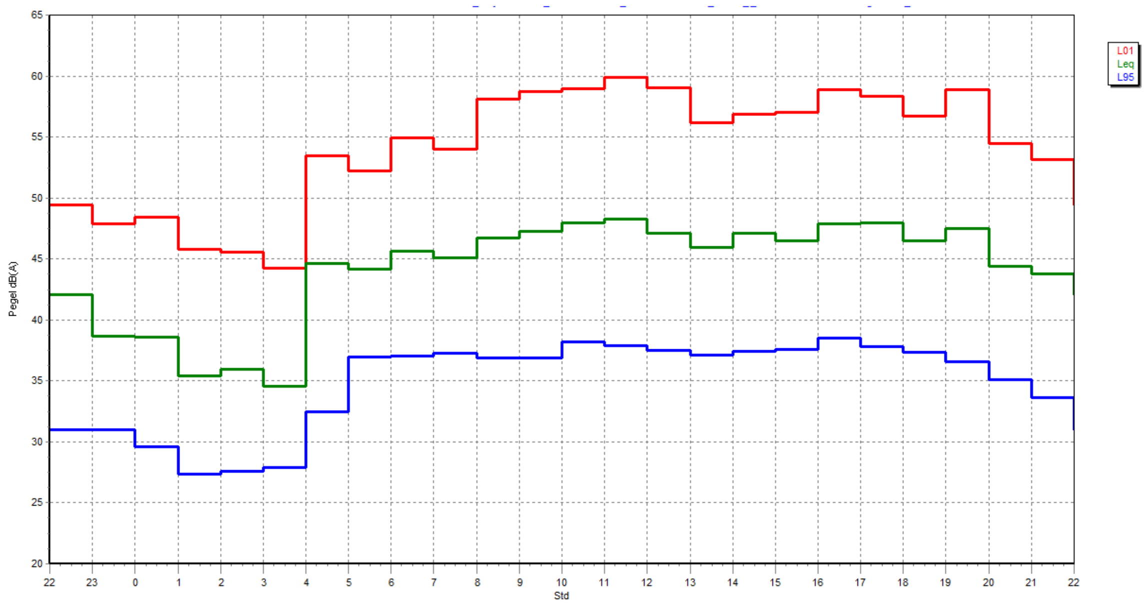
The following figures show, among other things, the curves for background levels (L_{95}), the averaging level (L_{eq}) and the peak level (L_1) in the long-term mean over the entire measurement period.

The averaged percentile spectra for the period from 2:00 a.m. to 4:00 a.m. are shown as representative of the noise situation at night, as this is the time when the lowest proportion of extraneous noise – due to road traffic or bird chirping, for example – is to be expected.

Depictions of the averaging levels over the electrical output of the wind turbines or over the wind speed at hub height exclude time periods that include identified, extraneous noise. If extraneous noise occurred within the averaging time of 10 minutes, the entire 10 minutes were excluded from the evaluation. Amplitude modulation is evaluated in averaging periods of 10 seconds. This permits a much more granular exclusion of extraneous noise. Given the different data basis, the results are comparable with each other only up to a point.

B.1 Study Area 1

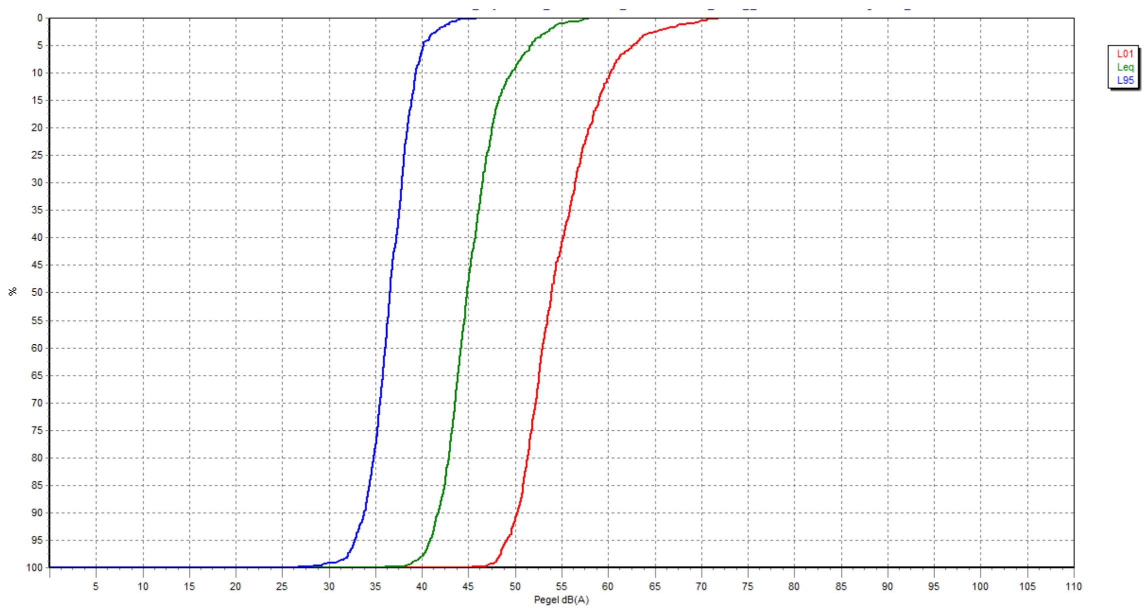
Figure 65: Diurnal pattern for averaging level SA 1



Source: own presentation, deBAKOM GmbH

Pegel dB(A) = Level dB(A); Std = Hours

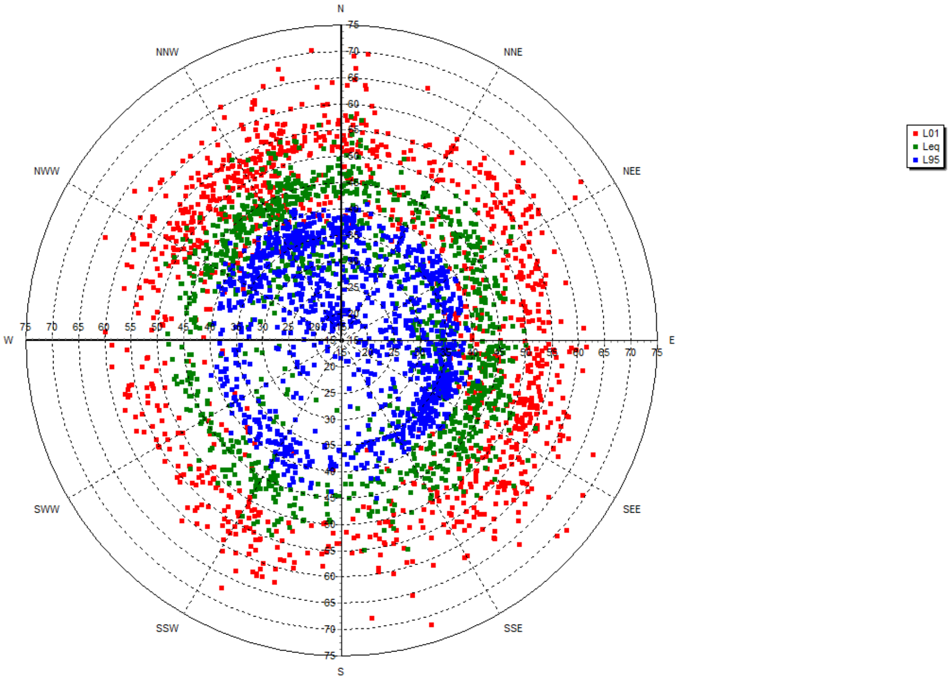
Figure 66: Cumulative frequency for averaging level SA 1



Source: own presentation, deBAKOM GmbH

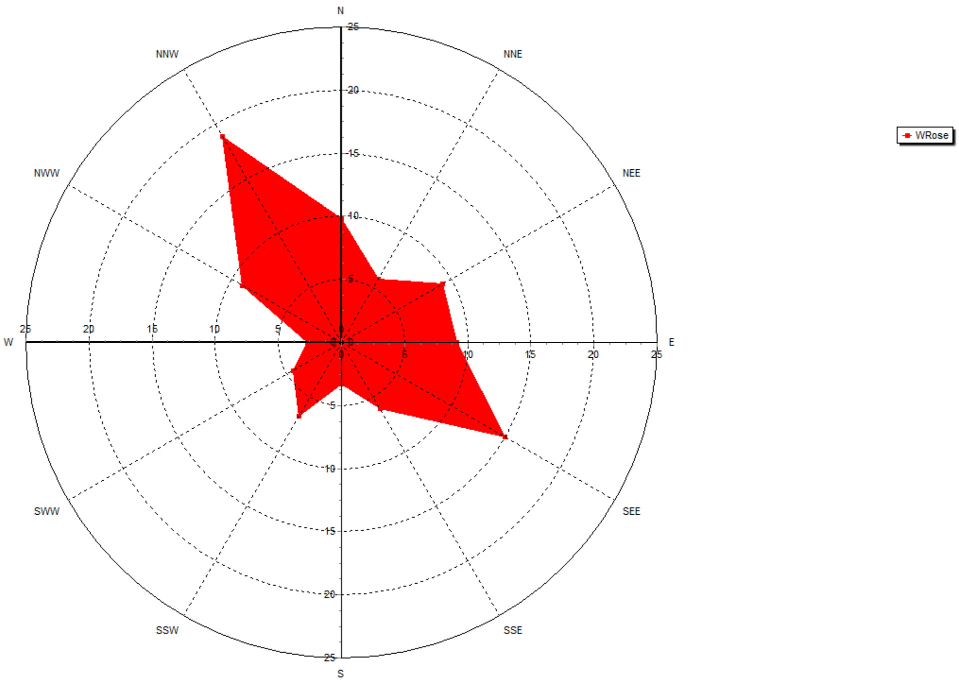
Std = Hours

Figure 67: Level distribution over wind direction SA 1



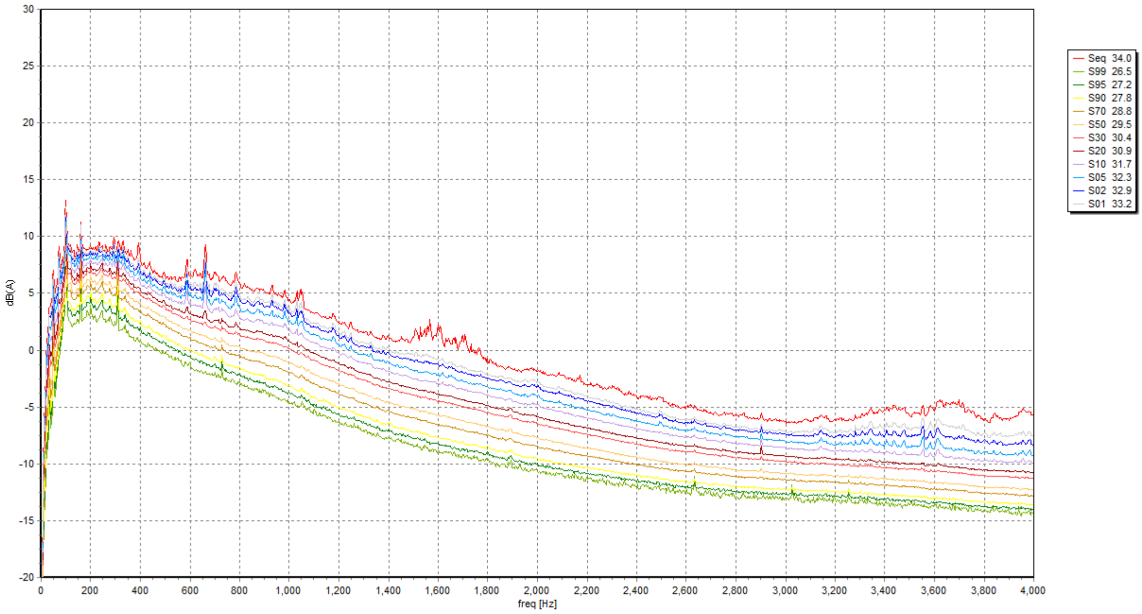
Source: own presentation, deBAKOM GmbH

Figure 68: Wind distribution in SA 1



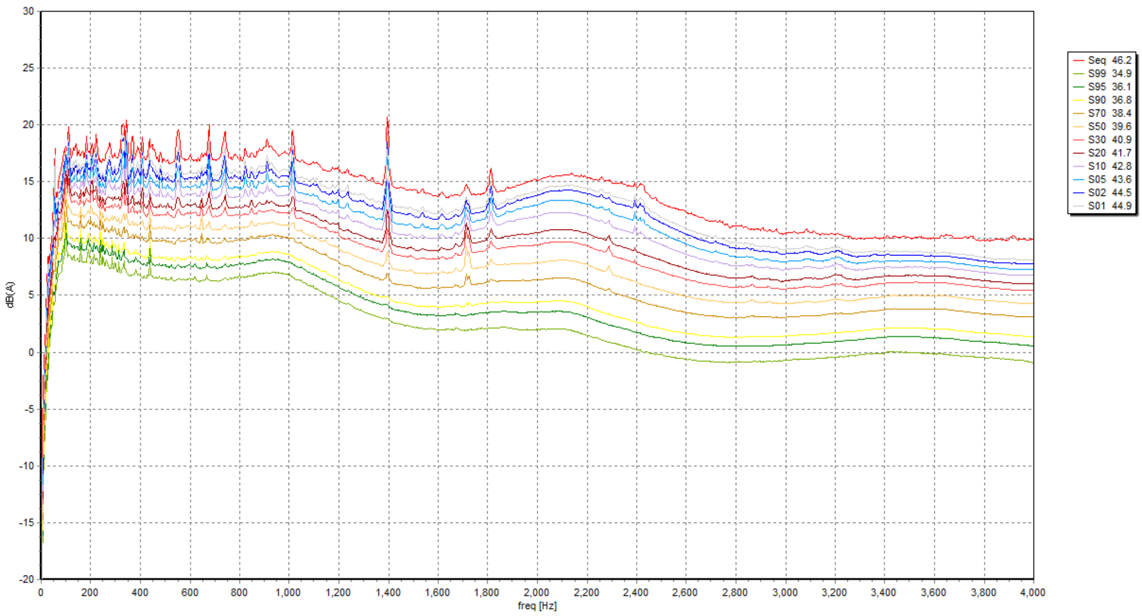
Source: own presentation, deBAKOM GmbH

Figure 69: Averaged percentile spectra, night (2:00 a.m. – 4:00 a.m.) SA 1



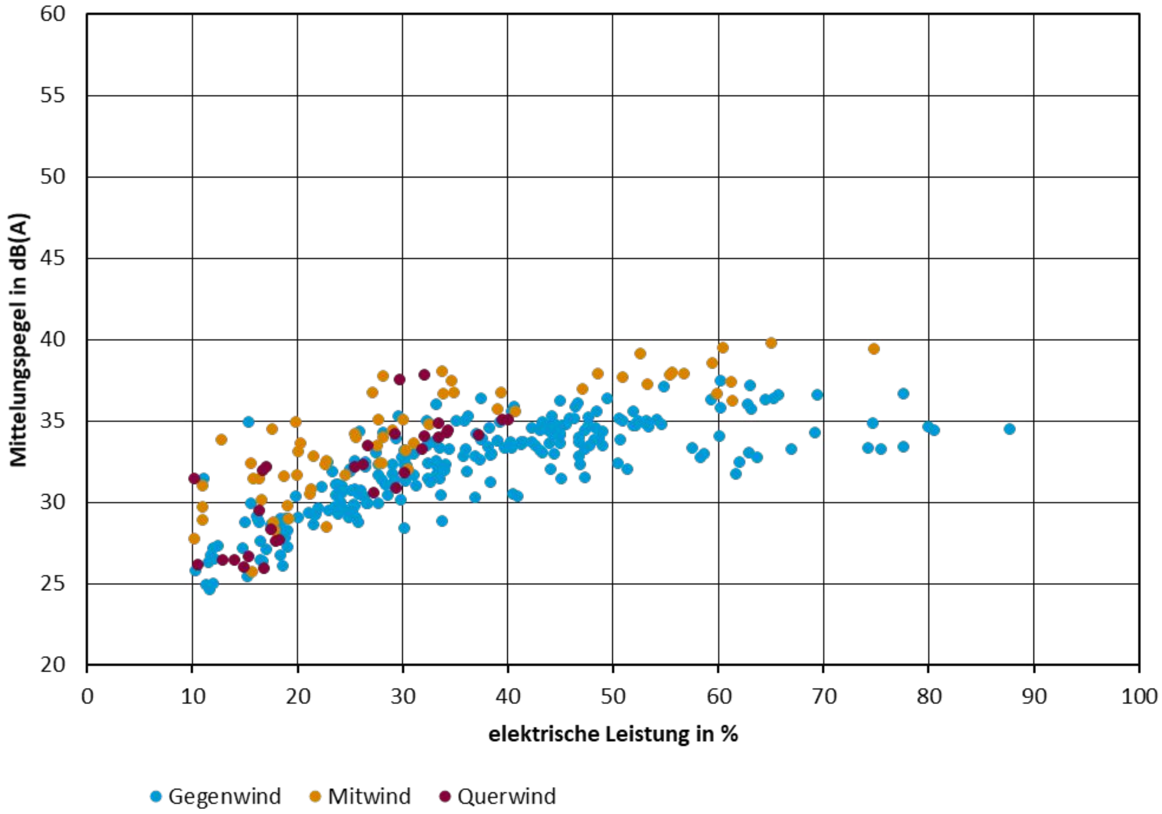
Source: own presentation, deBAKOM GmbH

Figure 70: Averaged percentile spectra, day (6:00 a.m. – 10:00 p.m.) SA 1



Source: own presentation, deBAKOM GmbH

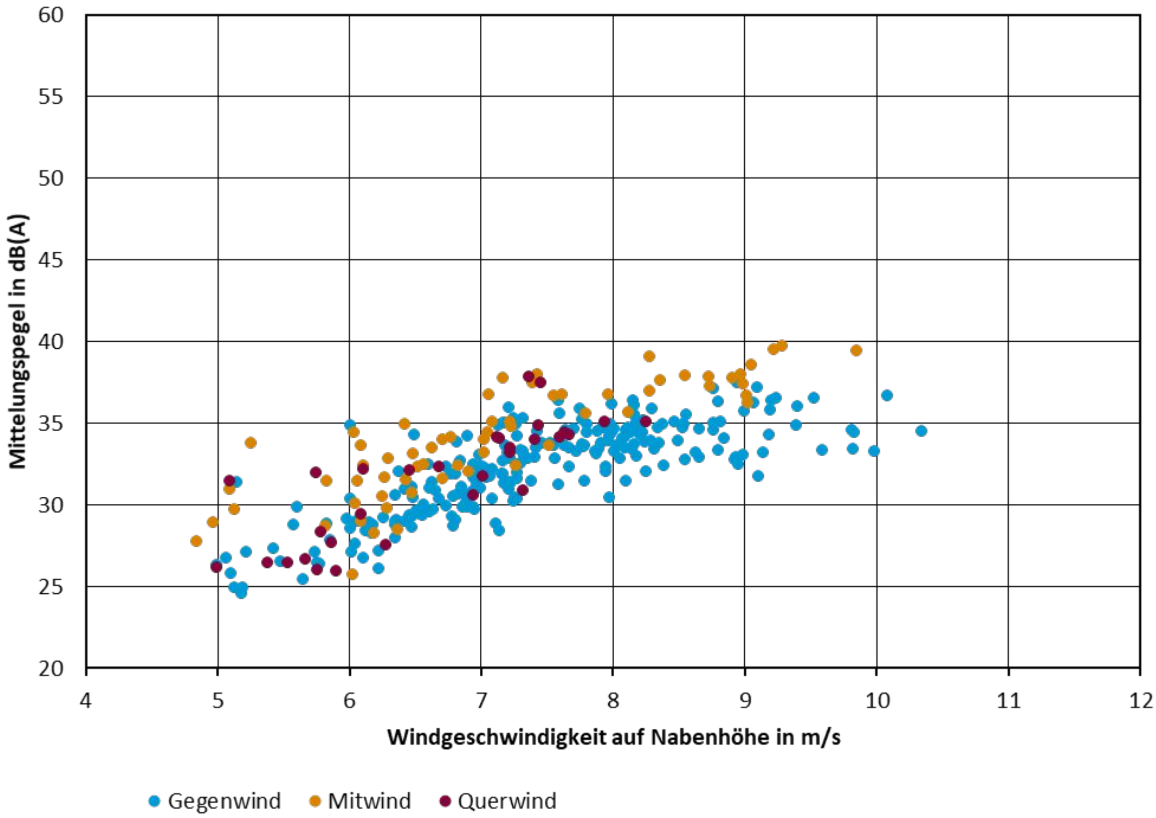
Figure 71: 10-min. average sound level during average output of the entire wind farm SA 1



Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); elektrische Leistung in % = Electrical output in %; Gegenwind = Headwind; Mitwind = Tailwind; Querwind = Crosswind

Figure 72: 10-min. average sound level during average wind speed SA 1

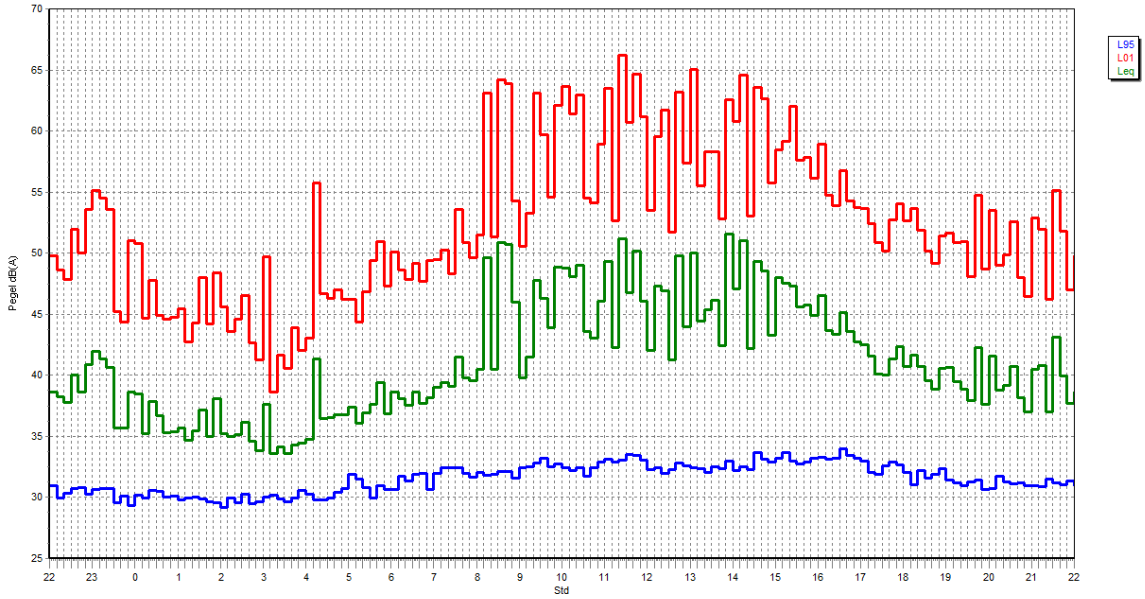


Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); Windgeschwindigkeit auf Nebenhöhe in m/s = Wind speed at hub height in m/s; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

B.2 Study Area 2

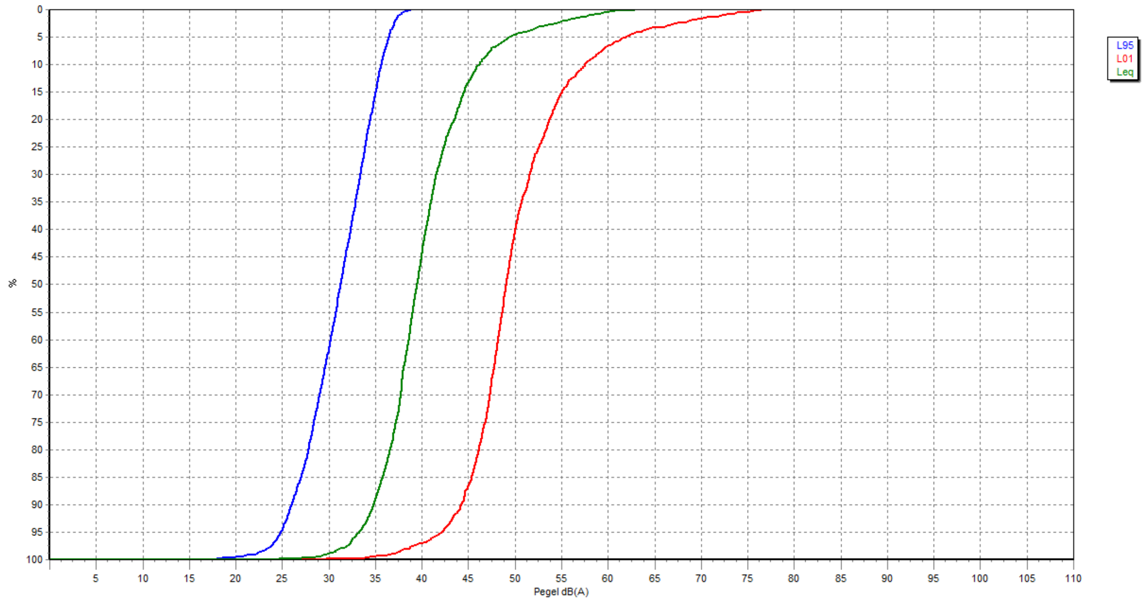
Figure 73: Diurnal pattern for averaging level SA 2



Pegel dB(A) = Level dB(A); Std = Hours

Source: own presentation, deBAKOM GmbH

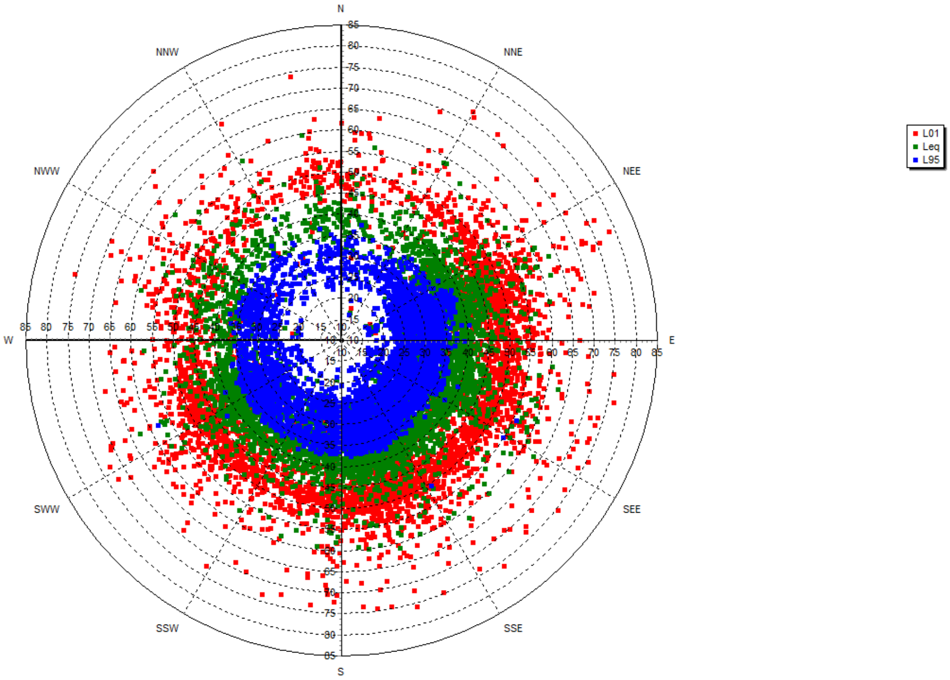
Figure 74: Cumulative frequency for averaging level SA 2



Pegel dB(A) = Level dB(A)

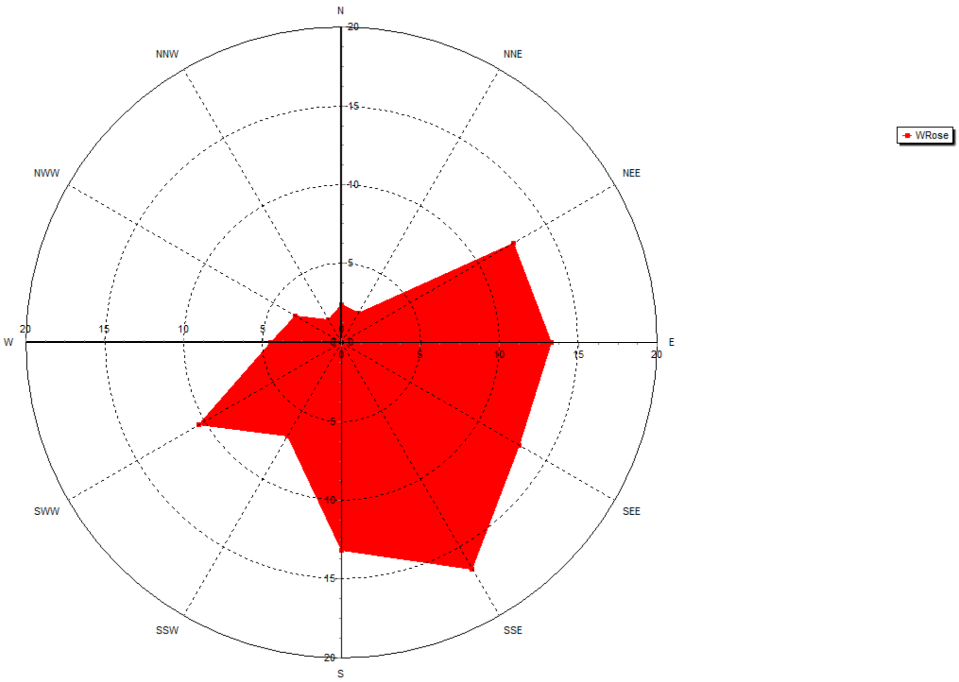
Source: own presentation, deBAKOM GmbH

Figure 75: Level distribution over wind direction SA 2



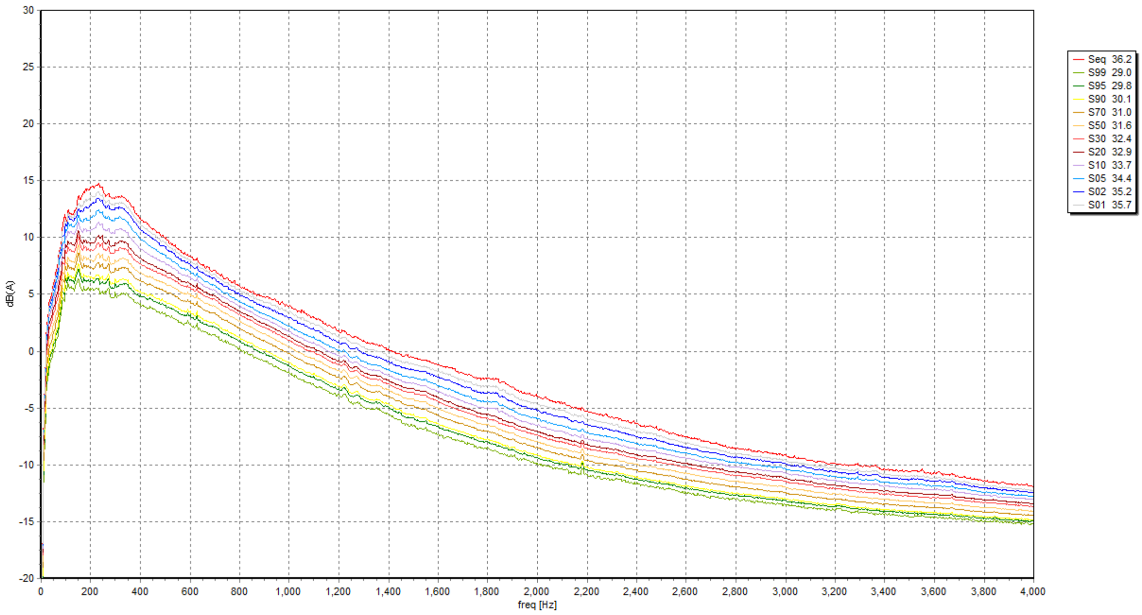
Source: own presentation, deBAKOM GmbH

Figure 76: Wind distribution in SA 2



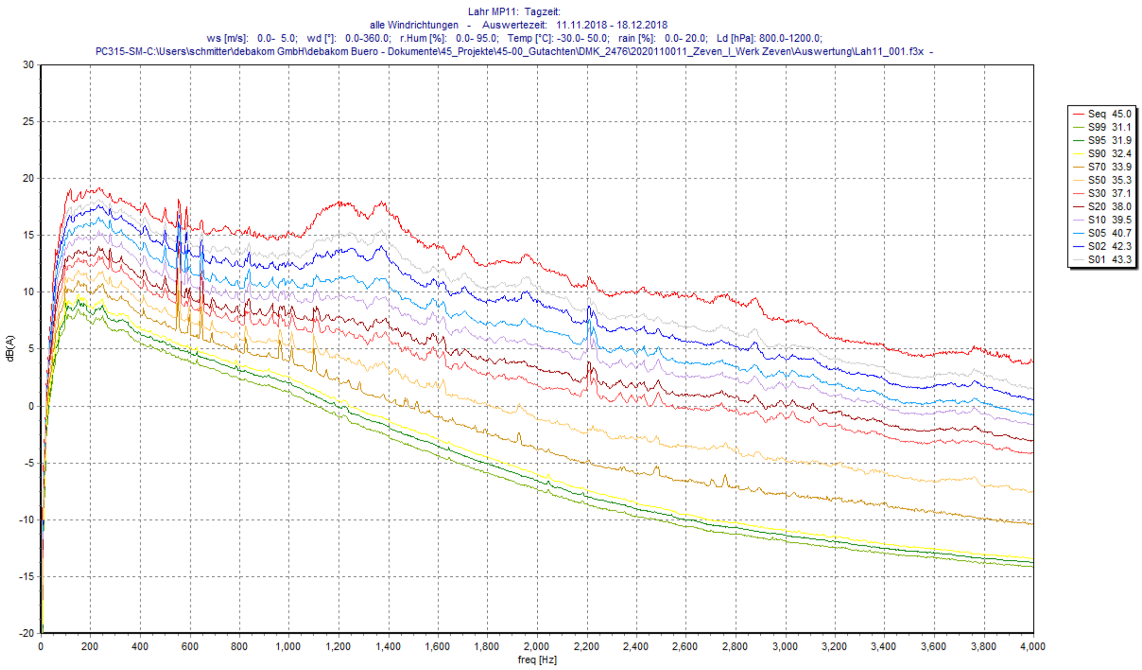
Source: own presentation, deBAKOM GmbH

Figure 77: Averaged percentile spectra, night (2:00 a.m. – 4:00 a.m.) SA 2



Source: own presentation, deBAKOM GmbH

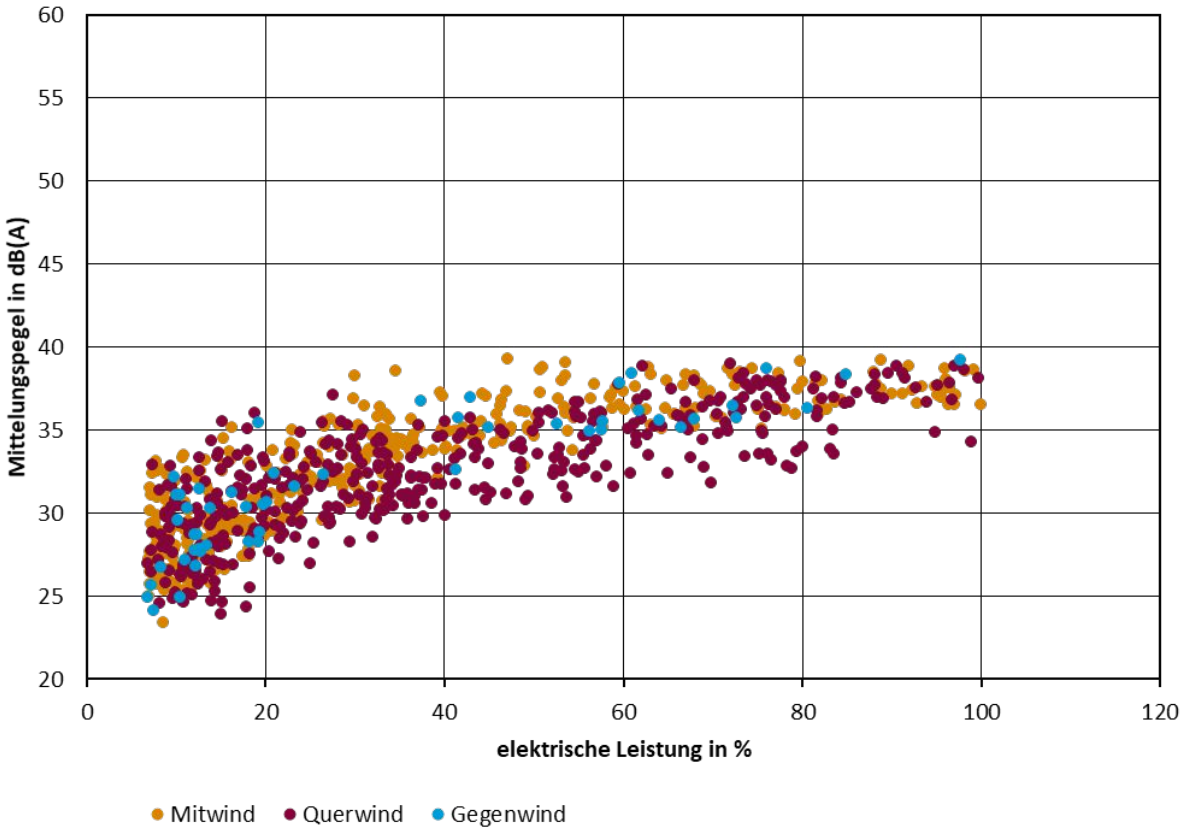
Figure 78: Averaged percentile spectra, day (6:00 a.m. – 10:00 p.m.) SA 2



Source: own presentation, deBAKOM GmbH

Lahr MP11: Tageszeit = Lahr MP11: Time of day; Alle Windrichtungen-Auswertezeit: 11.11.2018-18.12.2018 = All wind directions Evaluation time: 11 November 2018-18 December 2018; Ws [m/s]: 0.0- 5.0 = Wind speed [m/s]: 0.0- 5.0; wd [°]: 0.0-360.0 = wd [°]: 0.0-360.0; r.Hum [%]: 0.0-95.0 = r.Hum [%]: 0.0-95.0 ; Temp [°C]: -30.0-50.0 = Temp [°C]: -30.0-50.0 ; rain [%] 0.0- 20.0 = rain [%] 0.0- 20.0 ; Ld[hPa]:800.0-1200.0 = Ld[hPa]:800.0-1200.0

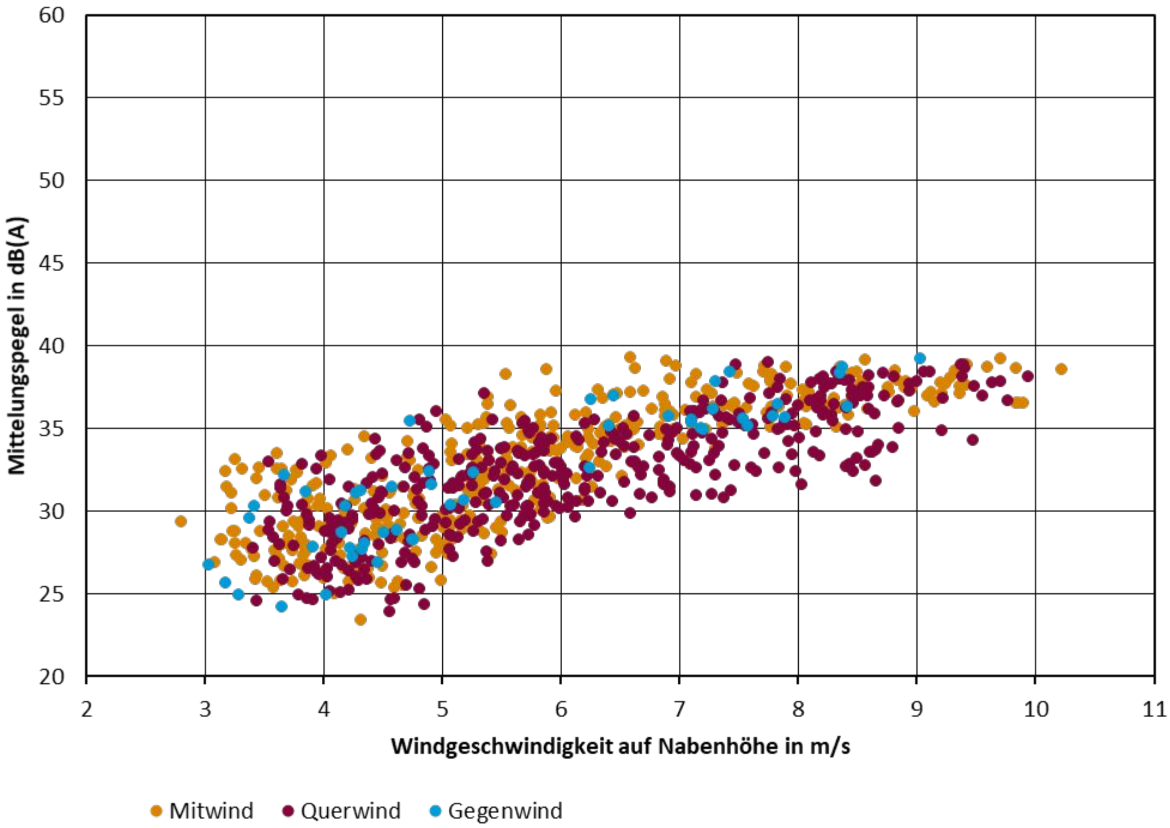
Figure 79: 10-min. average sound level during average output of the entire wind farm SA 2



Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); Elektrische Leistung in % = Electrical output in %; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

Figure 80: 10-min. average sound level during average wind speed SA 2

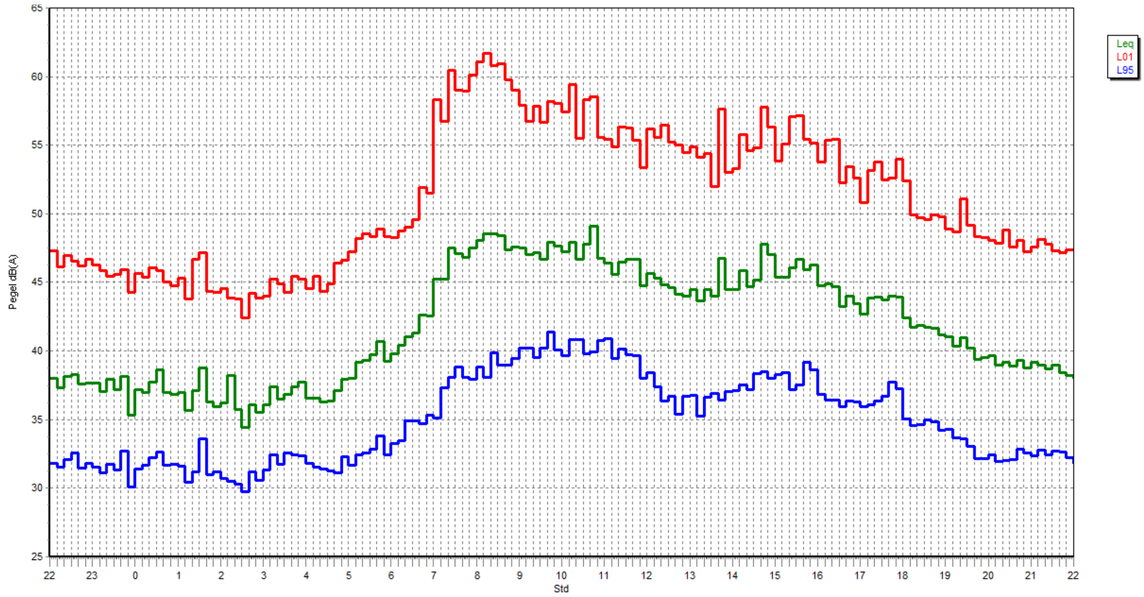


Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); Windgeschwindigkeit auf Nebenhöhe in m/s = Wind speed at hub height in m/s; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

B.3 Study Area 3

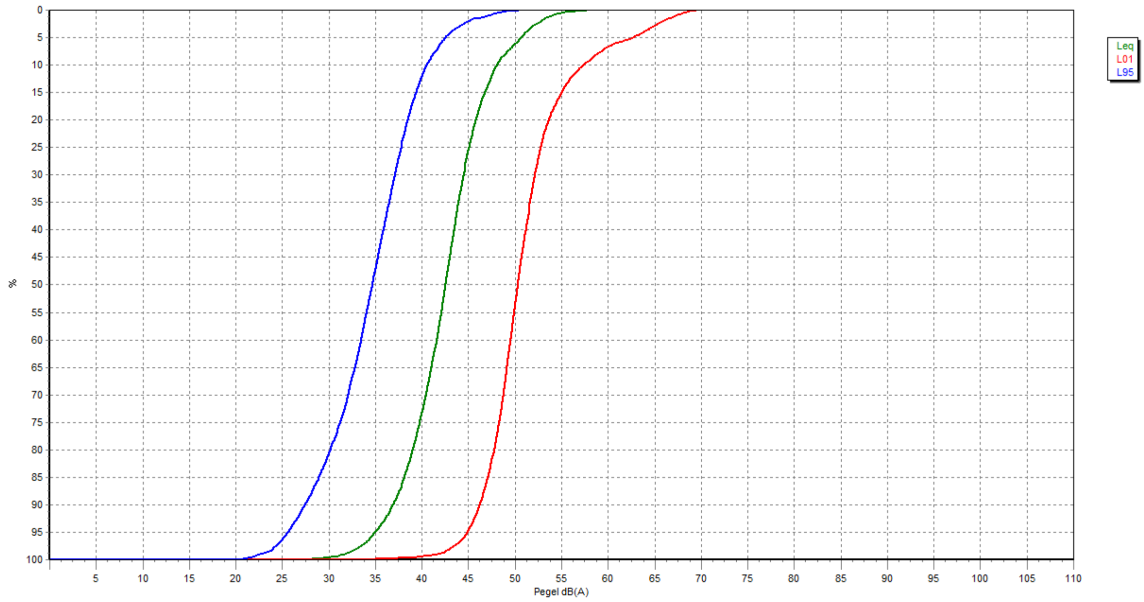
Figure 81: Diurnal pattern for averaging level SA 3



Source: own presentation, deBAKOM GmbH

Pegel dB(A) = Level dB(A); Std = Hours

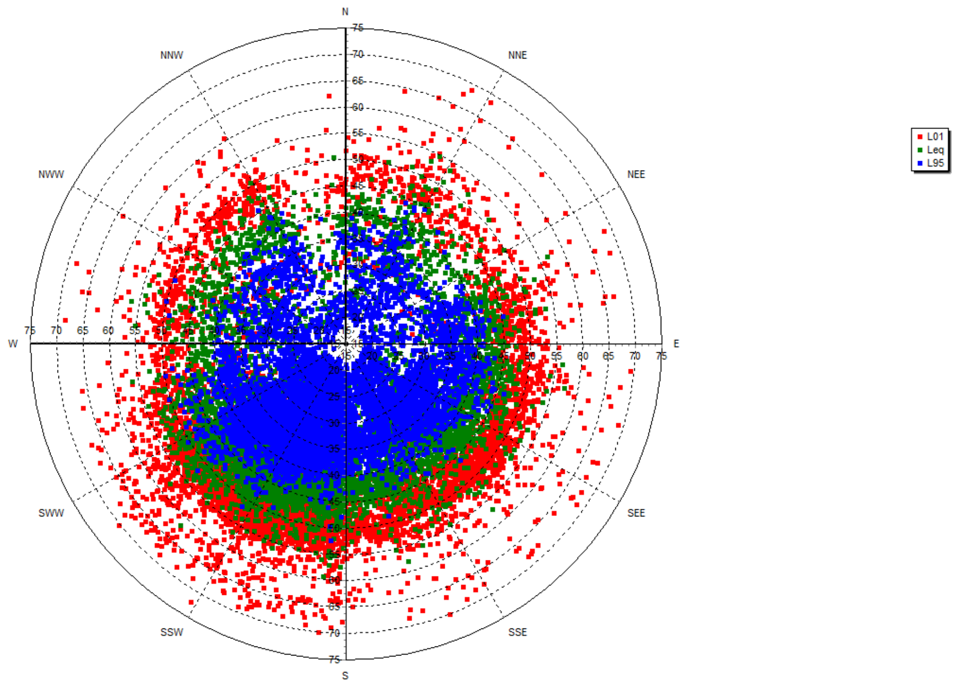
Figure 82: Cumulative frequency for averaging level SA 3



Source: own presentation, deBAKOM GmbH

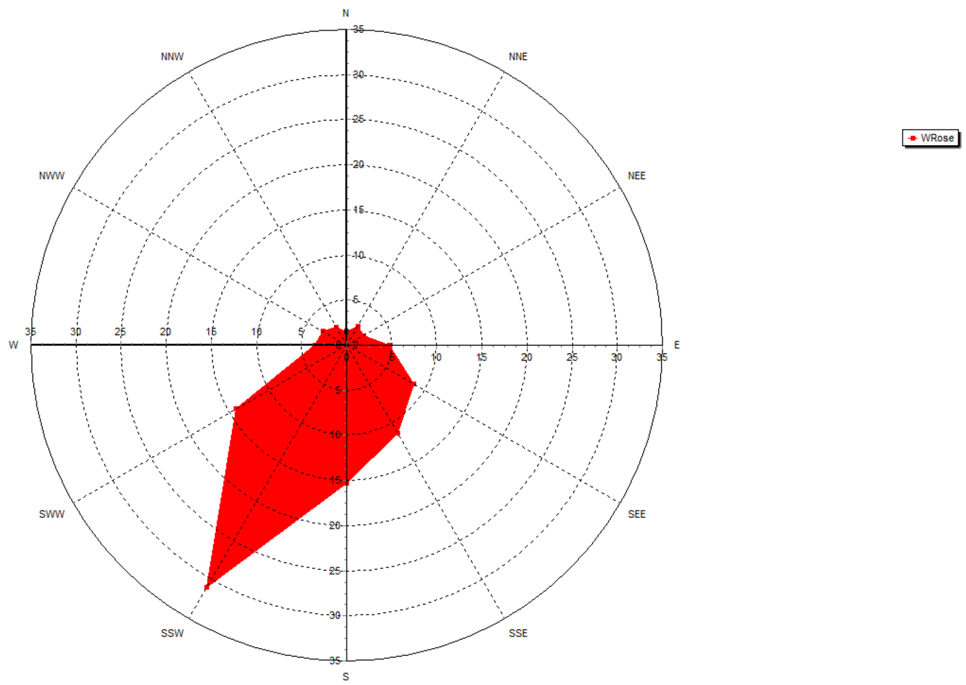
Pegel dB(A) = Level dB(A)

Figure 83: Level distribution over wind direction SA 3



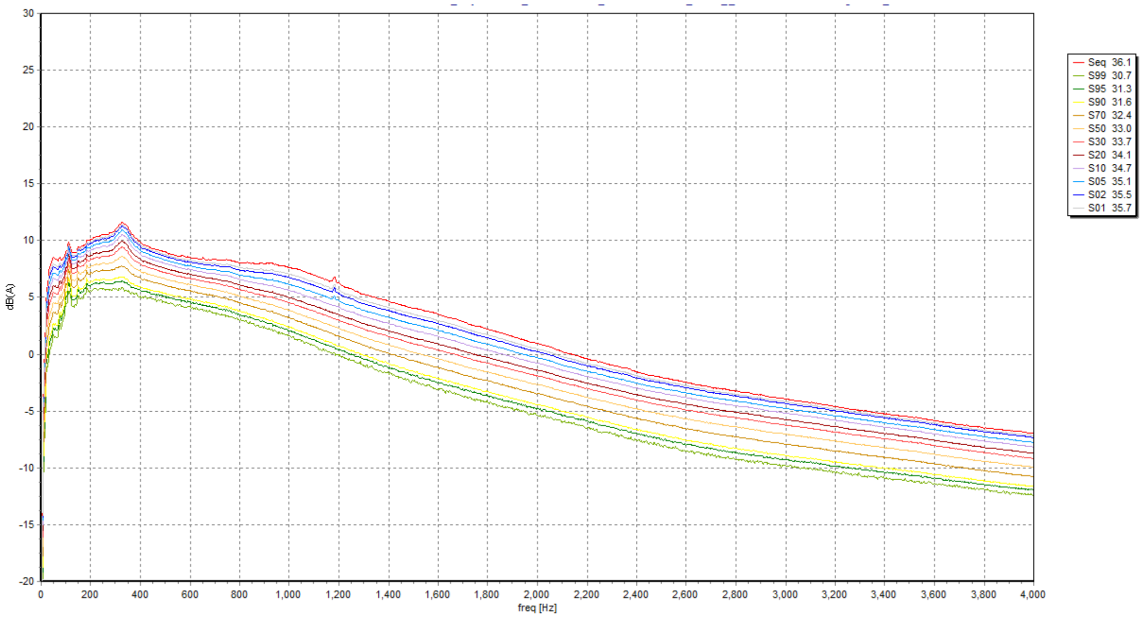
Source: own presentation, deBAKOM GmbH

Figure 84: Wind distribution in SA 3



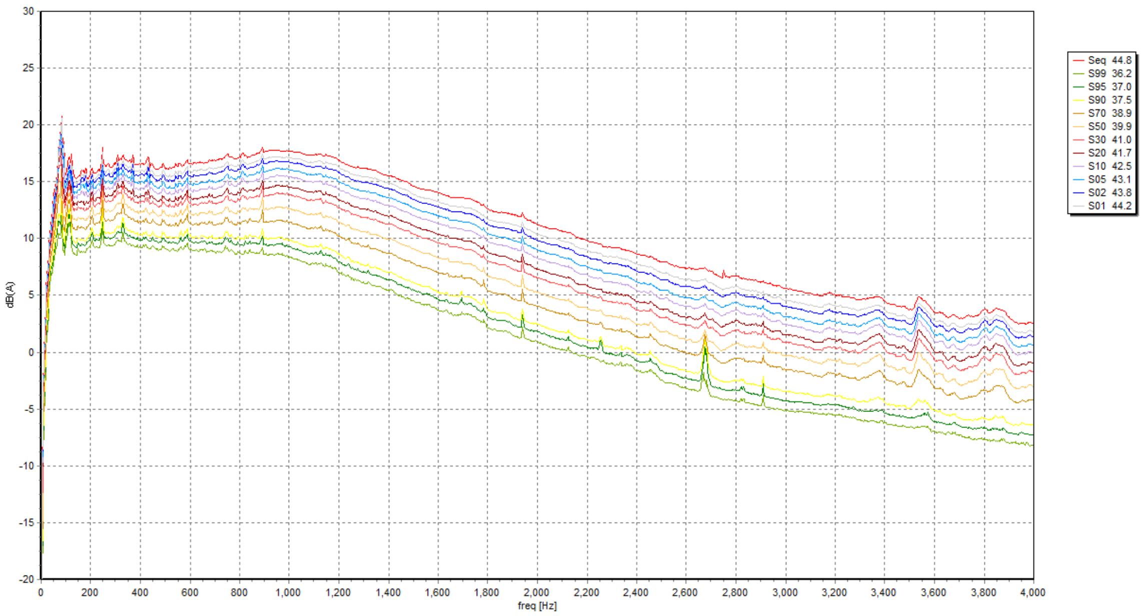
Source: own presentation, deBAKOM GmbH

Figure 85: Averaged percentile spectra, night (2:00 a.m. – 4:00 a.m.) SA 3



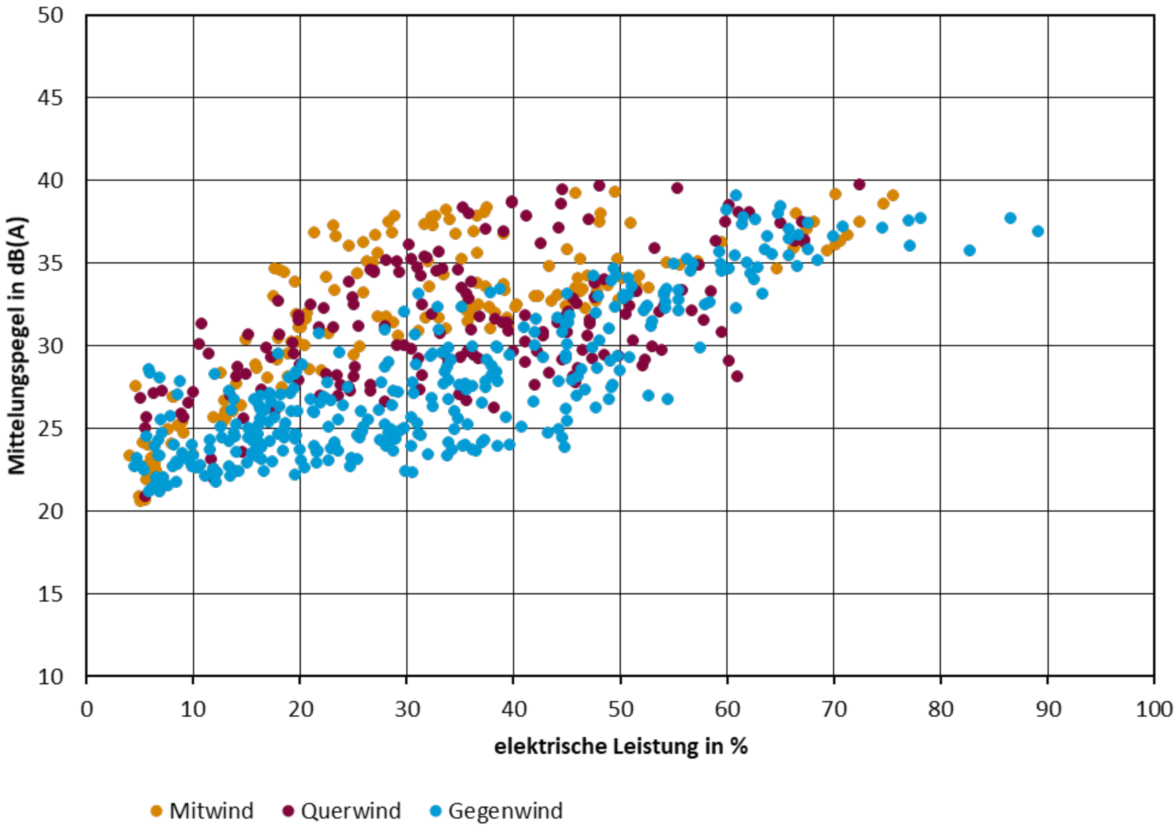
Source: own presentation, deBAKOM GmbH

Figure 86: Averaged percentile spectra, day (6:00 a.m. – 10:00 p.m.) SA 3



Source: own presentation, deBAKOM GmbH

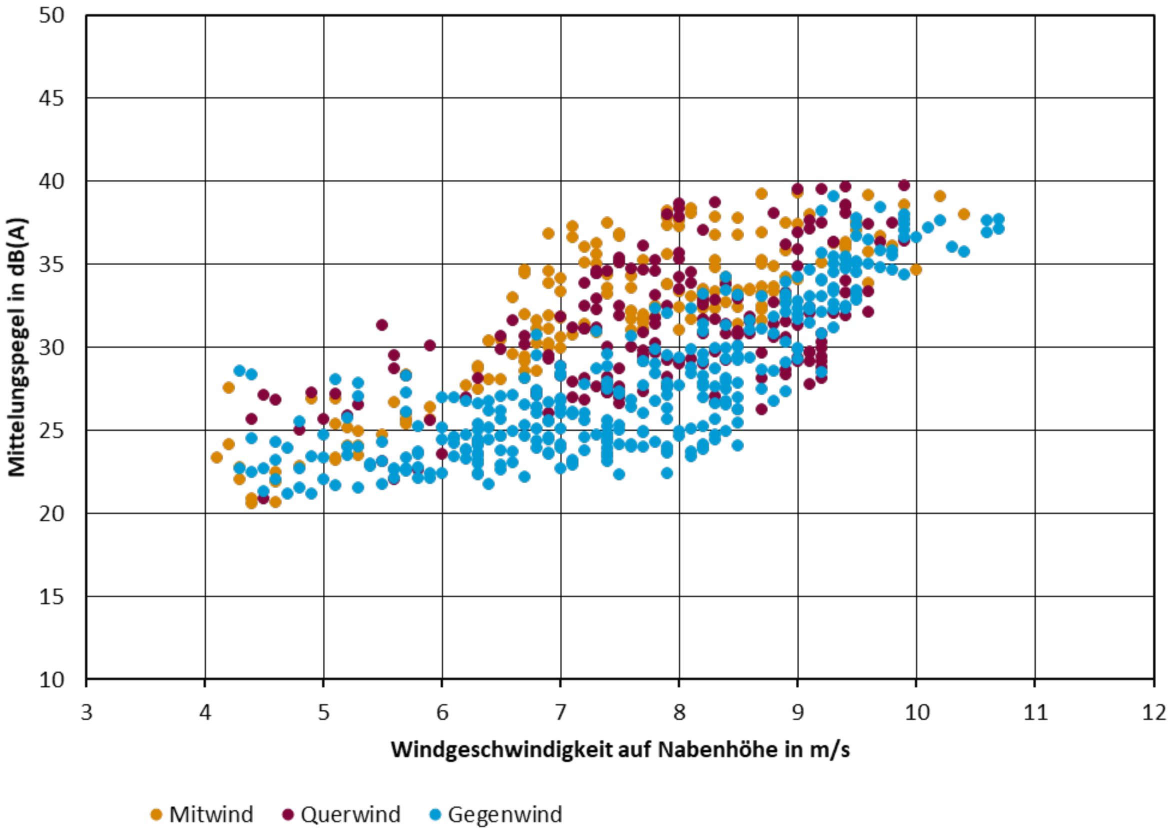
Figure 87: 10-min. average sound level during average output of the entire wind farm SA 3



Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); Elektrische Leistung in % = Electrical output in %; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

Figure 88: 10-min. average sound level during average wind speed SA 3

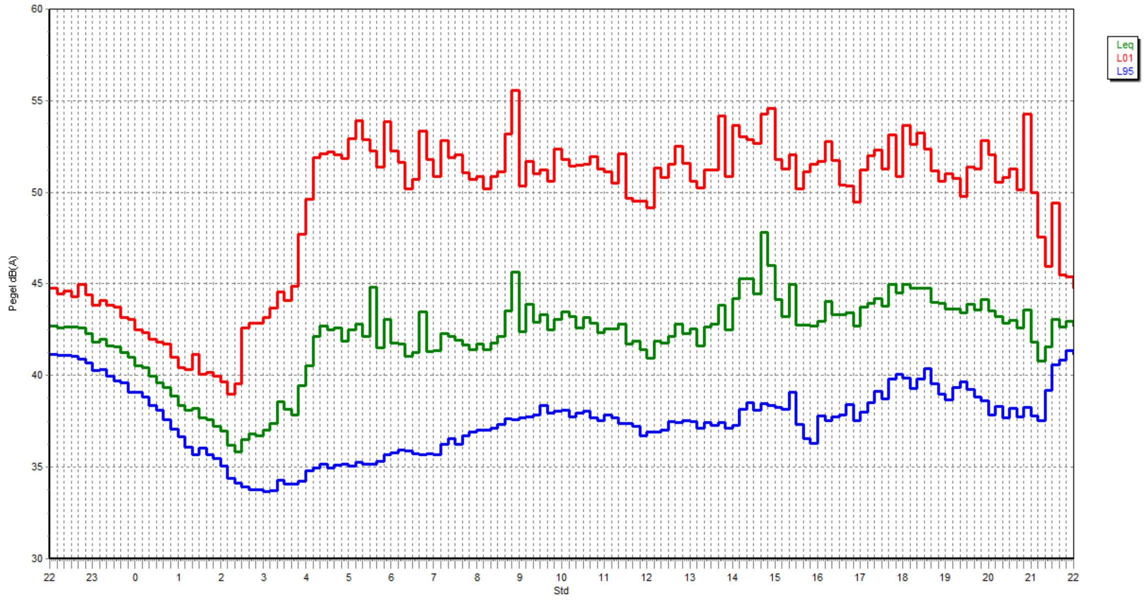


Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); Windgeschwindigkeit auf Nebenhöhe in m/s = Wind speed at hub height in m/s; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

B.4 Study Area 4

Figure 89: Diurnal pattern for averaging level SA 4

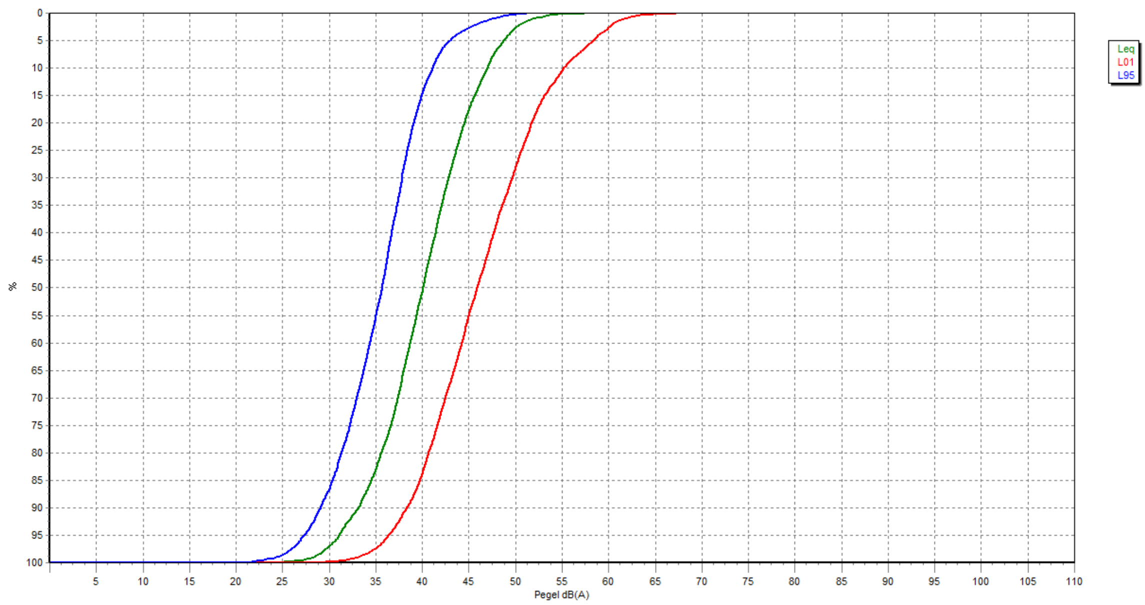


Source: own presentation, deBAKOM GmbH

Pegel dB(A) = Level dB(A); Std = Hours

Note: The diurnal pattern is significantly influenced by the noise of chirping crickets on individual measurement days; this decreased during the night.

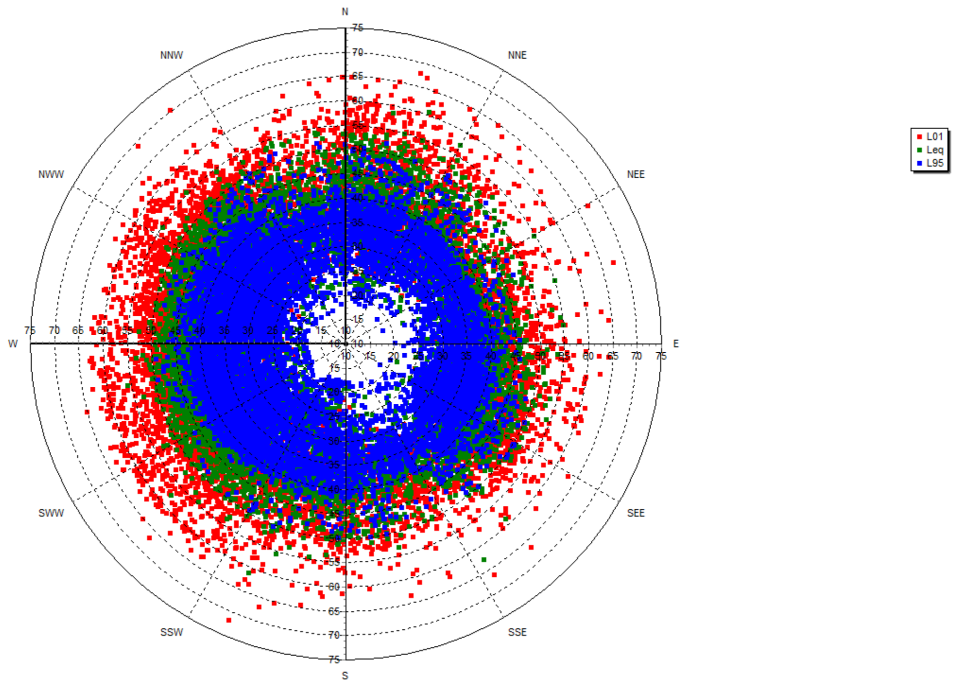
Figure 90: Cumulative frequency for averaging level SA 4



Source: own presentation, deBAKOM GmbH

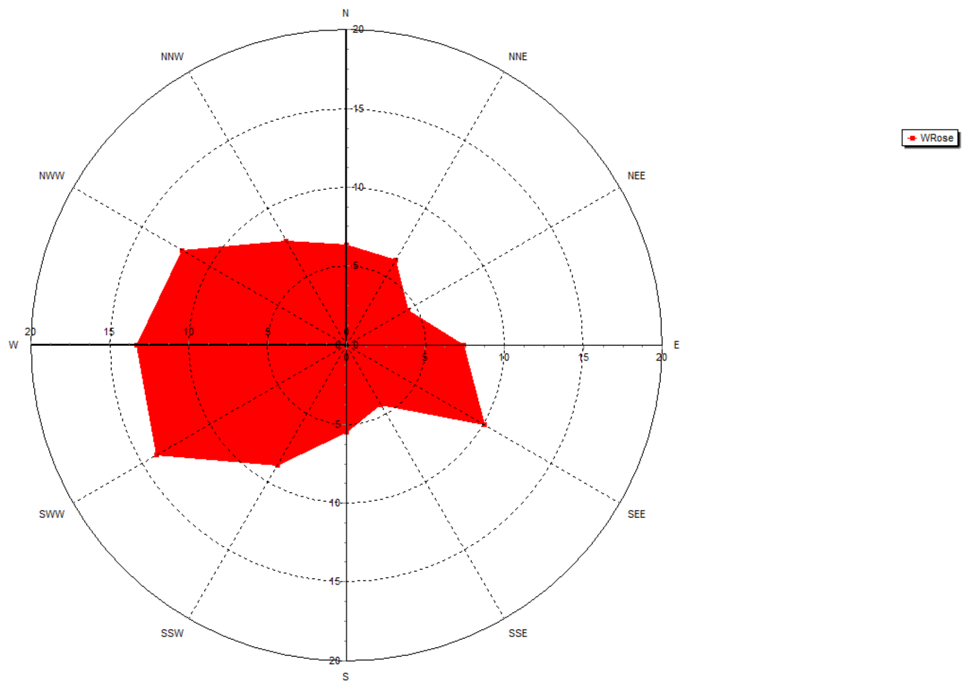
Pegel dB(A) = Level dB(A)

Figure 91: Level distribution over wind direction SA 4



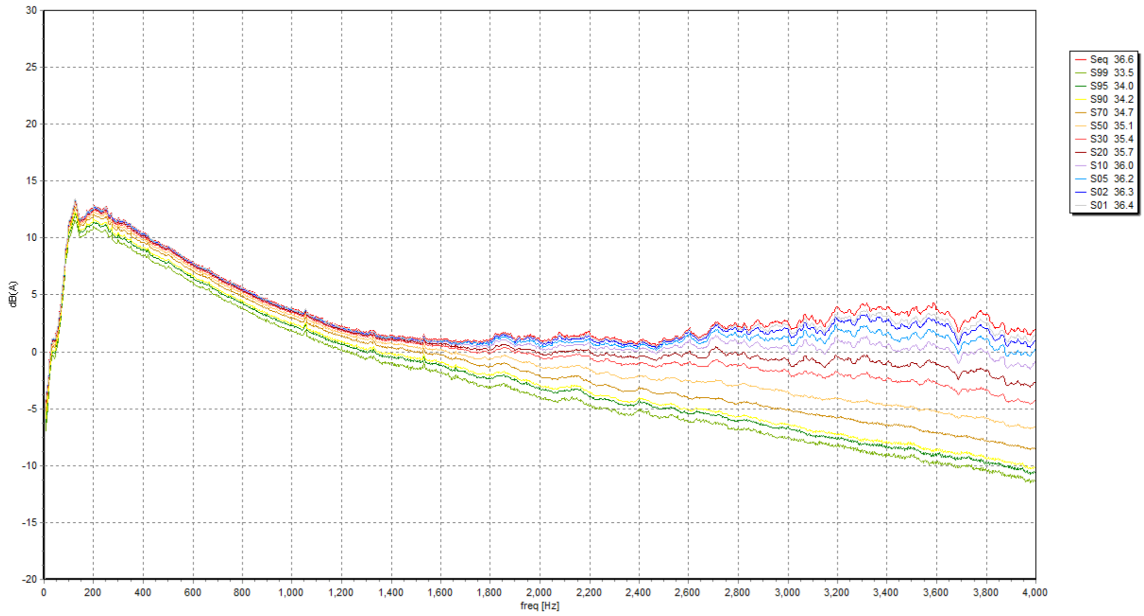
Source: own presentation, deBAKOM GmbH

Figure 92: Wind distribution in SA 4



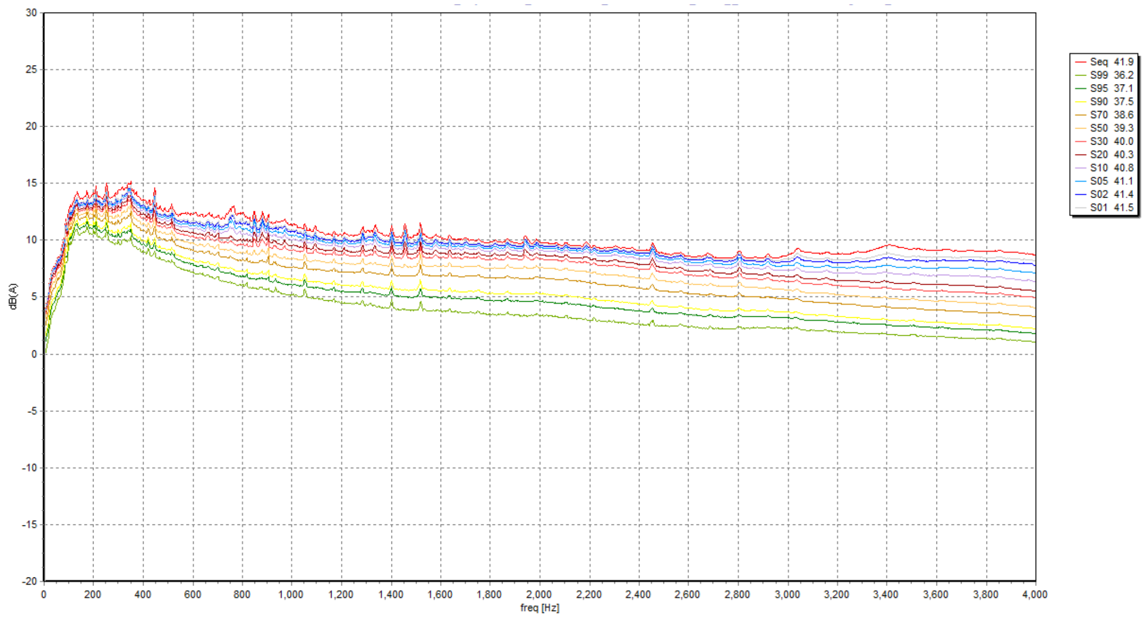
Source: own presentation, deBAKOM GmbH

Figure 93: Averaged percentile spectra, night (2:00 a.m. – 4:00 a.m.) SA 4



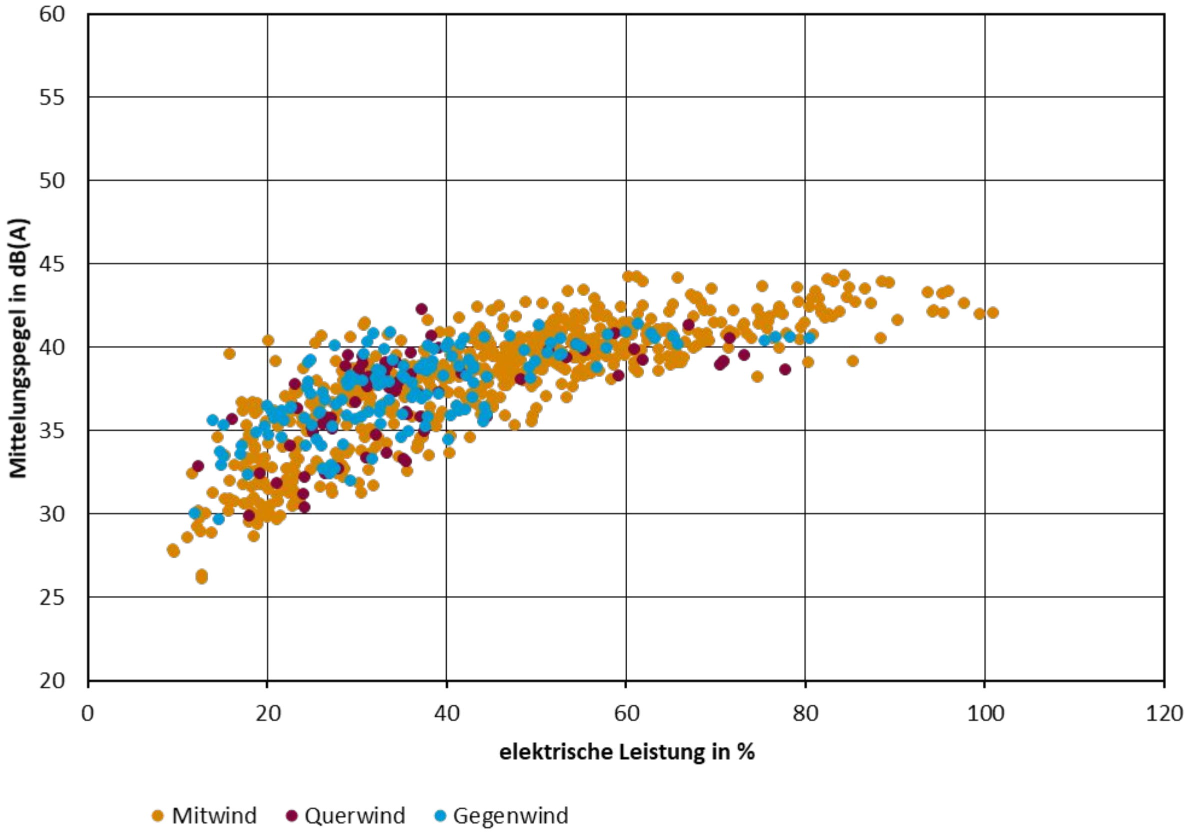
Source: own presentation, deBAKOM GmbH

Figure 94: Averaged percentile spectra, day (6:00 a.m. – 10:00 p.m.) SA 4



Source: own presentation, deBAKOM GmbH

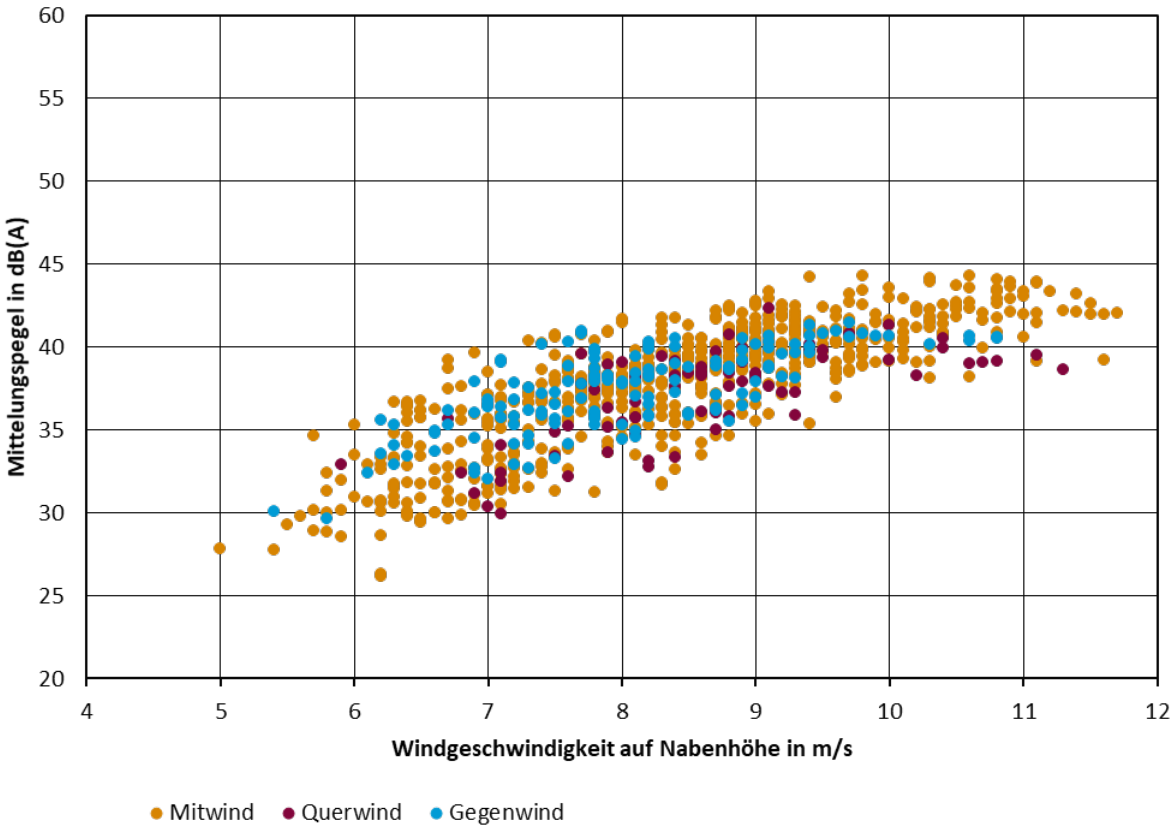
Figure 95: 10-min. average sound level during average output of the entire wind farm SA 4



Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); elektrische Leistung in % = Electrical output in %; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

Figure 96: 10-min. average sound level during average wind speed SA 4

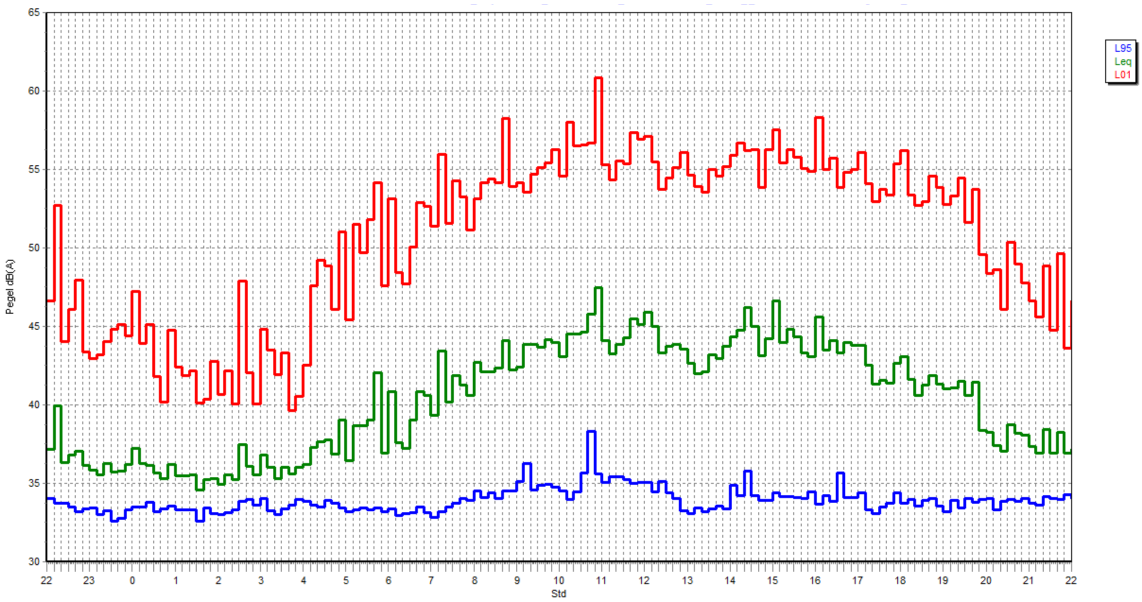


Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); Windgeschwindigkeit auf Nabenhöhe in m/s = Wind speed at hub height in m/s; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

B.5 Study Area 5

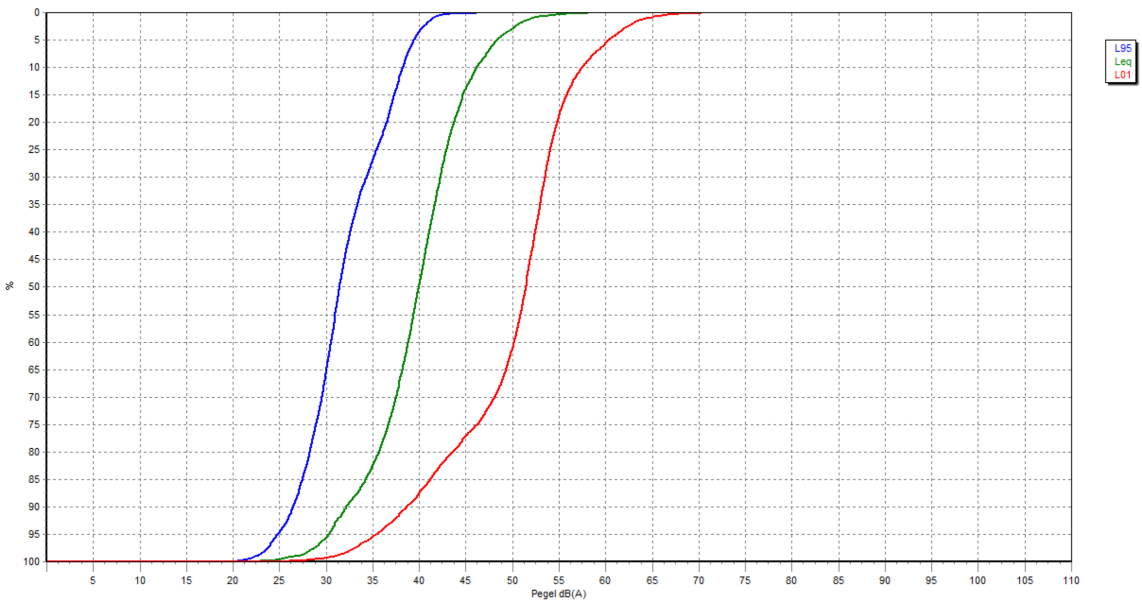
Figure 97: Diurnal pattern for averaging level SA 5



Source: own presentation, deBAKOM GmbH

Pegel dB(A) = Level dB(A); Std = Hours

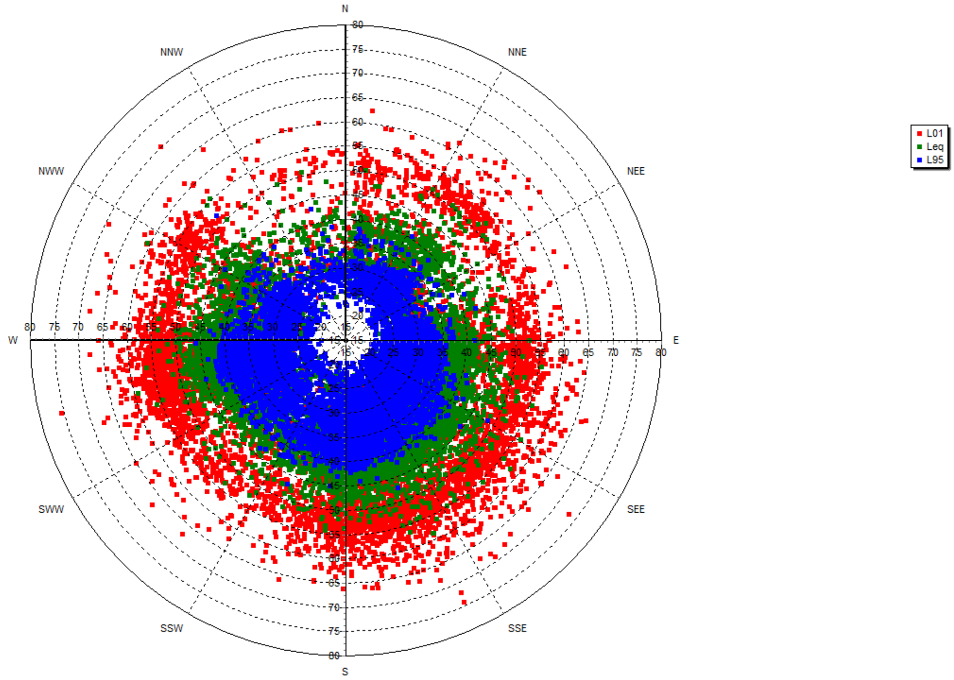
Figure 98: Cumulative frequency for averaging level SA 5



Source: own presentation, deBAKOM GmbH

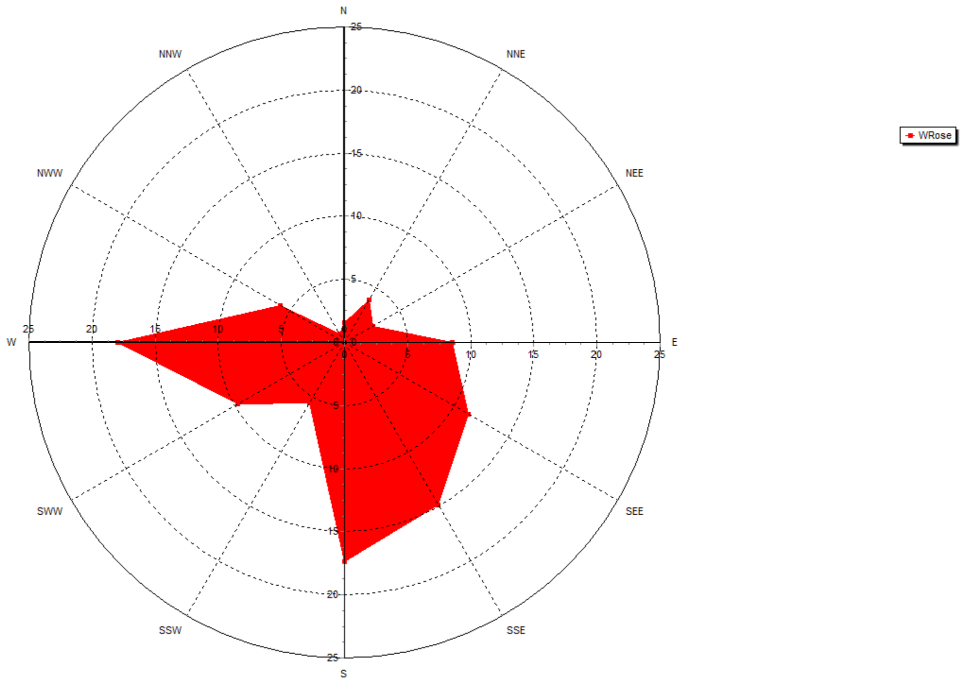
Pegel dB(A) = Level dB(A)

Figure 99: Level distribution over wind direction SA 5



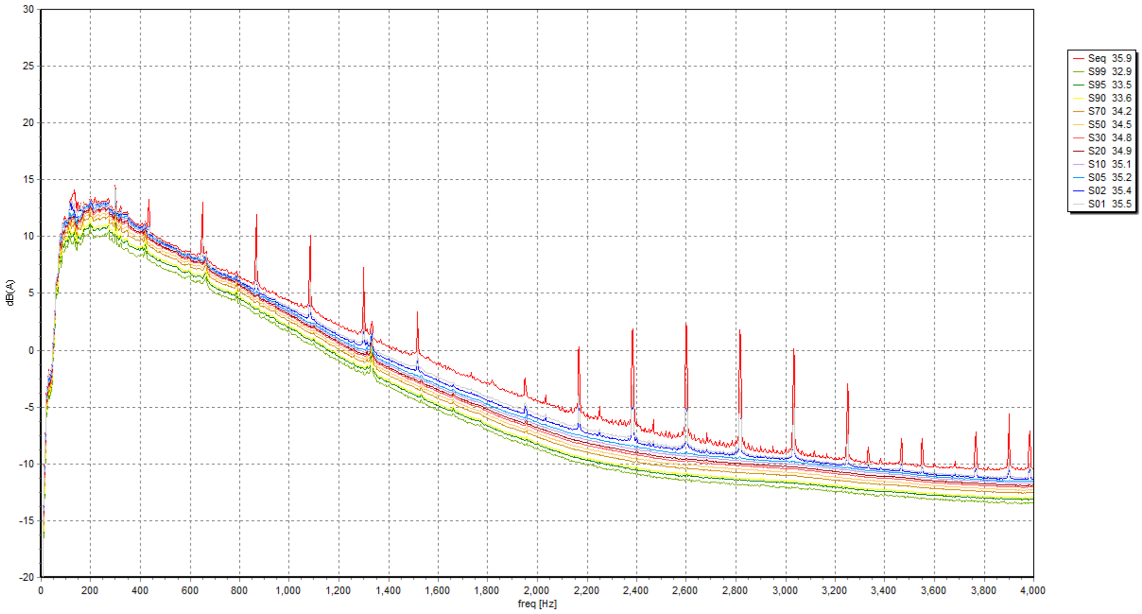
Source: own presentation, deBAKOM GmbH

Figure 100: Wind distribution in SA 5



Source: own presentation, deBAKOM GmbH

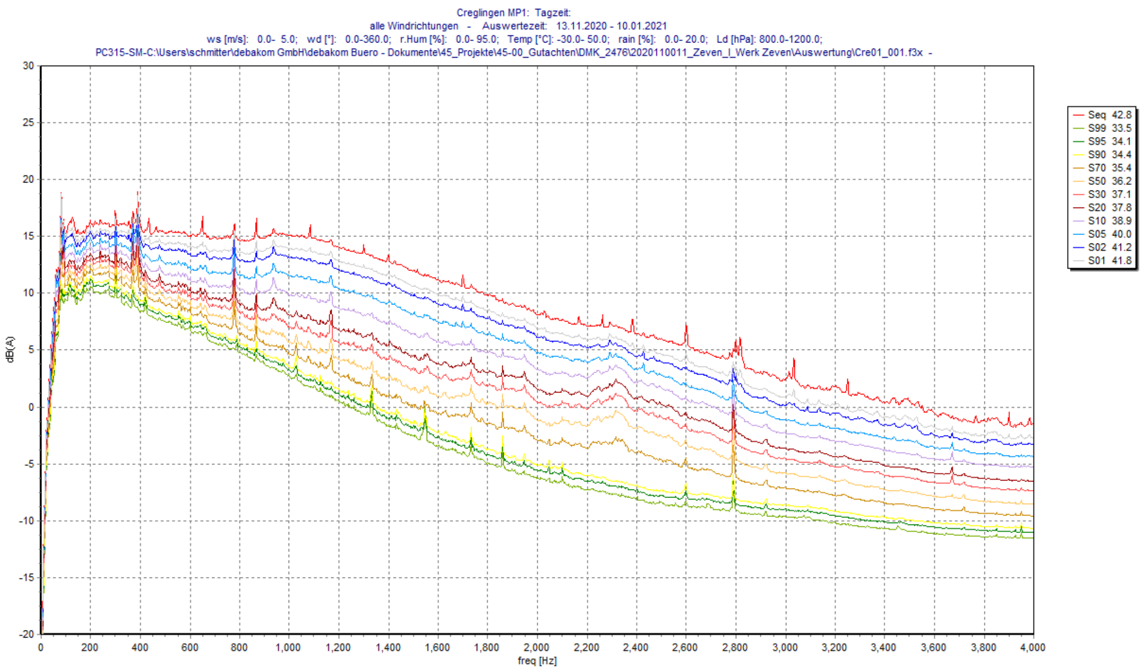
Figure 101: Averaged percentile spectra, night (2:00 a.m. – 4:00 a.m.) SA 5



Source: own presentation, deBAKOM GmbH

Note: Visible in the spectra are the short-term influences of the bell of the village church

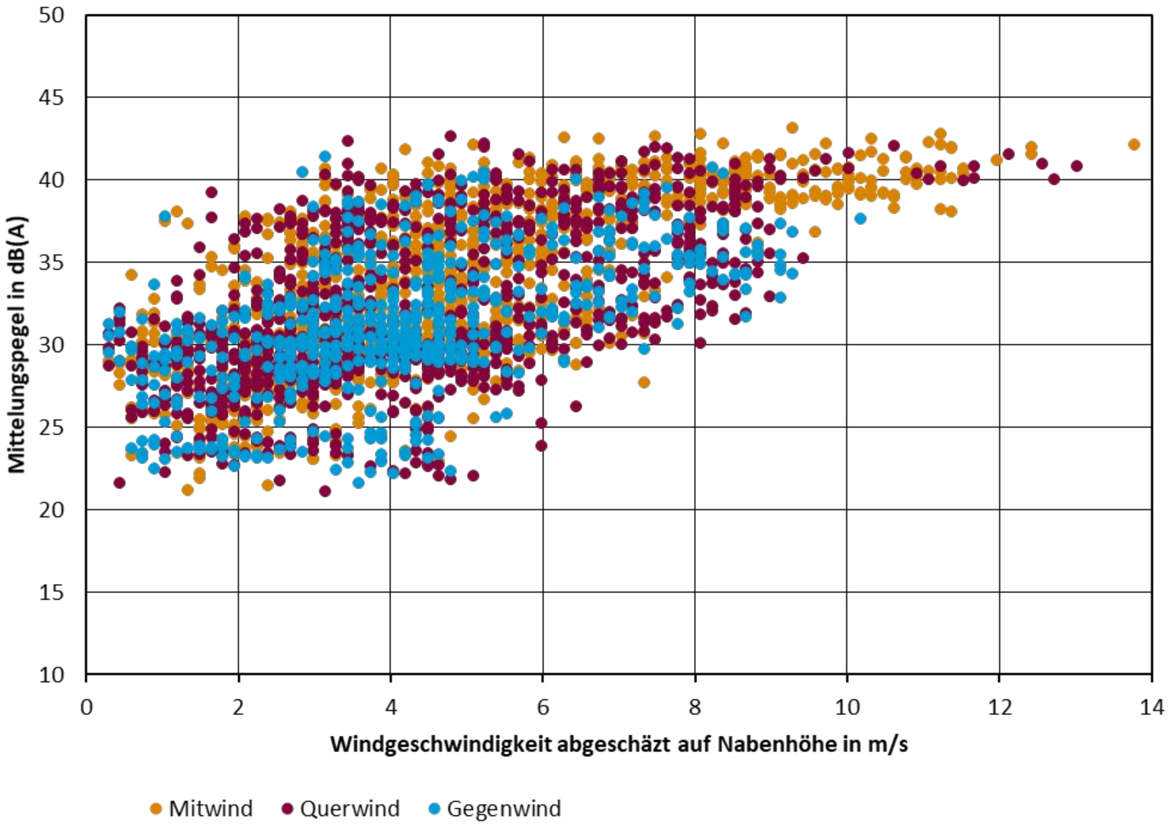
Figure 102: Averaged percentile spectra, day (6:00 a.m. – 10:00 p.m.) SA 5



Source: own presentation, deBAKOM GmbH

Creglingen MP1: Tagzeit: = Creglingen MP1: Time of day:; alle Windrichtungen - Auswertezeit = All wind directions – Evaluation time; Ws [m/s]: 0.0- 5.0 = Wind speed [m/s]: 0.0- 5.0; wd [°]: 0.0-360.0 = wd [°]: 0.0-360.0; r.Hum [%]: 0.0-95.0 = r.Hum [%]: 0.0-95.0; Temp [°C]: -30.0-50.0 = Temp [°C]: -30.0-50.0; rain [%] 0.0- 20.0 = rain [%] 0.0- 20.0; Ld[hPa]: 800.0-1200.0 = Ld[hPa]: 800.0-1200.0

Figure 103: 10-min. average sound level during average wind speed SA 5



Source: own presentation, deBAKOM GmbH

Mittelungspegel in dB(A) = Averaging level in dB(A); Windgeschwindigkeit abgeschätzt auf Nabenhöhe in m/s = Wind speed estimated at hub height in m/s; Mitwind = Tailwind; Querwind = Crosswind; Gegenwind = Headwind

Note: Because the measurements in Study Area 5 were performed without the aid of an operator, no system data are available. The wind speed at the microphone was partly influenced by the nearest building, and by trees near the measurement position. Presentation of the levels via wind speed at the measuring height reflects the noise behaviour of the wind turbines only to a limited extent. This is why wind speeds at hub height were estimated via the nearest weather station of the German Meteorological Service (at a distance of less than 20 km).

C Amplitude modulation

C.1 Algorithm

The following algorithm is used to determine the size and period length of AM in a 30-second time window.

1. The starting point is a noise level record of $L_{Aeq100ms}$, A-weighted 100ms L_{eq}, with a length of approx. 30 seconds and an increment of 20ms between the values.
2. In order to eliminate slower fluctuations from the level, e.g. due to changing meteorological conditions – the noise level record is high-pass-filtered with a base frequency of 0.25 Hz:

$$L_{HP} = Hochpassfilter\left(L_{eq100ms}, 0{,}25Hz\right)$$

3. Determining the AM frequency

a) The levels L_{HP} are shifted in such a way that the arithmetic mean value of the noise level record is zero, and then multiplied by a kernel density estimation. In this case, the window is selected such that the maximum lies in the middle of the time segment and goes to zero directly outside the time segment.

$$P(x) = \begin{cases} -2(-1+2x)^3 & f\ddot{u}r\ \frac{1}{4} < x \leq \frac{1}{2} \\ 2(1+2x)^3 & f\ddot{u}r\ -\frac{1}{2} \leq x < -\frac{1}{4} \\ 1-24x^2-48x^3 & f\ddot{u}r\ -\frac{1}{4} \leq x < 0 \\ 1-24x^2+48x^3 & f\ddot{u}r\ 0 \leq x \leq \frac{1}{4} \\ 0 & \text{sonst} \end{cases}$$

Kernel density estimation is very similar to the Gauss function. In the case of Fourier transformation, like the Gauss function, the kernel density estimation leads to a gentle broadening of lines.

b) The time series is expanded to ten times the length by appending zeros (padding).

c) A Fourier transformation is carried out for the newly created time series.
In the window from 0.3 to 1.2 Hz, the frequency with the greatest magnitude is sought in the Fourier transform of the spectrum. This frequency f_{AM} is regarded as a possible frequency for AM.

4. If the wind turbines generate (quasi-)periodic signals with a frequency of f_{AM}, then these should repeat with a period duration of $\tau = {}^{1}/_{f_{AM}}$. In the following, instead of $L_{HP}(t_i)$, the time series is 'telescoped' to a period length by replacing t_i with $t_i\ mod\ \tau$. Here, mod stands for the modulo value, i.e. if t_i is greater than τ, τ will be subtracted until t_i lies between 0 and τ.

a) The time from 0 to τ is divided into 25 intervals. An (energetic) averaging level $L_{eq\tau}$ is formed for each of the levels in these intervals.

b) The measure for AM is the level difference between the largest and the smallest $L_{eq\tau}$:

$$\Delta L_{AM} = max\left(L_{eq\tau}\right) - min\left(L_{eq\tau}\right)$$

5. The pairs of values determined in steps 2 c) and 4 b), f_{AM} and ΔL_{AM}, are regarded as data records.

a) The record of frequency f_{AM} is divided into twelve bands 0.1 Hz wide.

b) For a sliding window of 10 minutes, corresponding to 360 pairs of values, the number of points in the respective bands is counted. Under a uniform distribution, 20 values per band would be expected.

c) If there are more than 40 values within a band, the pair of values is classified as part of an accumulated quantity in terms of time and value, with a technical origin. Since this can mean amplitude modulation generated mainly by wind turbines in the frequency range under consideration and in the vicinity of wind turbines, the pair of values is used for further statistical evaluation.

In the context of this study, this means evaluation according to frequency distributions of the value ΔL_{AM} and the frequency f_{AM}

C.1.1 Evaluating amplitude modulation

In Table 34, modulation depths are classified according to standardised electrical output per measuring location. Here, 100% corresponds to the rated output of the respective reference wind turbine. For Study Area 5, due to the absence of system signals, frequencies are classed based on the wind speed measured at the immission-side microphone. In this case, 100% corresponds to 6 m/s. Experience has shown that wind speeds at hub height are greater than they are at the measurement location.

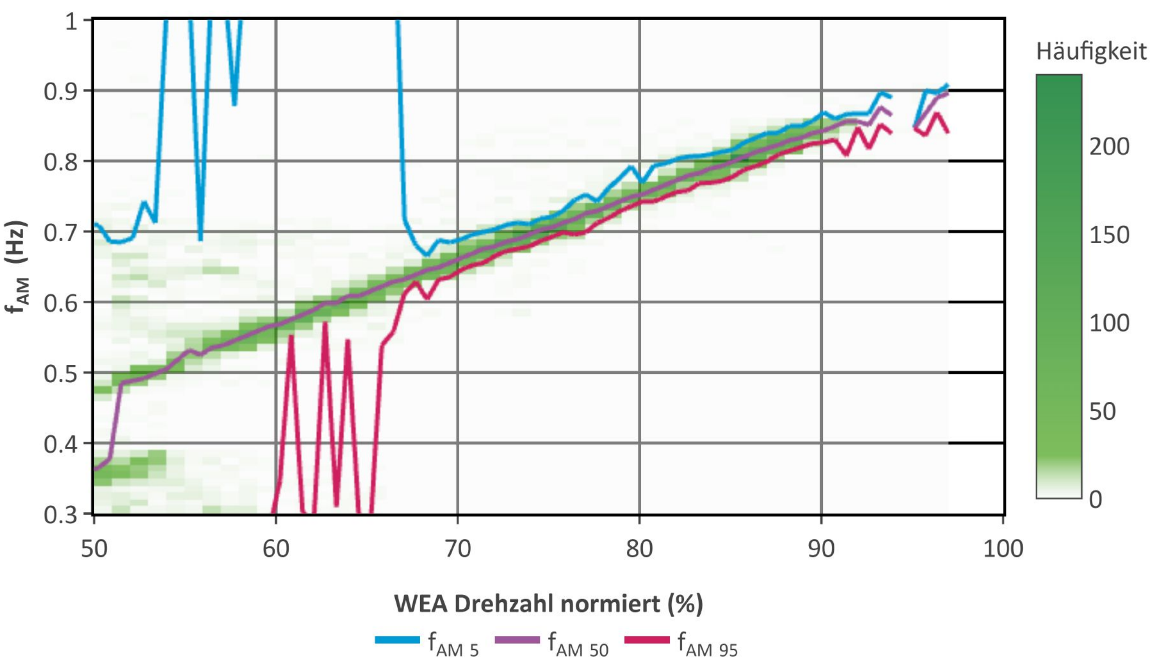
Table 34: Classification of modulation depth based on standardised electrical output

Percentile	Class	Immission range					Emission range		
		SA 1	SA 2	SA 3*	SA 4	SA 5	SA 1	SA 3	SA 4
ΔL_{AM05} in dB	1-20%	4.8	4.2	7.1	4.0	3.0	4.8	3.6	3.9
	20-40%	3.8	4.7	3.8	2.8	2.9	3.5	3.6	2.2
	40-60%	4.0	5.2	3.7	2.6	2.7	2.8	5.5	2.4
	60-80%	3.9	5.3	3.4	2.4	2.3	2.7	6.0	2.4
	80-100%	2.9	5.3	3.5	2.3	1.4	2.6	6.1	2.4
ΔL_{AM50} in dB	1-20%	2.1	2.1	1.8	1.6	1.5	2.0	1.8	1.4
	20-40%	2.0	2.5	1.2	1.5	1.6	2.2	2.2	1.6
	40-60%	2.2	2.9	1.1	1.5	1.5	1.9	2.7	1.6
	60-80%	2.2	3.0	1.2	1.5	1.3	1.9	2.9	1.6
	80-100%	1.7	3.0	1.2	1.4	1.4	1.8	2.7	1.6

Percentile	Class	Immission range					Emission range		
ΔL_{AM95} in dB	1-20%	1.0	1.2	0.8	0.9	0.7	0.9	1.0	0.8
	20-40%	1.1	1.4	0.6	0.9	0.9	1.3	1.3	1.0
	40-60%	1.2	1.6	0.5	0.9	0.9	1.2	1.4	1.0
	60-80%	1.1	1.7	0.5	0.9	0.8	1.2	1.4	1.0
	80-100%	0.9	1.7	0.5	0.9	1.4	1.2	1.4	1.0

*Low amount of data

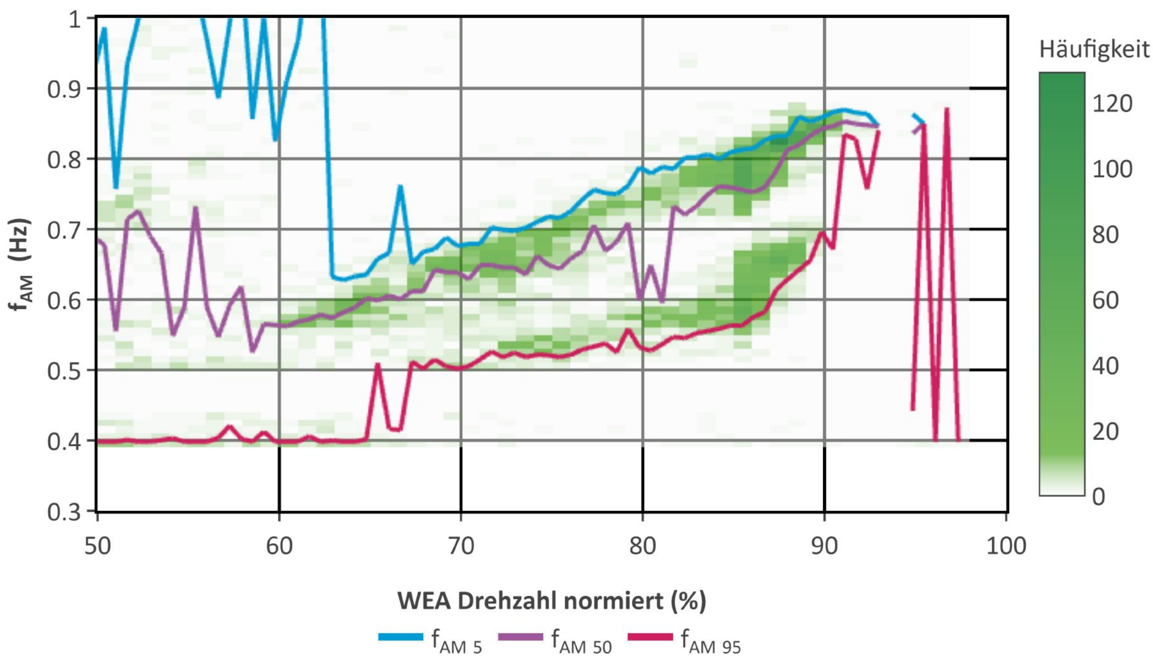
Figure 104: SA 1, emission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

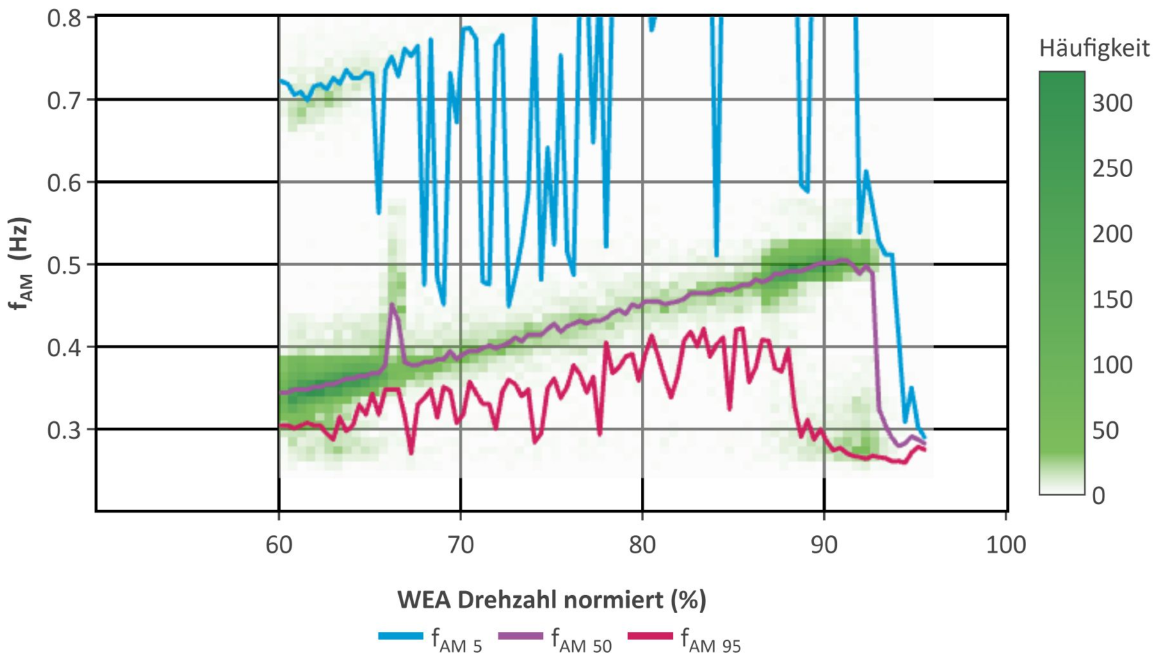
Figure 105: SA 1, immission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

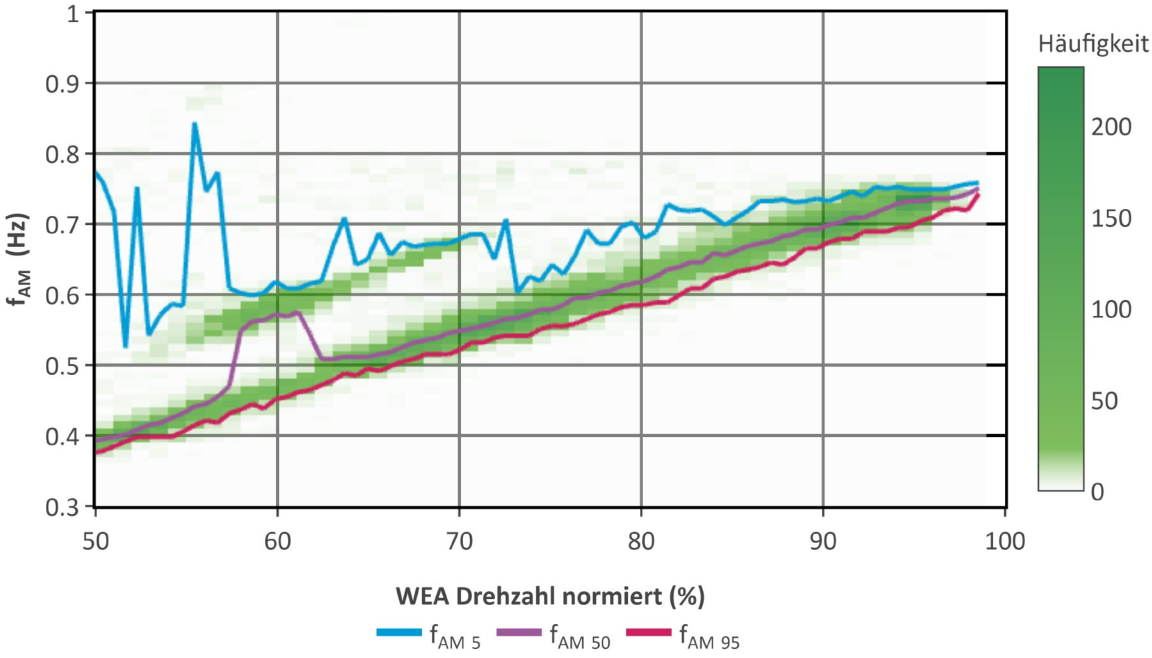
Figure 106: SA 2, immission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

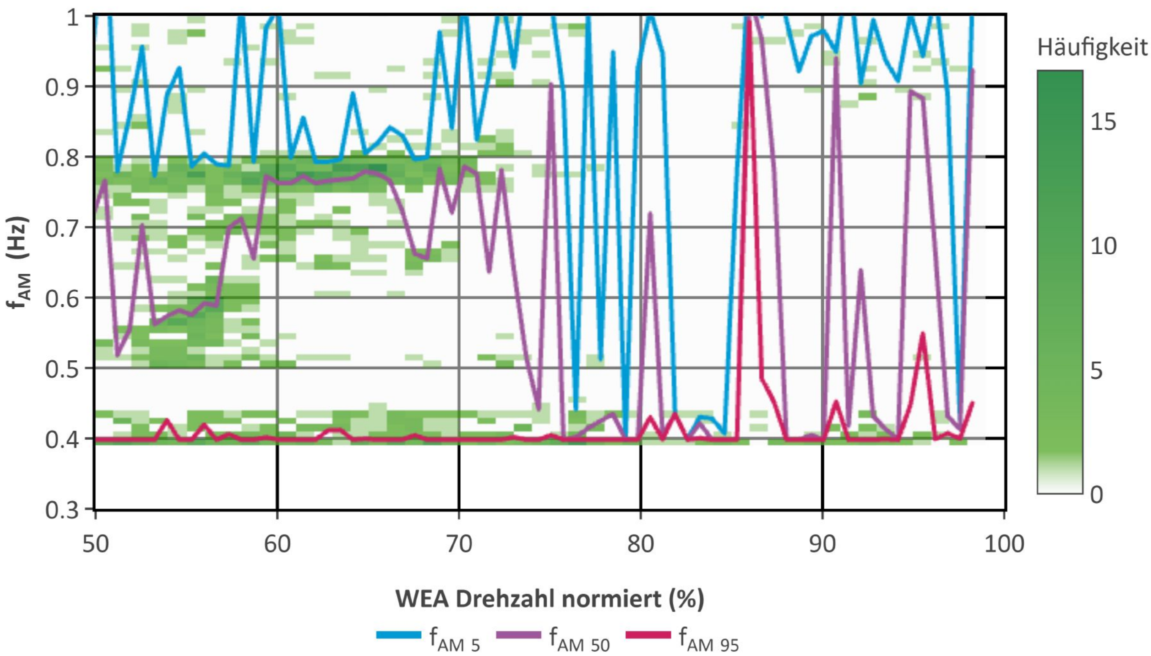
Figure 107: SA 3, emission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

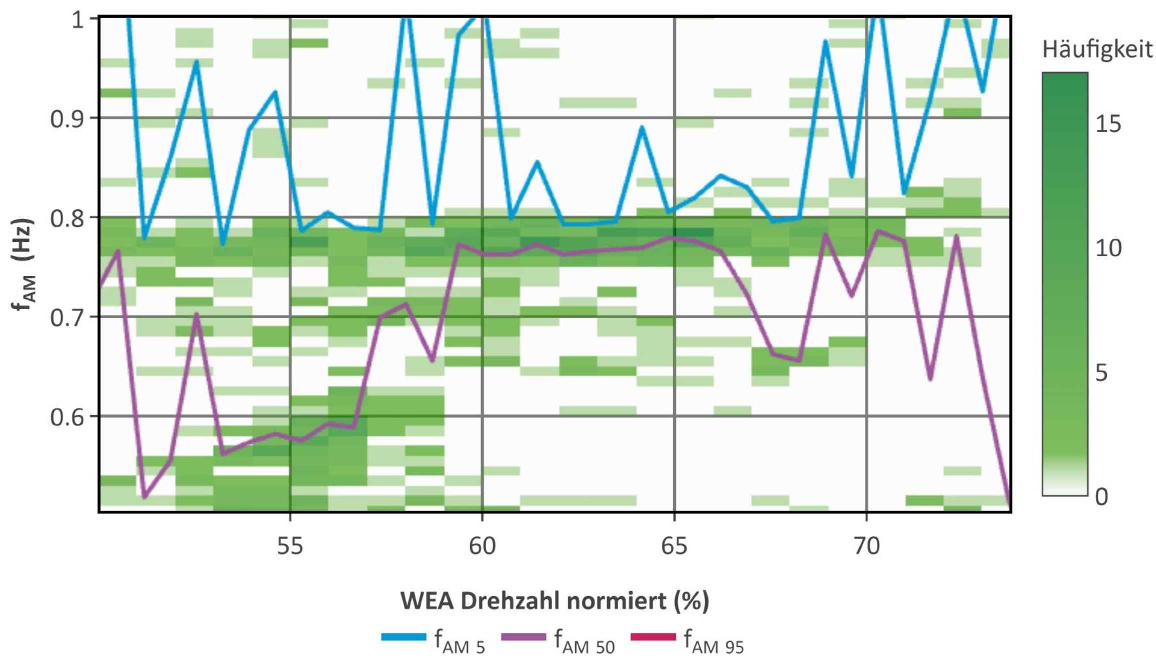
Figure 108: SA 3, immission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

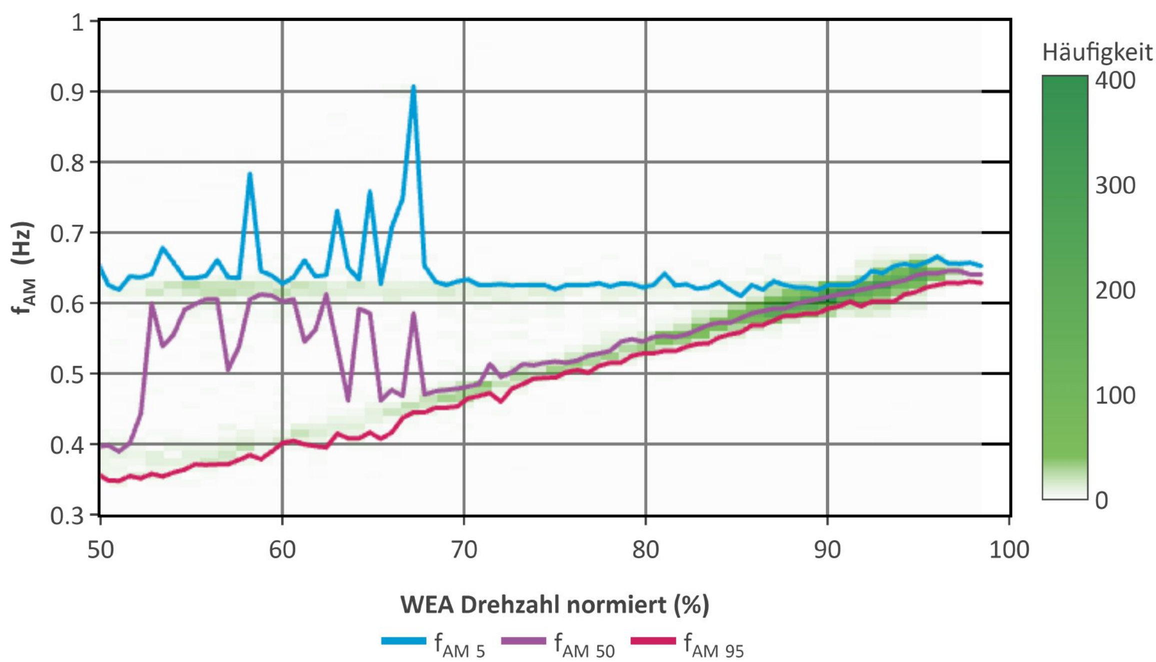
Figure 109: SA 3, immission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised) – view enlarged



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

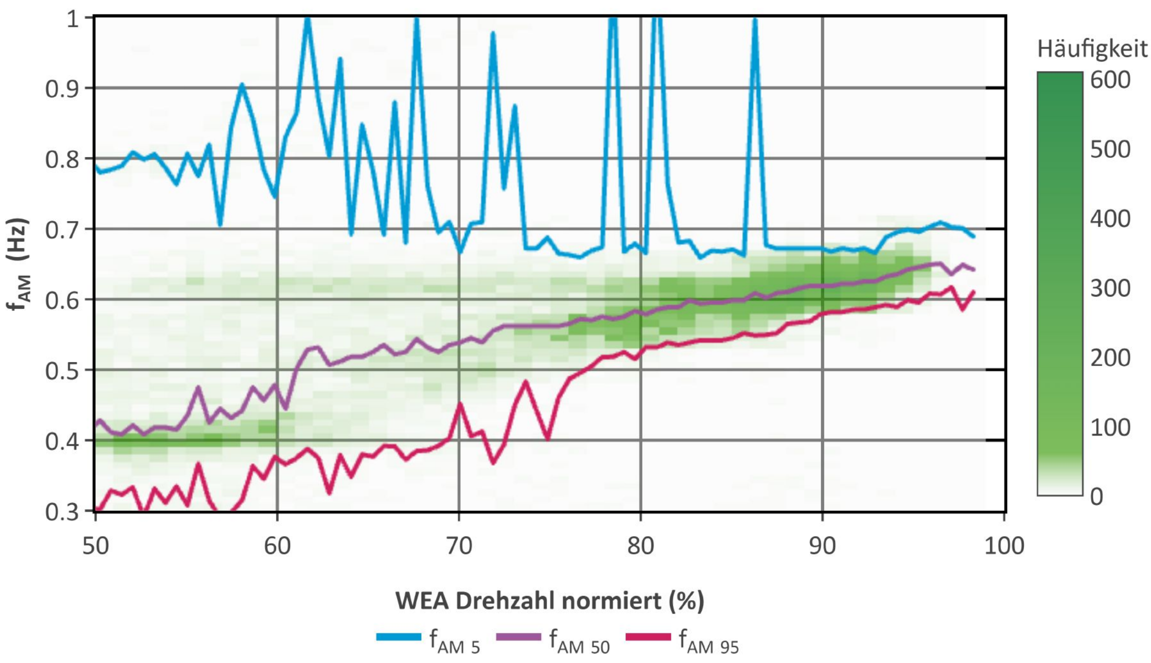
Figure 110: SA 4, emission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

Figure 111: SA 4, immission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)

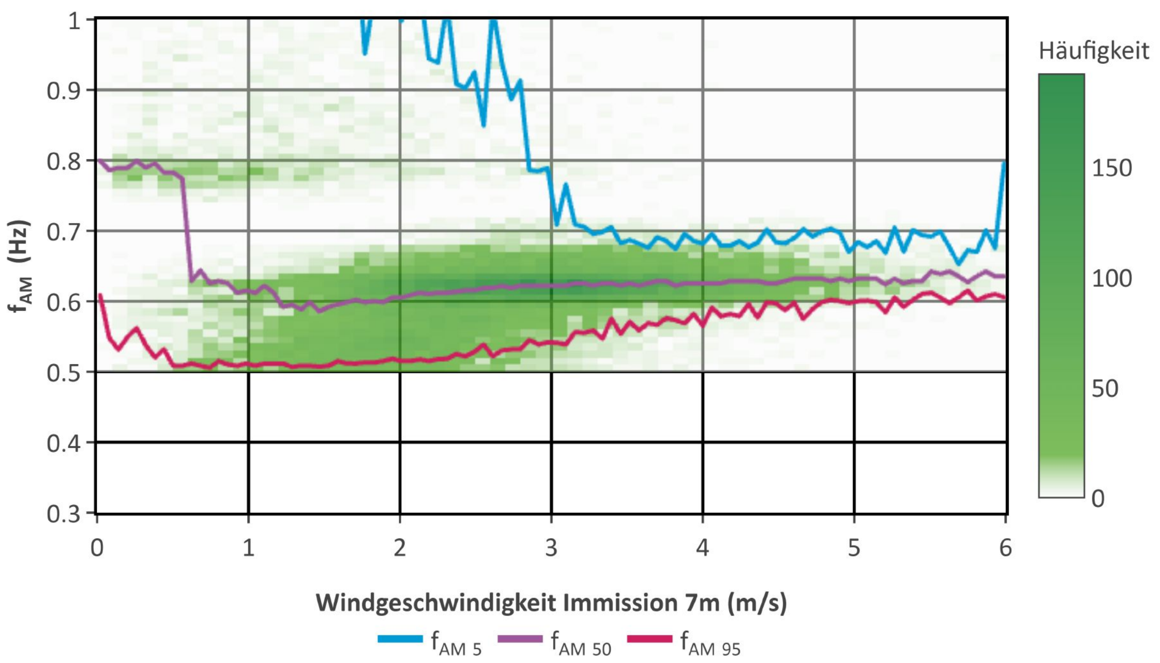


Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

In Figure 112, as no system data were available, the detected frequency is plotted against the immission-side wind speed. Here, too, the typical and expected increase in rotational speeds can be observed as wind speed increases.

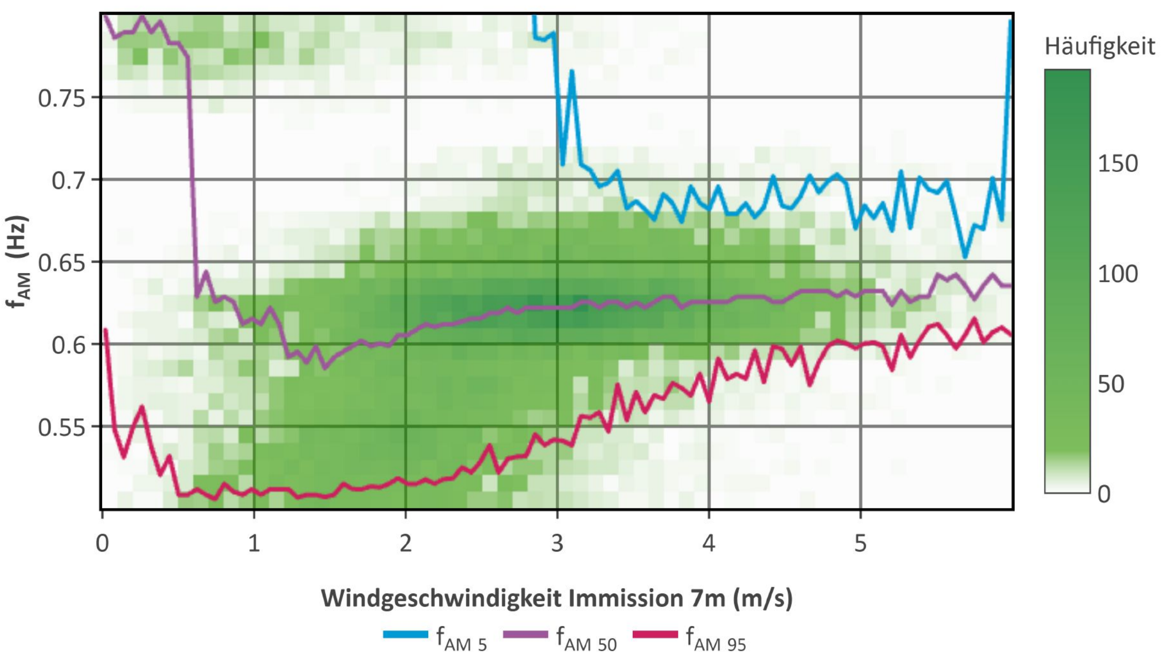
Figure 112: SA 5, immission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Drehzahl normiert (%) = Wind turbine rotational speed standardised (%)

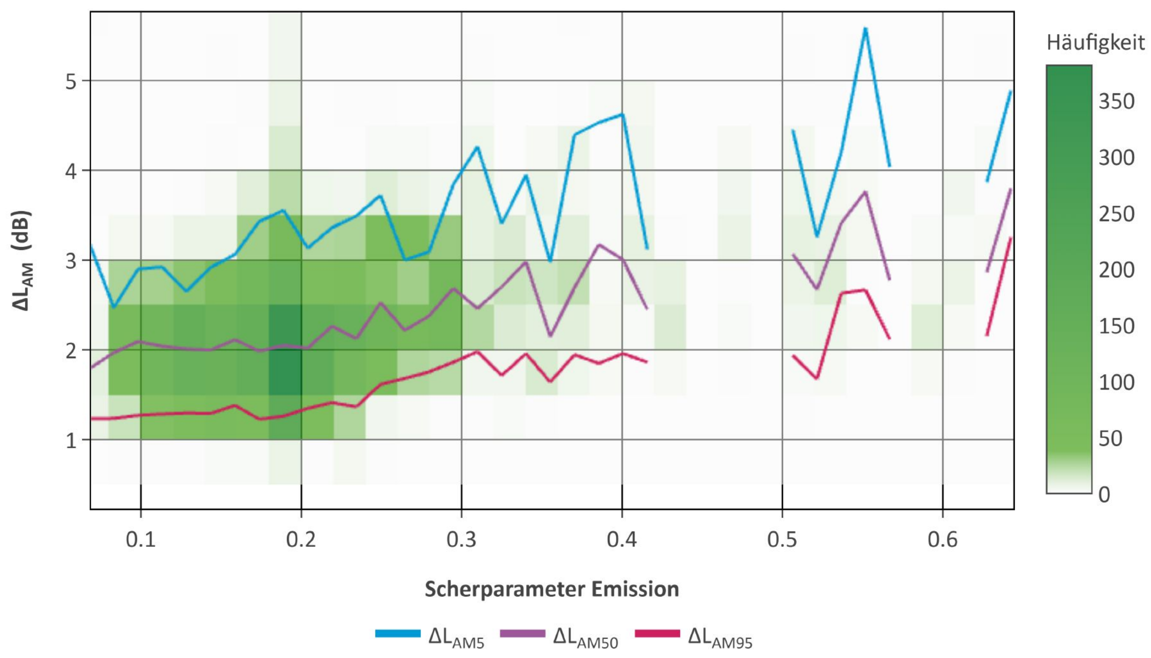
Figure 113: SA 5, immission, frequency of amplitude modulation and rotational speed of the wind turbines (standardised) – view enlarged



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Windgeschwindigkeit Immission 7m (m/s) = Wind speed, immission, 7m (m/s)

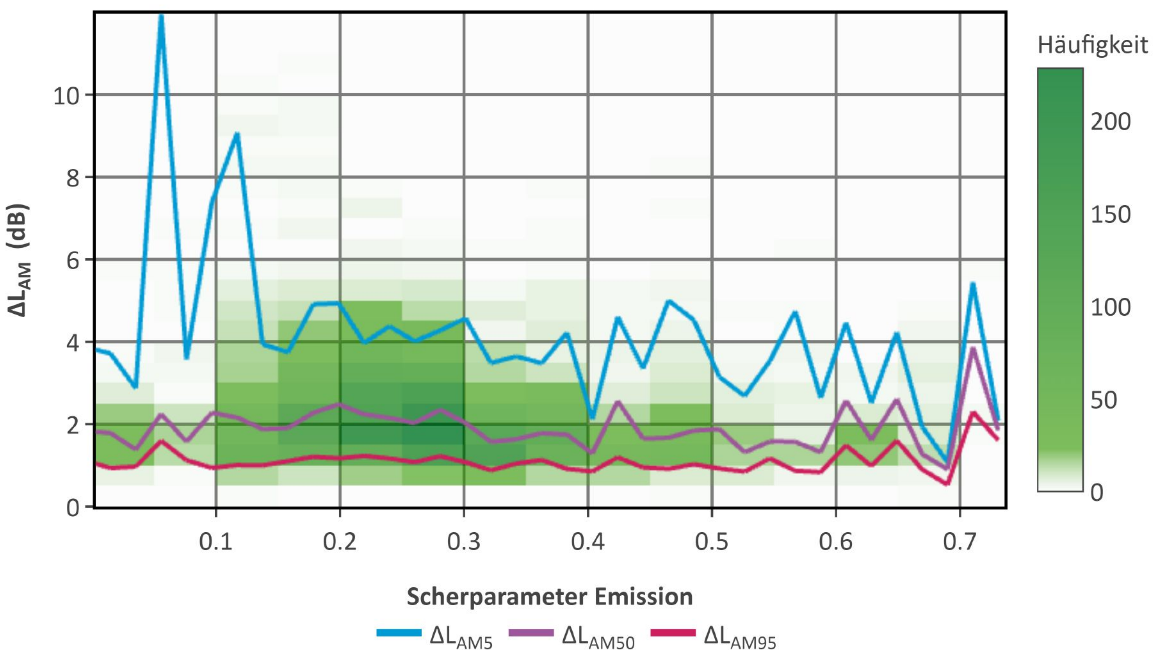
Figure 114: SA 1, emission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

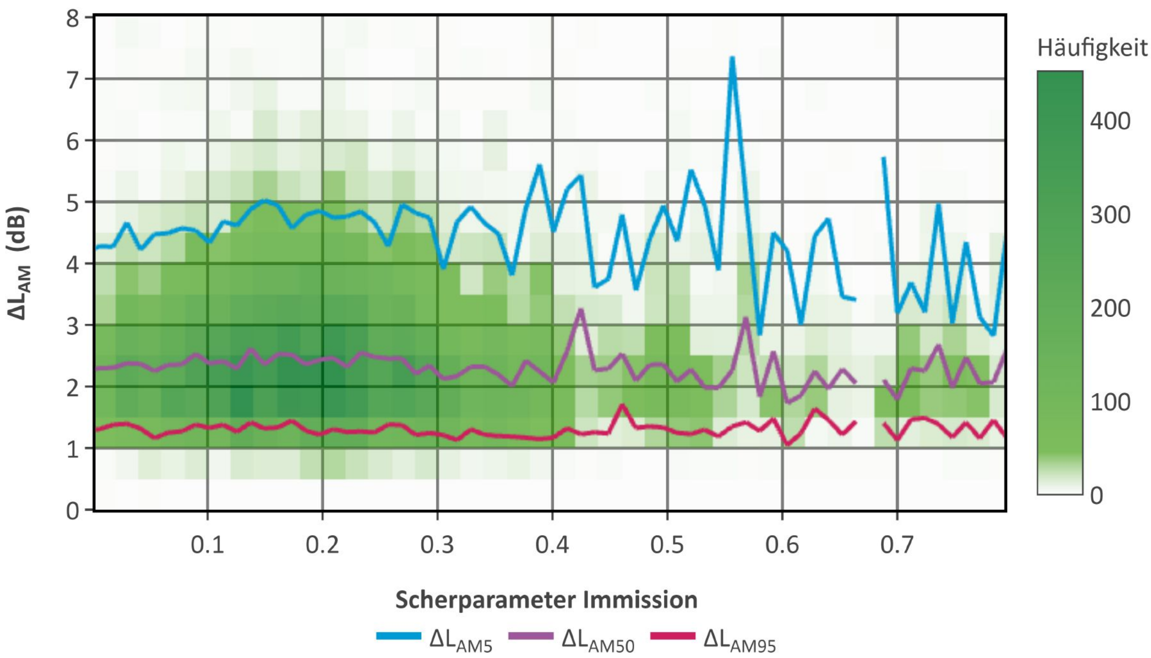
Figure 115: SA 1, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

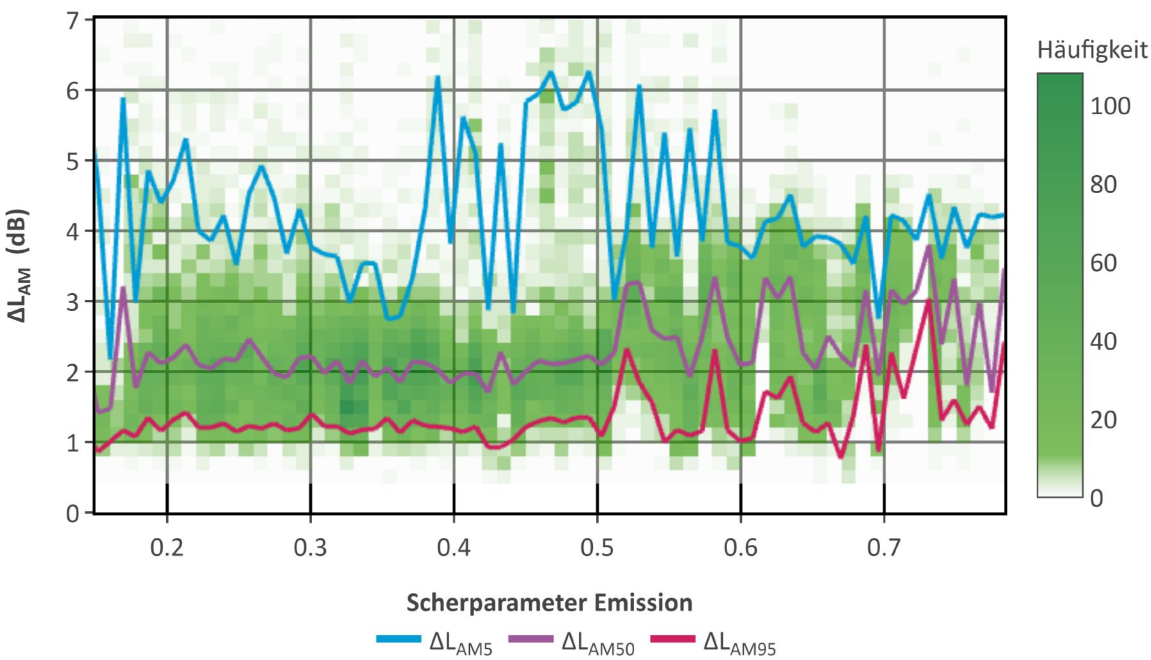
Figure 116: SA 2, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

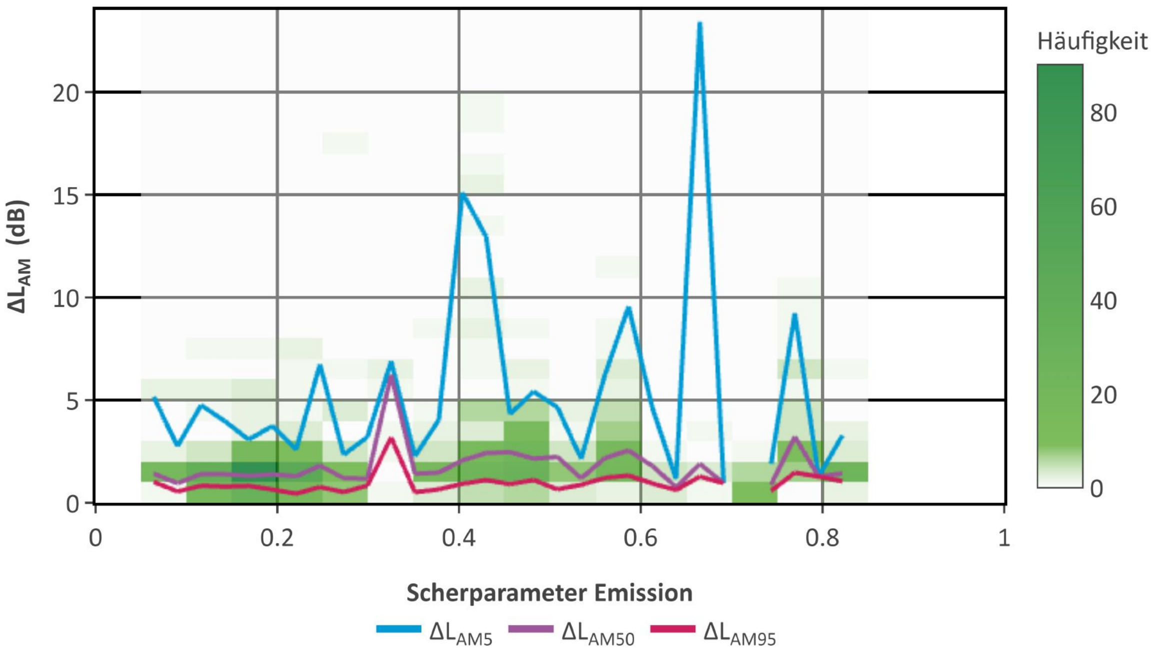
Figure 117: SA 3, emission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

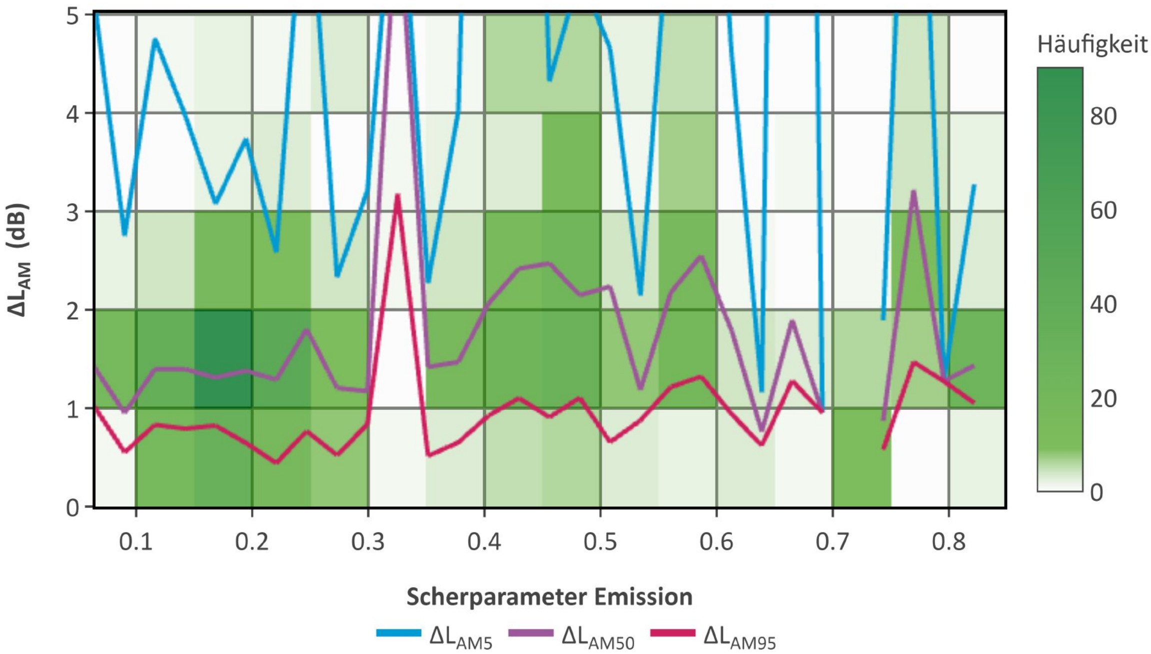
Figure 118: SA 3, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

Figure 119: SA 3, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters – view enlarged

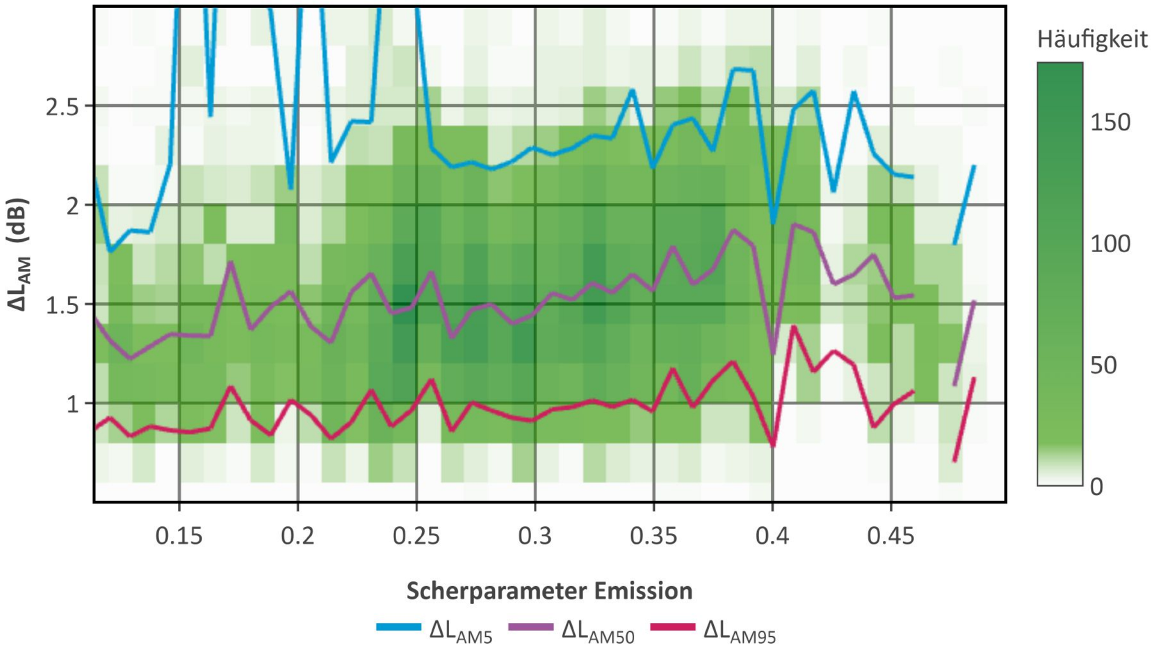


Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

Figure 120: SA 4, emission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters

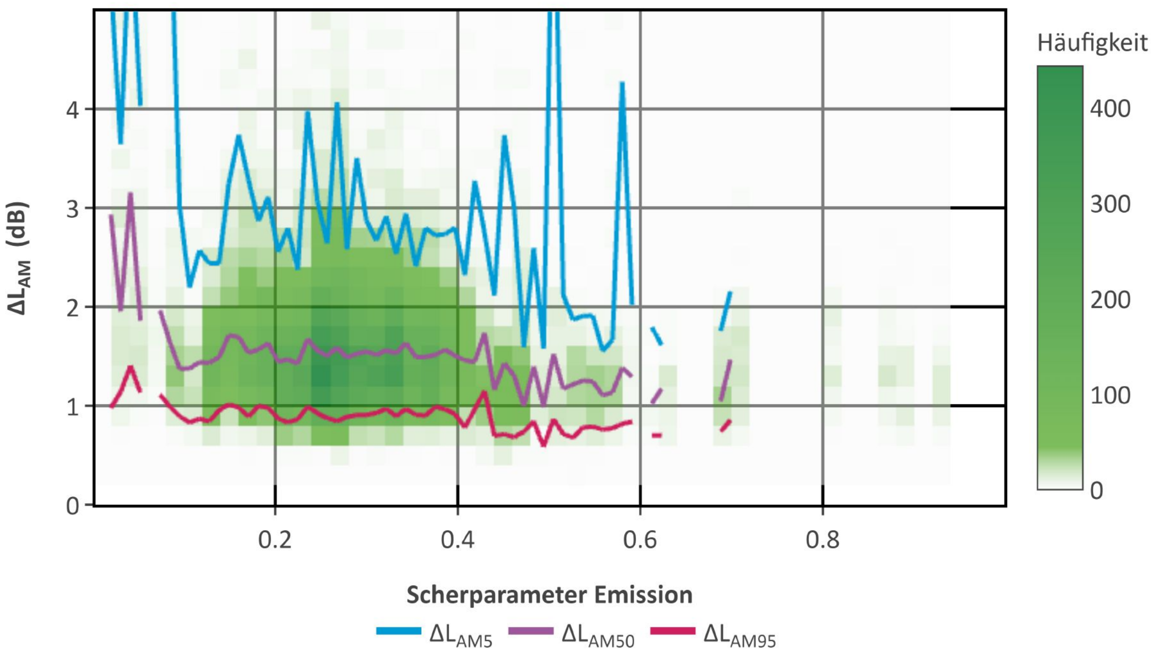
Low correlation between modulation depth and shear parameters



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

Figure 121: SA 4, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and shear parameters



Source: own presentation, Dr. Kühner GmbH

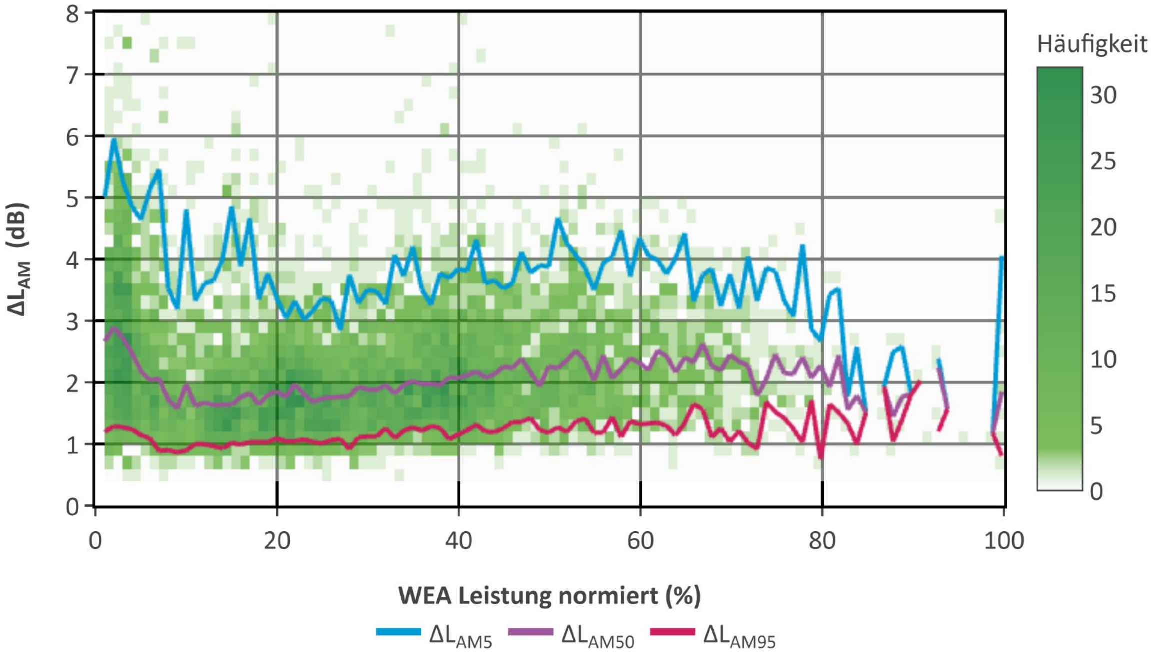
Häufigkeit = Frequency; Scherparameter Emission = Shear parameter, emission

Figure 122: SA 1, emission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind turbine output (standardised)

Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Leistung normiert (%) = Wind turbine output standardised (%)

Figure 123: SA 1, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind turbine output (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Leistung normiert (%) = Wind turbine output standardised (%)

Figure 124: SA 2, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind turbine output (standardised)

Source: own presentation, Dr. Kühner GmbH

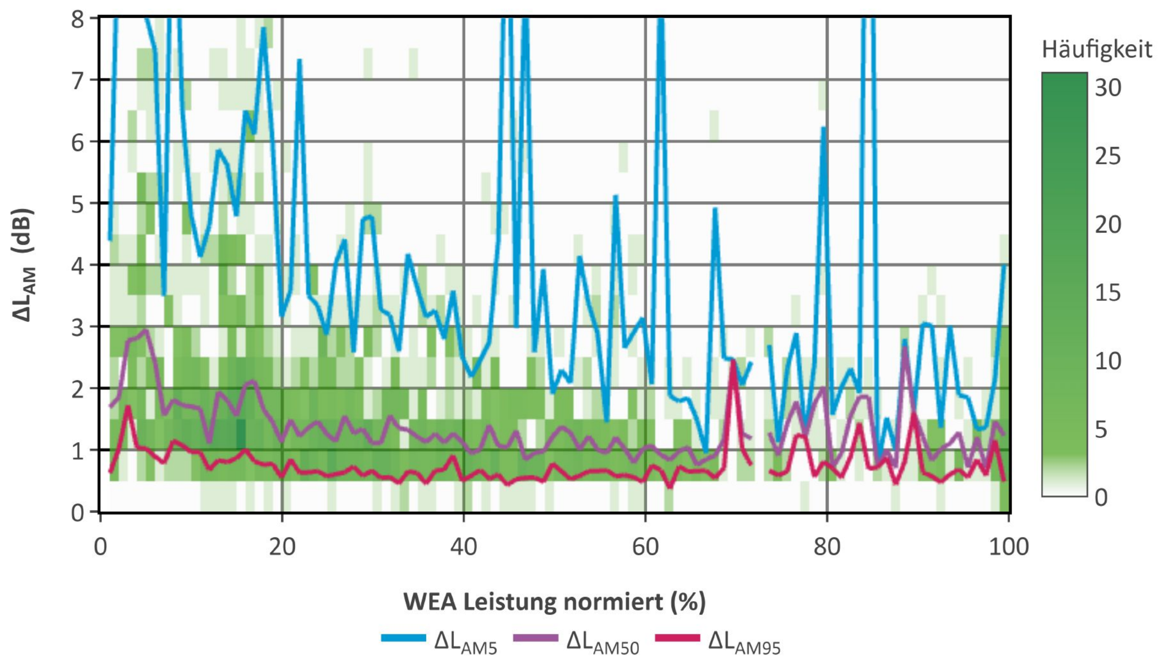
Häufigkeit = Frequency; WEA Leistung normiert (%) = Wind turbine output standardised (%)

Figure 125: SA 3, emission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind turbine output (standardised)

Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Leistung normiert (%) = Wind turbine output standardised (%)

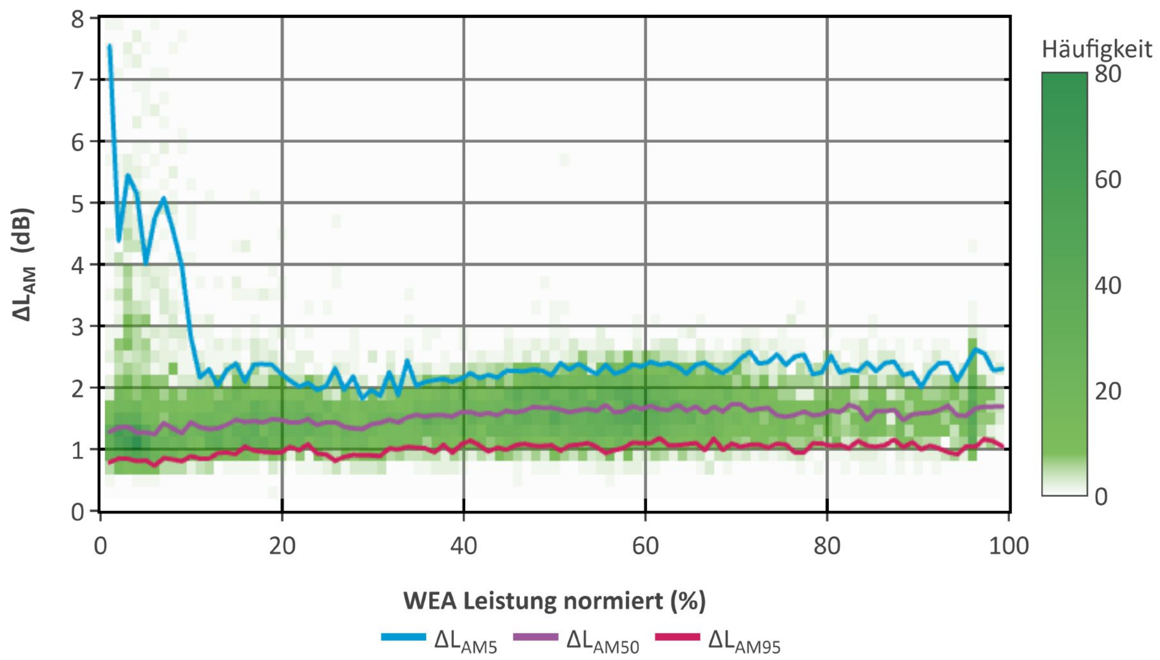
Figure 126: SA 3, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind turbine output (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Leistung normiert (%) = Wind turbine output standardised (%)

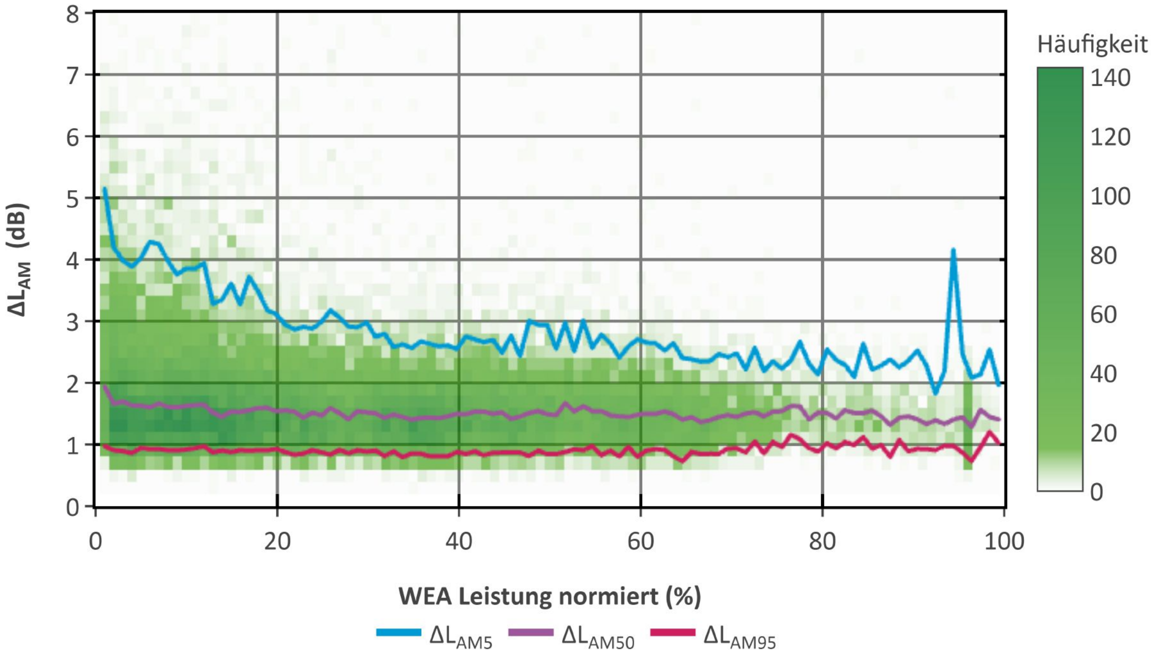
Figure 127: SA 4, emission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind turbine output (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Leistung normiert (%) = Wind turbine output standardised (%)

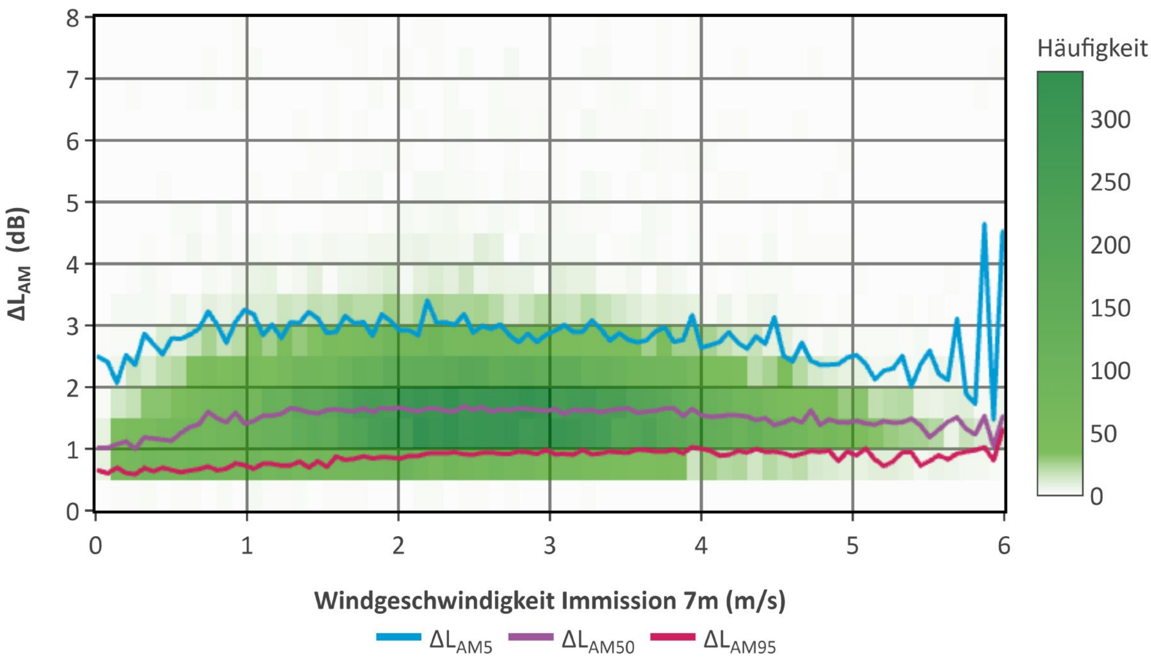
Figure 128: SA 4, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind turbine output (standardised)



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; WEA Leistung normiert (%) = Wind turbine output standardised (%)

Figure 129: SA 5, immission, modulation depth of amplitude modulation (5, 50 and 95 percentile) and wind speed immission at 7 m



Source: own presentation, Dr. Kühner GmbH

Häufigkeit = Frequency; Windgeschwindigkeit Immission 7m (m/s) = Wind speed, immission, 7m (m/s)

D Annoyance survey

D.1 Main survey questionnaire

Umfragen Analysen DataScience

Fragebogen "UBA WEA Telefon 3"

1. Guten Tag/Moin, mein Name ist %interviewer_name% Institut für Umfragen, Analysen und Data Science (UADS) - in Duisburg.

Sie haben von uns kürzlich ein Schreiben erhalten, in dem wir Sie um die Teilnahme an einer vom Umweltbundesamt (UBA) in Auftrag gegebenen wissenschaftlichen Studie gebeten haben.
In der Befragung geht es um Wohn- und Lebensbedingungen und Umgebungsgeräusche. Dabei sollen die Auswirkungen von Umwelteinflüssen im Wohngebiet auf die Wohnbevölkerung und deren Lebensqualität untersucht werden.

Zu diesem Zweck würde ich gerne mit %u_anrede% %u_vorname% %u_name% sprechen.

Sind Sie das selbst oder ist das eine andere Person in Ihrem Haushalt?

Interviewer:

- Zielperson (ZP) ist am Apparat ○
- Zielperson wird an den Apparat geholt ○
- Kontaktperson (KP) verweigert Zugang zu ZP ○
- Verweigerung, unklar ob KP oder ZP ○
- Termin mit KP oder ZP ○
- Sprachqualität schlecht, Termin vereinbaren ○
- ZP in Feldzeit nicht erreichbar ○
- Neutraler Ausfall, ZP verzogen, nicht befragbar ○

2. Wenn Sie damit einverstanden sind, würden wir Ihnen jetzt gerne einige Fragen stellen.
Die Befragung wird ca. 15-20 Minuten in Anspruch nehmen.

Haben Sie jetzt Zeit, oder sollen wir zu einer anderen Zeit anrufen?

Interviewer:

- Ja, Interview ○
- Nein, Verweigerung (ZP) ○
- Termin vereinbaren ○
- Unterlagen erneut senden, Termin ca. eine Woche später legen ○
- Unterlagen erneut senden, aber Interview beginnen ○

3. Guten Tag, mein Name ist %interviewer_name% Institut für Umfragen, Analysen und Data Science (UADS) - in Duisburg.

Sie haben von uns kürzlich ein Schreiben erhalten, in dem wir Sie um die Teilnahme an einer vom Umweltbundesamt (UBA) in Auftrag gegebenen wissenschaftlichen Studie gebeten haben.
In der Befragung geht es um Wohn- und Lebensbedingungen und Umgebungsgeräusche. Dabei sollen die Auswirkungen von Umwelteinflüssen im Wohngebiet auf die Wohnbevölkerung und deren Lebensqualität untersucht werden.

Wenn Sie damit einverstanden sind, würden wir Ihnen jetzt gerne einige Fragen stellen.
Die Befragung wird ca. 15 Minuten in Anspruch nehmen.

Haben Sie jetzt Zeit, oder sollen wir zu einer anderen Zeit anrufen?

Interviewer:

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- Ja, Interview ○
- Nein, Verweigerung (ZP) ○
- Termin vereinbaren ○
- Unterlagen erneut senden, Termin ca. eine Woche später legen ○
- Unterlagen erneut senden, aber Interview beginnen ○

4. Wie lautet Ihre E-Mail-Adresse?

Interviewer:
Die E-Mail-Adresse wird ausschließlich dazu verwendet, die Informationen zur Befragung zususenden.

- E-Mail-Adresse:
- (keine Angabe) ○

5. Wären Sie so freundlich mir bitte kurz zu sagen, weshalb Sie an der Befragung nicht teilnehmen wollen?

Interviewer:
Wir fragen dies aus Qualitätsgründen, denn nur wenn wir wissen, weshalb einzelne Personen die Teilnahme verweigern.
Nur dann können wir die Qualität der Ergebnisse dieser Studie vernünftig einschätzen.

- Person gibt eine Antwort ○
- Person verweigert Auskunft bzw. hat bereits aufgelegt ○
- Person möchte doch kooperieren ○

6. Wie lautet/ lauten die Antwort(en) der Person auf die Frage, weshalb sie an der Umfrage nicht teilnehmen will?

Interviewer:
Mehrfachantworten möglich.
Falls keine Gründe genannt wurden: "Keine Angabe von Verweigerungsgründen" auswählen.

Source: own presentation, ZEUS GmbH

- **Keine Zeit/ Interesse allgemein**
- keine Zeit, Zeitmangel (auch keine Terminfindung möglich)
- Keine Lust, kein Interesse, "habe Wichtigeres zu tun"
- **Bedenken, Ängste bzgl. Fragen und Datenschutz**
- Datenschutz-/ Anonymitätsbedenken/ Auswahlfragen (Herkunft der Nummer)
- Angst vor Verkäufen
- Angst vor heiklen Fragen
- Wissensfrage oder Befürchtung, zu dem Thema nichts sagen zu können.
- **Ablehnende Haltung gegenüber Befragungen allgemein**
- Ständige Befragungen, Person hat "oft genug" an Befragungen teilgenommen
- Prinzipiell keine Teilnahme
- **Themenbezogene Ablehnung**
- Diese Befragung bringt nichts
- Zweck dieser Befragung unklar.
- Person fühlt sich nicht lärmbelästigt, nicht betroffen, Thema Lärm interessiert nicht
- Resignation: Umfragen ändern nichts (an Lärmsituation) etc.
- **Mangelnde Eignung**
- Person fühlt sich zu alt
- Person ist dauerhaft erkrankt
- Person meint: "ich spreche nicht gut genug deutsch"
- **Sonstige/ weitere Gründe**
- Weiterleitung auf Mobiltelefon
- Anderer Modus (z.B. online oder postalisch) gewünscht
- Sonstige Verweigerungsgründe:
- Person hat wortlos aufgelegt
- Person hat etwas Unverständliches gesagt und aufgelegt
- Person will/ wollte keine Verweigerungsgründe nennen
- Person möchte doch kooperieren

7. Darf ich Sie aus Qualitätsgründen noch nach Ihrer Lärmbeeinträchtigung fragen?

Wenn Sie einmal an die letzten 12 Monate dort bei Ihnen denken:
Wie stark haben Sie sich durch den Lärm vom Windenergieanlagen insgesamt gestört oder belästigt gefühlt?

Haben Sie sich (in den letzten 12 Monaten)...

Interviewer:

- 1 überhaupt nicht,
- 2 etwas,
- 3 mittelmäßig,
- 4 stark oder
- 5 äußerst gestört oder belästigt gefühlt?
- (weiß nicht)
- (keine Angabe)

8. Geschlecht erheben ohne nachzufragen:

Interviewer:
Antworten vorlesen.

- männlich
- weiblich
- (weiß nicht)
- (keine Angabe)

9. In welchem Jahr sind Sie geboren?

Interviewer:
Falls Person die Antwort verweigert, dann bitte die Kategorien vorlesen).

- Geburtsjahr:
- 1999 bis 2018 (unter 20 Jahre)
- 1979 bis 1998 (20 bis unter 40 Jahre)
- 1959 bis 1978 (40 bis unter 60 Jahre)
- bis einschl. 1958 (60 Jahre und älter)
- (weiß nicht)
- (keine Angabe)

10. Bitte Alter der Befragungsperson einschätzen:

Interviewer:

- unter 20 Jahre
- 20 bis unter 40 Jahre
- 40 bis unter 60 Jahre
- älter als 60 Jahre
- (weiß nicht)
- (keine Angabe)

11. Welchen höchsten Schulabschluss haben Sie?

Interviewer:
Antworten vorlesen.

- Hauptschul-/ Volksschulabschluss
- Realschulabschluss/ mittlere Reife
- Polytechnische Oberschule der DDR mit Abschluss der 10. Klasse
- Fachhochschulreife, Abschluss Fachoberschule
- Allgemeine oder fachgebundene Hochschulreife/ Abitur (Gymnasium bzw. Erweiterte Oberschule (EOS), auch EOS mit Lehre)
- Schule beendet ohne Abschluss
- noch keinen Schulabschluss
- Polytechnische Oberschule der DDR mit Abschluss der 8. oder 9. Klasse
- sonstiger Schulabschluss
- (weiß nicht)
- (keine Angabe)

12. Dann bedanke ich mich recht herzlich bei Ihnen und wünsche Ihnen noch einen schönen Tag.

Interviewer:
Verweigerung
Bitte das Gespräch beenden und die angezeigte Ergebniskategorie zuordnen:

050 Verweigerung: Kontaktperson (KP) verweigert Zugang zu ZP 051 Verweigerung, unklar ob KP oder ZP 074 ZP in Feldzeit nicht erreichbar 075 ZP verzogen, nicht befragbar 052 Verweigerung ZP

13. Interviewer:
Termin
Bitte das Gespräch beenden und die angezeigte Ergebniskategorie zuordnen:

020 Termin mit KP (unbestimmt) 022 Termin Sprachqualität 021 Termin mit ZP (bestimmt) 023 Termin Unterlagen erneut zusenden

Interviewer:
Bei Klick auf "Weiter" erfolgt ein Sprung zum Anfang des Screenings!

14. Bevor wir mit der Befragung beginnen, benötige ich noch Ihr Einverständnis zum Datenschutz. Haben Sie die Information zum Datenschutz in dem Forschungsvorhaben, die wir dem Anschreiben beigefügt haben, gelesen?
Ich würde mit Ihnen die wichtigsten Punkte gern noch einmal kurz durchgehen:

• Zweck, Verantwortlichkeit: In der Befragung geht es um Wohn- und Lebensbedingungen und Umgebungsgeräusche.
Die Studie ist vom Umweltbundesamt beauftragt, wir, das UADS und das umweltpsychologische Unternehmen ZEUS GmbH aus Hagen sind für die Befragung verantwortlich; bei uns ist es Herr Prof. Frank Faulbaum und bei der ZEUS GmbH Herr Dr. Dirk Schreckenberg
• Erhaltene Daten: Ihren Namen und Ihre Anschrift haben wir per Zufall aus Meldeamtsdaten gezogen, Ihre Rufnummer aus einem öffentlichen Telefonverzeichnis.
Zum Forschungsvorhaben gehört, dass das Ingenieurbüro deBAKOM, Odenthal, Immissionsberechnungen für die Wohngebäude aller Befragungspersonen durchführt, dazu verfügen die Ingenieure über Haus-Geokoordinaten der Wohngebäude (bei Nachfrage: Bei den Immissionsberechnungen handelt es sich um Geräuschpegelberechnungen von Lärmquellen aus der Umgebung Ihres Wohngebäudes)
• Freiwilligkeit: Ihre Interviewteilnahme ist freiwillig; Sie können sie verweigern oder das Interview jederzeit beenden. Es entstehen Ihnen dadurch keine Nachteile.
• Vertraulichkeit, Anonymität: Ihre Befragungsdaten werden getrennt von Ihren personenbezogenen Daten, d.h. Ihrem Namen und Ihrer Anschrift oder den Hauskoordinaten gespeichert.
Die Auswertungen erfolgen ausschließlich statistisch und lassen später keinerlei Rückschlüsse auf Ihre Person oder Ihre Adresse zu. Die Verarbeitung Ihrer Daten erfolgt ausschließlich zu Zwecken der wissenschaftlichen Forschung zu Wohn- und Lebensbedingungen und Umgebungsgeräuschen.
• Verarbeitung, Speicherung: Ihr Name und Ihre Anschrift (Straße, Hausnummer und –zusatz, Postleitzahl, Ort) werden nach Abschluss des Forschungsvorhabens gelöscht; die Befragungsdaten bleiben zusammen mit einer ID-Nummer ohne Ihren Namen und ihre Anschrift für die weiteren wissenschaftlichen, statistischen Datenauswertungen erhalten.
Die Geo-Koordinaten der Wohngebäude werden beim Ingenieurbüro deBAKOM zusammen mit den Immissionsdaten getrennt für dieses Forschungsprojekt und für etwaige wissenschaftliche Nachnutzungen gespeichert. Sie haben jederzeit das Recht dieser Speicherung der Geo-Koordinaten für die wissenschaftliche Nachnutzung zu widersprechen und die Löschung dieser Daten zu veranlassen.

Haben Sie die Datenschutzbestimmungen gelesen und stimmen Sie diesen zu?

Interviewer:

- Ja (=> Weiter zum Interview)
- Nein (=> Verabschiedung)

15. Ihre Entscheidung, nicht an der Befragung teilzunehmen bedauern wir sehr.

Bitte bestätigen Sie durch einen Klick auf "Weiter", dass Sie nicht teilnehmen möchten.

Ein Zurückgehen bzw. ein erneuter Aufruf der Fragebogenseite ist nach einem Klick auf "Weiter" nicht möglich!

16. In welchem Jahr sind Sie in Ihre Wohnung bzw. Ihr Haus eingezogen?

Interviewer:

- Jahr des Einzugs:
- (weiß nicht)
- (keine Angabe)

Source: own presentation, ZEUS GmbH

17. Wie zufrieden sind Sie insgesamt mit Ihrer Wohngegend bzw. Ihrer näheren Wohnumgebung?

Interviewer:
Antworten vorlesen.

- 1 nicht zufrieden
- 2 wenig zufrieden
- 3 mittelmäßig zufrieden
- 4 ziemlich zufrieden
- 5 sehr zufrieden
- (weiß nicht)
- (keine Angabe)

18. Und wie zufrieden sind Sie insgesamt mit Ihrer Wohnung bzw. mit Ihrem Haus?

Interviewer:
Antworten vorlesen.

- 1 nicht zufrieden
- 2 wenig zufrieden
- 3 mittelmäßig zufrieden
- 4 ziemlich zufrieden
- 5 sehr zufrieden
- (weiß nicht)
- (keine Angabe)

19. Wohnen Sie in einem/ einer...

Interviewer:
Antworten vorlesen.

- freistehenden Einfamilienhaus
- Reihenendhaus
- Reihenmittelhaus
- Doppelhaushälfte
- Wohnung in einem mehrstöckigen Mehrfamilienhaus, einschließlich Hochhaus
- (weiß nicht)
- (keine Angabe)

20. In welchem Stockwerk liegt Ihre Wohnung?

Interviewer:

- Stockwerk:
- Erdgeschoss
- Keller
- Dachgeschoss
- (weiß nicht)
- (keine Angabe)

21. Wie viele Stockwerke (ohne Keller und unbewohntem Dachgeschoss) hat das Mehrfamilienhaus insgesamt?

Interviewer:

- Anzahl Stockwerke:
- (weiß nicht)
- (keine Angabe)

22. Sind Sie bzw. jemand aus Ihrem Haushalt Eigentümer/in Ihrer Wohnung bzw. Ihres Hauses oder wohnen Sie zur Miete?

Interviewer:

- Eigentümer/ in
- Mieter/ in
- (weiß nicht)
- (keine Angabe)

23.
Im Folgenden geht es darum, wie stark Sie sich bei Ihnen durch bestimmte Lärmquellen gestört oder belästigt fühlen.
Wenn Sie einmal an die letzten 12 Monate bei Ihnen denken:

Wie stark haben Sie sich durch den Lärm vom Straßenverkehr gestört oder belästigt gefühlt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

24.
Im Folgenden geht es darum, wie stark Sie sich bei Ihnen durch bestimmte Lärmquellen gestört oder belästigt fühlen.
Wenn Sie einmal an die letzten 12 Monate bei Ihnen denken:

Wie stark haben Sie sich durch den Lärm von Windenergieanlagen insgesamt gestört oder belästigt gefühlt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

25.
Im Folgenden geht es darum, wie stark Sie sich bei Ihnen durch bestimmte Lärmquellen gestört oder belästigt fühlen.
Wenn Sie einmal an die letzten 12 Monate bei Ihnen denken:

Wie stark haben Sie sich durch den Lärm von Windenergieanlagen in Ihrer Wohnung/ Ihrem Haus gestört oder belästigt gefühlt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

26.
Im Folgenden geht es darum, wie stark Sie sich bei Ihnen durch bestimmte Lärmquellen gestört oder belästigt fühlen.
Wenn Sie einmal an die letzten 12 Monate bei Ihnen denken:

Wie stark haben Sie sich durch den Lärm von Windenergieanlagen außerhalb Ihrer Wohnung/ Ihres Hauses, z.B. im Garten oder auf der Terrasse/ dem Balkon gestört oder belästigt gefühlt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

27. Wenn Sie an die Geräusche von Windenergieanlagen denken:

Wie stark haben Sie sich insbesondere durch das "Wuschgeräusch" von Windenergieanlagen gestört oder belästigt gefühlt?

Interviewer:
Wuschgeräusch nachmachen ("SchuhSchuh...")
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

28. Wenn Sie noch einmal an die Geräusche von Windenergieanlagen denken:

Was belästigt Sie sonst noch genau an der Lärmquelle?

Interviewer:

- Nennung:
- (weiß nicht)
- (keine Angabe)

29. Gibt es weitere Lärmquellen?

Falls ja, nennen Sie bitte die drei Quellen, die Sie am stärksten belästigt haben.

Interviewer:

- sonstige Lärmquelle 1:
- sonstige Lärmquelle 2:
- sonstige Lärmquelle 3:
- Nein, keine weiteren Lärmquellen
- (weiß nicht)
- (keine Angabe)

30. Wenn Sie wieder an die letzten 12 Monate bei Ihnen denken:

Wie stark haben Sie sich durch den Lärm von %Q29A1% gestört oder belästigt gefühlt?

Interviewer:
Antworten vorlesen.

Source: own presentation, ZEUS GmbH

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

31. Wenn Sie wieder an die letzten 12 Monate bei Ihnen denken:

Wie stark haben Sie sich durch den Lärm von
%Q29A2%
gestört oder belästigt gefühlt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

32. Wenn Sie wieder an die letzten 12 Monate bei Ihnen denken:

Wie stark haben Sie sich durch den Lärm von
%Q29A3%
gestört oder belästigt gefühlt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

33.
Jeder Mensch reagiert anders auf Belastungen aus der Umwelt.
Für wie empfindlich halten Sie sich selbst im Allgemeinen gegenüber Geräuschen aus der Umgebung?

Bassgeräuschen, tiefen Tönen

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

34.
Jeder Mensch reagiert anders auf Belastungen aus der Umwelt.
Für wie empfindlich halten Sie sich selbst im Allgemeinen gegenüber Geräuschen aus der Umgebung?

polternden Geräuschen, z.B. von Waschmaschinen, Gehgeräusche im Treppenhaus

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

35.
Jeder Mensch reagiert anders auf Belastungen aus der Umwelt.
Für wie empfindlich halten Sie sich selbst im Allgemeinen gegenüber Geräuschen aus der Umgebung?

Musik mit Bass

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

36.
Jeder Mensch reagiert anders auf Belastungen aus der Umwelt.
Für wie empfindlich halten Sie sich selbst im Allgemeinen gegenüber Geräuschen aus der Umgebung?

monotones Summen, z.B. von Computern, Lüftungsanlagen

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

37.
Jeder Mensch reagiert anders auf Belastungen aus der Umwelt.
Für wie empfindlich halten Sie sich selbst im Allgemeinen gegenüber Geräuschen aus der Umgebung?

Geräuschen allgemein

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht
- 2 etwas
- 3 mittelmäßig
- 4 stark
- 5 äußerst
- (weiß nicht)
- (keine Angabe)

38.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft wurden Sie im letzten Monat von unerwarteten Ereignissen überrascht?

Interviewer:
Antworten vorlesen.

- 1 nie
- 2 fast nie
- 3 manchmal
- 4 ziemlich oft
- 5 sehr oft
- (weiß nicht)
- (keine Angabe)

39.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft hatten Sie im letzten Monat das Gefühl, dass es Ihnen nicht möglich ist, wichtige Dinge in Ihrem Leben zu kontrollieren?

Interviewer:
Antworten vorlesen.

- 1 nie
- 2 fast nie
- 3 manchmal
- 4 ziemlich oft
- 5 sehr oft
- (weiß nicht)
- (keine Angabe)

40.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft haben Sie sich im letzten Monat nervös oder "gestresst" gefühlt?

Interviewer:
Antworten vorlesen.

- 1 nie
- 2 fast nie
- 3 manchmal
- 4 ziemlich oft
- 5 sehr oft
- (weiß nicht)
- (keine Angabe)

41.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft haben Sie sich im letzten Monat zuversichtlich gefühlt, dass Sie in der Lage sind, persönliche Probleme zu regeln?

Interviewer:
Antworten vorlesen.

Source: own presentation, ZEUS GmbH

- 1 nie ○
- 2 fast nie ○
- 3 manchmal ○
- 4 ziemlich oft ○
- 5 sehr oft ○
- (weiß nicht) ○
- (keine Angabe) ○

42.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft hatten Sie im letzten Monat das Gefühl, dass die Dinge in Ihrem Leben genauso laufen, wie sie es sollen?

Interviewer:
Antworten vorlesen.

- 1 nie ○
- 2 fast nie ○
- 3 manchmal ○
- 4 ziemlich oft ○
- 5 sehr oft ○
- (weiß nicht) ○
- (keine Angabe) ○

43.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft hatten Sie im letzten Monat das Gefühl, dass Sie mit anfallenden Aufgaben nicht zu Rande kommen?

Interviewer:
Antworten vorlesen.

- 1 nie ○
- 2 fast nie ○
- 3 manchmal ○
- 4 ziemlich oft ○
- 5 sehr oft ○
- (weiß nicht) ○
- (keine Angabe) ○

44.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft waren Sie in der Lage mit Widrigkeiten des Lebens kontrolliert umzugehen?

Interviewer:
Antworten vorlesen.

- 1 nie ○
- 2 fast nie ○
- 3 manchmal ○
- 4 ziemlich oft ○
- 5 sehr oft ○
- (weiß nicht) ○
- (keine Angabe) ○

45.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft fühlten sie sich als Herr der Lage?

Interviewer:
Antworten vorlesen.

- 1 nie ○
- 2 fast nie ○
- 3 manchmal ○
- 4 ziemlich oft ○
- 5 sehr oft ○
- (weiß nicht) ○
- (keine Angabe) ○

46.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft haben Sie sich über Dinge geärgert, die außerhalb Ihrer Kontrolle lagen?

Interviewer:
Antworten vorlesen.

- 1 nie ○
- 2 fast nie ○
- 3 manchmal ○
- 4 ziemlich oft ○
- 5 sehr oft ○
- (weiß nicht) ○
- (keine Angabe) ○

47.
Im Folgenden geht es um Ihre Gefühle und Gedanken während des letzten Monats
Wählen Sie bitte die Antwort aus, die Ihrer Zustimmung am besten entspricht.

Wie oft hatten Sie das Gefühl, dass sich Schwierigkeiten so sehr auftürmten, dass sie Ihnen über den Kopf wachsen?

Interviewer:
Antworten vorlesen.

- 1 nie ○
- 2 fast nie ○
- 3 manchmal ○
- 4 ziemlich oft ○
- 5 sehr oft ○
- (weiß nicht) ○
- (keine Angabe) ○

48. Wie stark hängen Ihre Gefühle und Gedanken während des letzten Monats mit der Corona-Pandemie zusammen?

- 1 nicht ○
- 2 wenig ○
- 3 mittelmäßig ○
- 4 ziemlich ○
- 5 sehr ○
- (weiß nicht) ○
- (keine Angabe) ○

49.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Bei Unterhaltungen oder beim Telefonieren in der Wohnung/ im Haus

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

50.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Beim Radio-/Musikhören oder Fernsehen

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

51.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Beim Lesen, Nachdenken oder Konzentrieren in der Wohnung/ im Haus

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

52.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Beim Entspannen und der Feierabendruhe in der Wohnung/ im Haus

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

Source: own presentation, ZEUS GmbH

53.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Bei häuslicher Geselligkeit oder, wenn Sie Besuch in der Wohnung/ im Haus haben

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

54.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Bei Aufenthalt und Erholung im Freien

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

55.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Bei Unterhaltungen/Gespräche im Freien

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

56.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Beim Einschlafen

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

57.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Nachts, während des Schlafs (bzw. bei Nachtschicht: während der üblichen Schlafenszeit)

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

58.
Wie stark hat Sie Lärm von Windenergieanlagen in den letzten 12 Monaten in den folgenden Situationen insgesamt gestört?

Beim Ausschlafen am Ende der Schlafzeit

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

59.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Windenergieanlagen fördern die Weiterentwicklung der/ einer Region.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

60.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Durch den Betrieb von Windenergieanlagen kommt es zu einer Wertminderung der umgebenden Häuser und Grundstücke.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

61.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Durch den Betrieb von Windenergieanlagen entstehen neue Arbeitsplätze in der Region.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

62.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Durch den Betrieb von Windenergieanlagen wird einem der Aufenthalt im Garten, auf der Terrasse oder auf dem Balkon verleidet.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

63.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Die Windenergieanlagen sind Grundlage für Streitigkeiten innerhalb der Nachbarschaft.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

Source: own presentation, ZEUS GmbH

64.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Durch Windenergieanlagen wird das Landschaftsbild verschandelt.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

65.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Der Betrieb von Windenergieanlagen ist gut für den Umweltschutz.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

66.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Der Schattenwurf der Windenergieanlagen stört mich innerhalb meiner Wohnräume.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

67.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Durch den Betrieb der Windenergieanlagen wird die Naherholung erschwert.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

68.
Nun kommen wir zu allgemeinen Ansichten zum Betrieb von Windenergieanlagen an Land.
Bitte sagen Sie mir, inwieweit Sie den folgenden Aussagen zustimmen.

Durch den Betrieb von Windenergieanlagen sinken die Stromkosten.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 stimme wenig zu ○
- 3 mittelmäßig ○
- 4 stimme ziemlich zu ○
- 5 stimme sehr zu ○
- (weiß nicht) ○
- (keine Angabe) ○

69. Können Sie von Ihrer jetzigen Wohnung/ Ihrem Haus aus die Windenergieanlagen sehen?

Interviewer:

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

70. Wie viele Windenergieanlagen können Sie sehen?

Interviewer:

- Anzahl:
- (weiß nicht) ○
- (keine Angabe) ○

71. Wie stark fühlen Sie sich von dem
Anblick der Windenergieanlagen
in Ihrer Wohnumgebung belästigt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

72. Wie stark fühlen Sie sich von dem
Schattenwurf der Windenergieanlagen
in Ihrer Wohnumgebung belästigt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

73. Wie stark fühlen Sie sich von der
Hinderniskennzeichnung der Windenergieanlagen
in Ihrer Wohnumgebung belästigt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

74. Wie stark fühlen Sie sich von der
Drehbewegung der Windenergieanlagen
in Ihrer Wohnumgebung belästigt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

75. Wie stark fühlen Sie sich von der
Wirkung im Landschaftsbild
der Windenergieanlagen in Ihrer Wohnumgebung belästigt?

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

76. Steht Ihr Beschäftigungsverhältnis oder das einer anderen Person aus Ihrem Haushalt jetzt oder zukünftig in irgendeiner Weise in Verbindung mit der/ den Windenergieanlage/n?

Interviewer:

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

77. Sind Sie oder eine andere Person aus Ihrem Haushalt finanziell an der/ den Windenergieanlage/n beteiligt (außerhalb eines Beschäftigungsverhältnisses, z.B. am Betrieb der Anlage oder der Verpachtung der Windenergieanlagenfläche)?

Interviewer:

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

78. Haben Sie in Ihrem Haushalt eine Stromkostenersparnis bzw. einen vergünstigten Stromtarif aufgrund der Windenergieanlage/n in Ihrer Wohnumgebung?

Interviewer:

Source: own presentation, ZEUS GmbH

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

79. Sind Sie in einer Bürgerinitiative oder sonstigen Vereinigung aktiv, die sich mit Windenergieanlagen auseinandersetzt?

Interviewer:

- Ja, für Windenergieanlagen ○
- Ja, gegen Windenergieanlagen ○
- Nein, weder noch ○
- (weiß nicht) ○
- (keine Angabe) ○

80. Haben Sie seit der Errichtung der Windenergieanlagen eine Änderung des WEA-Lärms wahrgenommen?

Interviewer:
Antworten vorlesen.

- ja, der Lärm hat insgesamt zugenommen ○
- ja, der Lärm hat insgesamt abgenommen ○
- nein, der Lärm hat sich nicht geändert ○
- (weiß nicht) ○
- (keine Angabe) ○

81. Hat sich die Art der Geräusche der Windenergieanlagen mit der Zeit verändert?

Interviewer:

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

82. Können Sie beschreiben wie sich das Geräusch verändert hat?

Interviewer:

- Beschreibung:
- (weiß nicht) ○
- (keine Angabe) ○

83. Hat es dort bei Ihnen ansonsten seit der Errichtung der Windenergieanlagen weitere Veränderungen in Ihrer Nachbarschaft gegeben?

Interviewer:

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

84. Was hat sich geändert?

Interviewer:

- Änderung:
- (weiß nicht) ○
- (keine Angabe) ○

85. Was meinen Sie:

Wie stark werden Sie sich dort bei Ihnen in den nächsten 12 Monaten durch den Lärm von Windenergieanlagen belästigt fühlen:

Würden Sie sagen...

Interviewer:
Antworten vorlesen.

- 1 überhaupt nicht ○
- 2 etwas ○
- 3 mittelmäßig ○
- 4 stark ○
- 5 äußerst ○
- (weiß nicht) ○
- (keine Angabe) ○

86.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Ich würde das Geräusch beschreiben als ein...
Poltern

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

87.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Ich würde das Geräusch beschreiben als ein...
Dröhnen

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

88.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Ich würde das Geräusch beschreiben als ein...
Rauschen

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

89.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Ich würde das Geräusch beschreiben als ein...
Brummen

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

90.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Ich würde das Geräusch beschreiben als ein...
Pulsieren

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

91.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Ich würde das Geräusch beschreiben als ein...
Pfeifen

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

Source: own presentation, ZEUS GmbH

92.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Ich würde das Geräusch beschreiben als ein...
Wuschen

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

93.
Bitte beschreiben Sie das Geräusch der Windenergieanlagen anhand der folgenden Begriffe genauer.

Das Geräusch unterliegt einer ständigen Schwankung, d.h. wechselt ständig zwischen laut und leise.

Interviewer:
Antworten vorlesen.

- 1 stimme nicht zu ○
- 2 ○
- 3 ○
- 4 ○
- 5 ○
- 6 ○
- 7 stimme voll zu ○
- (weiß nicht) ○
- (keine Angabe) ○

94. Welches der genannten Geräuschmerkmale ist für Sie am stärksten belästigend?

Interviewer:
Antworten vorlesen.

- Poltern ○
- Dröhnen ○
- Rauschen ○
- Brummen ○
- Pulsieren ○
- Pfeifen ○
- Wuschen ○
- Ständige Schwankungen ○
- (weiß nicht) ○
- (keine Angabe) ○

95. Gibt es weitere Begriffe, die das Geräusch beschreiben könnten?

Interviewer:

- Ja, und zwar:
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

96. Wie ist die Ausrichtung Ihres Schlafzimmers zur Windenergieanlage?

Interviewer:
Antworten vorlesen.

- von der Windenergieanlage abgewandt ○
- seitlich zur Windenergieanlage ausgerichtet ○
- der Windenergieanlage zugewandt ○
- (weiß nicht) ○
- (keine Angabe) ○

97. Wie ist die Ausrichtung Ihres Wohnzimmers zur Windenergieanlage?

Interviewer:
Antworten vorlesen.

- von der Windenergieanlage abgewandt ○
- seitlich zur Windenergieanlage ausgerichtet ○
- der Windenergieanlage zugewandt ○
- (weiß nicht) ○
- (keine Angabe) ○

98. Und welche Verglasung haben die Fenster in Ihrem Schlafzimmer?

Interviewer:
Antworten vorlesen.

- einfache Fensterscheiben ○
- Doppelverglasung oder Doppelfenster (Isolierglas, Kastenfenster) ○
- Schallschutzfenster, Dreifachverglasung, oder Fenster mit dicken Scheiben ○
- Schallschutzfenster in Verbindung mit Lüftern ○
- (weiß nicht) ○
- (keine Angabe) ○

99. Welche Verglasung haben die Fenster im Wohnraum Ihrer Wohnung bzw. Ihres Hauses (Hauptwohnraum)?

Interviewer:
Antworten vorlesen.

- einfache Fensterscheiben ○
- Doppelverglasung oder Doppelfenster (Isolierglas, Kastenfenster) ○
- Schallschutzfenster, Dreifachverglasung, oder Fenster mit dicken Scheiben ○
- Schallschutzfenster in Verbindung mit Lüftern ○
- (weiß nicht) ○
- (keine Angabe) ○

100. Wie ist das bei Ihnen üblicherweise in den warmen Jahreszeiten?

Haben Sie tagsüber die Fenster in Ihren Wohnräumen überwiegend...

Interviewer:
Antworten vorlesen.

- geschlossen oder ○
- geöffnet bzw. gekippt ○
- (weiß nicht) ○
- (keine Angabe) ○

101. Und haben Sie in warmen Jahreszeiten nachts die Fenster in Ihrem Schlafzimmer überwiegend...

Interviewer:
Antworten vorlesen.

- geschlossen oder ○
- geöffnet bzw. gekippt ○
- (weiß nicht) ○
- (keine Angabe) ○

102. Gibt es in Ihrer Wohnung bzw. Ihrem Haus einen ruhigen, von dem Umgebungslärm draußen abgewandten Raum, in den Sie sich zurückziehen können?

Interviewer:
Antworten vorlesen.

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

103. Unterscheidet sich die jetzige Geräuschsituation hier bei Ihnen von der Geräuschsituation bei Ihnen vor der Corona-Pandemie?

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

104. Wie unterscheidet sich die Situation?

- Nennung:
- (weiß nicht) ○
- (keine Angabe) ○

105. Wir sind jetzt fast am Ende angelangt, abschließend haben wir nur noch einige Fragen zur Statistik.

Bitte geben Sie Ihr Geschlecht an:

Interviewer:
Antworten vorlesen.

- männlich ○
- weiblich ○
- divers ○
- (weiß nicht) ○
- (keine Angabe) ○

106. In welchem Jahr sind Sie geboren?

Interviewer:

- Geburtsjahr:
- (weiß nicht) ○
- (keine Angabe) ○

107. Haben Sie ein Hörgerät?

Interviewer:

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

Source: own presentation, ZEUS GmbH

108. Können Sie hören bzw. verstehen, was in einem Gespräch gesagt wird, wenn mehrere Personen gleichzeitig sprechen, gegebenenfalls mit Hörgerät?

Interviewer:
Antworten vorlesen.

- Ja, ohne Schwierigkeiten ○
- Ja, mit leichten Schwierigkeiten ○
- Ja, mit großen Schwierigkeiten ○
- Nein, gar nicht ○
- (weiß nicht) ○
- (keine Angabe) ○

109. Welchen höchsten Schulabschluss haben Sie?

Interviewer:
Antworten vorlesen.

- Hauptschul-/ Volksschulabschluss ○
- Realschulabschluss/ mittlere Reife ○
- Polytechnische Oberschule der DDR mit Abschluss der 10. Klasse ○
- Fachhochschulreife, Abschluss Fachoberschule ○
- Allgemeine oder fachgebundene Hochschulreife/ Abitur (Gymnasium bzw. Erweiterte Oberschule (EOS), auch EOS mit Lehre) ○
- Schule beendet ohne Abschluss ○
- noch keinen Schulabschluss ○
- Polytechnische Oberschule der DDR mit Abschluss der 8. oder 9. Klasse ○
- sonstiger Schulabschluss ○
- (weiß nicht) ○
- (keine Angabe) ○

110. Welche höchste abgeschlossene Berufsausbildung haben Sie?

Interviewer:
Antworten vorlesen.

- noch in beruflicher Ausbildung (Berufsvorbereitungsjahr, Auszubildende/r, Praktikant/-in, Student/-in) ○
- keinen beruflichen Abschluss und nicht in beruflicher Ausbildung ○
- beruflich-betriebliche Berufsausbildung (Lehre) abgeschlossen ○
- beruflich-schulische Ausbildung (Berufsfachschule, Handelsschule, Vorbereitungsdienst für den mittleren Verwaltungsdienst abgeschlossen) ○
- Ausbildung an einer Fachschule der DDR abgeschlossen ○
- Ausbildung an Meister-, Berufs- oder Fachakademie abgeschlossen ○
- Ausbildung an Ingenieur-/ Technikerschule abgeschlossen ○
- Bachelor an Fachhochschule abgeschlossen ○
- Bachelor an Hochschule/ Universität abgeschlossen ○
- Fachhochschulabschluss (z.B. Diplom, Master) ○
- Universitätsabschluss (z.B. Diplom, Magister, Staatsexamen, Master ○
- einen anderen beruflichen Abschluss ○
- (weiß nicht) ○
- (keine Angabe) ○

111. Sind Sie...

Interviewer:
Antworten vorlesen.

- vollzeiterwerbstätig ○
- teilzeiterwerbstätig ○
- geringfügig erwerbstätig, 400-Euro-Job, Minijob, Gelegentlich oder unregelmäßig beschäftigt ○
- "Ein-Euro-Jobber/in" (bei Bezug von Arbeitslosengeld II) ○
- Altersteilzeit (in der Arbeitsphase befindlich) ○
- in einer beruflichen Ausbildung/Lehre oder Umschulung ○
- Schüler/in oder Studierende/r, die/der nicht gegen Geld arbeitet ○
- in Mutterschafts-, Erziehungsurlaub, Elternzeit oder sonstige Beurlaubung ○
- in Pension/Rente, Altersteilzeit (in Freistellungsphase befindlich) ○
- zurzeit nicht erwerbstätig (arbeitslos, Vorruheständler/-innen) ○
- noch nie erwerbstätig gewesen ○
- im Wehrdienst/Zivildienst, freiwilliges Soziales Jahr (BuFi) ○
- Hausmann/-frau ○
- Sonstiges ○
- (weiß nicht) ○
- (keine Angabe) ○

112. Welche berufliche Position nehmen Sie gegenwärtig ein?

Interviewer:
Antworten vorlesen.

- Arbeiter/in
- ungelernter Arbeiter/in ○
- Angelernter oder gelernter Arbeiter/in ○
- Facharbeiter/in ○
- Vorarbeiter/in ○
- Meister ○
- Angestellte/r
- mit einfacher Tätigkeit ○
- mit qualifizierter Tätigkeit ○
- Industrie-/Werkmeister ○
- mit hochqualifizierter Tätigkeit oder Leitungsfunktion ○
- mit umfassender Führungstätigkeit u. Entscheidungsbefugnissen ○
- Selbständige/r
- selbständiger Landwirt/ Genossenschaftsbauer/in ○
- Freiberuflich, selbständige/r Akademiker/in ○
- sonstiger Selbständige/r mit bis zu 9 Mitarbeitern/innen oder Partnern/innen ○
- sonstiger Selbständige/r mit 10 und mehr Mitarbeitern/innen oder Partnern/innen ○
- Mithelfende/r Familienangehörige/r ○
- Beamter/in
- einfacher Dienst ○
- mittlerer Dienst ○
- gehobener Dienst ○
- höherer Dienst ○
- (weiß nicht) ○
- (keine Angabe) ○

113. Wie viele Personen leben ständig in Ihrem Haushalt, Sie selbst mit eingerechnet?

Zählen Sie dabei bitte auch Kinder mit.

- Anzahl Personen:
- (weiß nicht) ○
- (keine Angabe) ○

114. Wie viele davon sind Kinder unter 14 Jahren?

- Anzahl Kinder < 14:
- (weiß nicht) ○
- (keine Angabe) ○

115. Wie viele davon sind Jugendliche von 14 bis unter 18 Jahren?

- Anzahl Jugendliche 14 bis < 18:
- (weiß nicht) ○
- (keine Angabe) ○

116. Wie viele davon sind Erwachsene über 18 Jahren?

- Anzahl Erwachsene:
- (weiß nicht) ○
- (keine Angabe) ○

117. Noch eine letzte Frage zu Ihrem Haushalt:

Damit wir in unserer Studie die Angaben aus verschiedenen Einkommensgruppen vergleichen können, würde es uns sehr helfen, wenn Sie uns sagen, in welche Gruppe das monatliche Nettoeinkommen Ihres Haushaltes – also aller im Haushalt lebenden Personen - gehört?

Ist es...

Interviewer:
Antworten vorlesen.
Zum Nettoeinkommen zählt das Einkommen aller Haushaltsmitglieder zusammen (einschließlich Erziehungsgeld, Kindergeld, Beihilfen, sonstige Einkünfte), nach Abzug von Steuern und Sozialabgaben

- unter 1250 € ○
- 1250 bis unter 1750 € ○
- 1750 bis unter 2250 € ○
- 2250 bis unter 3000 € ○
- 3000 bis unter 4000 € ○
- 4000 bis unter 5000 € ○
- 5000 € und mehr ○
- (weiß nicht) ○
- (keine Angabe) ○

118. Im Zeitraum von August 2020 und März 2021 wird die Technische Hochschule Köln zusammen mit dem Forschungspartner ZEUS (Zentrum für angewandte Psychologie, Umwelt- und Sozialforschung) eine Vertiefungsstudie zu diesem Forschungsprojekt durchführen.
Diese schließt Hörversuche ein, um die Lästigkeit von Geräuschen von Windenergieanlagen näher zu untersuchen.

Es ist wichtig, dass an diesen Hörversuchen auch Personen teilnehmen, die im Alltag mit Geräuschen von Windenergieanlagen konfrontiert sind. Die Hörversuche finden in Ihrer Nähe statt, die genaue Räumlichkeit würde Ihnen noch bekannt gegeben.

Darf die Technische Hochschule Köln Sie hierzu kontaktieren?

Interviewer:

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

119. Vielen Dank!

Wie dürfen Sie die Kolleginnen und Kollegen der Technischen Hochschule Köln Sie am besten erreichen, per E-Mail oder Telefon?

Source: own presentation, ZEUS GmbH

- E-Mail-Adresse:
- Telefonnummer:
- (keine Angabe, verweigert) ☐

120. Zusätzlich werden durch das Institut ZEUS, Zentrum für angewandte Psychologie, Umwelt und Sozialforschung ab Ende Juli 2020 vertiefende Telefoninterviews durchgeführt.

Darin geht es darum, mehr von Ihren Eindrücken der Geräusche von den Windenergieanlagen bei Ihnen zu erfahren. Eine Terminabsprache mit den Mitarbeitern von ZEUS kann hierfür flexibel und nach Ihren Präferenzen abgestimmt werden.

Darf das Institut ZEUS Sie in den kommenden Wochen zwecks einer Terminabsprache hierzu kontaktieren?

- Ja ○
- Nein ○
- (weiß nicht) ○
- (keine Angabe) ○

121. Vielen Dank!

Wie dürfen Sie die Kolleginnen und Kollegen von ZEUS Sie am besten erreichen, per E-Mail oder Telefon? (Doppelte Angabe, da nur diese Angaben an den jeweiligen Projektpartner weitergegeben werden.)

- E-Mail-Adresse:
- Telefonnummer:
- (keine Angabe, verweigert) ☐

122. Vielen Dank für Ihre Teilnahme!

Falls Sie weitere Anmerkungen haben, können Sie diese hier eingeben:

- Bemerkungen:
- keine Bemerkungen ○

Source: own presentation, ZEUS GmbH

D.2 Guideline for in-depth interviews

Guideline for qualitative in-depth interviews

On the topic of wind turbine noise in the project 'Noise effects of the use of land-based wind energy'

Project on behalf of the German Environment Agency

Qualitative telephone interviews

Study Area: Date:

Identification number of the quantitative questionnaire:

Opening the conversation:

Today we want to talk in greater depth about wind turbines near you; you were presented with a number of questions on this topic in the questionnaire a few weeks ago. We are interested in certain aspects of wind turbine noise. But we'd also like to give you another chance to talk about a few things you might like to have addressed in the questionnaire you completed a few weeks ago but didn't have the time or opportunity to do so.

1. **First off: Based on the telephone interview on wind turbine noise you participated in at the end of last year or at the beginning of this year, are there any other things you would like to comment on?**

2. **What is your view on wind turbines?**
    - Do you have a personal connection to them?
    - When you think about *your* everyday life at home or at work, are there one or more points of contact with wind energy or a related subfield?

3. **What would you say: What aspects of energy production through wind power are the most important to people in general?**
    - How do you justify your arguments?
    - Apart from your personal situation, how do you view wind turbines generally?

4. **In your opinion, what are the negative or positive effects of wind turbines located in the vicinity of residential areas?**
    - And in general?

5. **Was there a time when you didn't live near a wind turbine? Perhaps in a different place of residence, or before the turbines were put into operation?**

If so:

How would you describe the changes in your everyday life that you attribute to wind turbines specifically?

6. **In addition to wind turbine noise, are there any other side effects that you have noticed or that you generally suspect?**
   - If nothing specific is said about symptoms, ask: Pressure, vibration, discomfort?

7. **Are you able to hear one or more wind turbines at home?**
   - If you think about the last 12 months here where you live, how loud are the wind turbines near you?

very loud	loud	more loud than quiet	neither loud nor quiet	more quiet than loud	quiet	very quiet
+3	+2	+1	0	-1	-2	-3

8. **If you are acutely disturbed by wind turbine noise, what do you feel?**

9. **Are there certain countermeasures that you take immediately when you notice bothersome noise?**

10. **Are you active in a citizens' initiative or other associations that deal with wind turbines?**
    - If so, are you in favour of or against the operation of the wind turbines? Please tell us what is important to you in this regard!
    - Is the engagement directed against or in favour of wind turbines as a whole, or only against the wind turbines here locally?

Conclusion

Apart from what we have already discussed, are there any other things you would like to say about wind turbines?

Thank you very much for participating!

D.3 Table of mean values and standard deviations for the most important questionnaire items and calculated scores

	Study areas					
Items/scores	SA 1	SA 2	SA 3	SA 4	SA 5	Overall
Wind turbine noise annoyance overall	1.37 (0.93)	1.62 (1.12)	1.37 (0.8)	2.29 (1.5)	2.91 (1.48)	1.75 (1.24)
Wind turbine noise annoyance indoors	1.17 (0.56)	1.35 (0.87)	1.2 (0.56)	1.69 (1.24)	2.01 (1.15)	1.39 (0.88)
Wind turbine noise annoyance outdoors	1.32 (0.85)	1.6 (1.08)	1.53 (0.89)	2.22 (1.51)	2.91 (1.5)	1.75 (1.23)
Score for communication disturbances	1.13 (0.49)	1.1 (0.35)	1.15 (0.43)	1.27 (0.63)	1.36 (0.61)	1.17 (0.49)
Disturbance of the peace/concentration	1.17 (0.61)	1.18 (0.54)	1.15 (0.46)	1.33 (0.8)	1.48 (0.77)	1.23 (0.62)
Outdoor disturbances	1.39 (0.92)	1.52 (0.99)	1.49 (0.76)	2.13 (1.27)	2.66 (1.29)	1.7 (1.1)
Difficulty sleeping due to wind turbines	1.17 (0.59)	1.23 (0.72)	1.14 (0.52)	1.5 (0.94)	1.71 (1.01)	1.29 (0.75)
Lack of rest	1.82 (0.97)	2 (1.05)	1.97 (0.67)	2.24 (1.08)	2.76 (1.01)	2.08 (1.01)
Negative impacts for residential area	3.07 (1.14)	4.03 (0.49)	2.87 (0.85)	3.54 (1.23)	3.78 (1.1)	3.42 (1.07)
Positive impacts for residential area	1.84 (0.99)	1.8 (1.03)	2.26 (0.88)	1.81 (1.12)	1.54 (0.83)	1.85 (0.99)
Visual nuisance	1.46 (0.83)	1.94 (1.06)	1.4 (0.58)	2.2 (1.08)	2.49 (1.12)	1.78 (1)
Future annoyance due to wind turbines	1.53 (1.01)	1.8 (1.23)	1.37 (0.8)	1.81 (1.1)	2.63 (1.36)	1.77 (1.17)

D.4 Frequency tables for other variables

	Percentage of 'yes' responses in study areas					
	SA 1	SA 2	SA 3	SA 4	SA 5	Overall
Items						
Employment relationship relating to wind turbines	0.65	0.43	0.22	0.65	0.65	2.59
Financial participation in wind turbines	0.43	1.3	1.95	0.22	0.87	4.76
Electricity cost savings due to wind turbines	0.24	0.24	0.47	0.71	0.47	2.12
Engagement in favour of wind turbines	0.22	0.43	0.43	0.22	0	1.29
Engagement in opposition to wind turbines	1.29	0.22	0.43	0.22	2.15	4.3
Increase in wind turbine noise since construction	3.64	5.24	1.82	3.19	9.11	23.01
Decrease in wind turbine noise since construction	0	0	1.14	0	0	1.14

D.5 Results of regression calculations on the proportion of annoyed and highly annoyed persons (exposure-response analyses)

Basic models

Parameter	B	SE	p	OR	95% Wald confidence interval for OR	
					Lower limit	Upper limit
%HA overall						
(Constant term)	-6.934	1.532	0.000	0.001	0.000	0.020
L_r dB(A)	0.154	0.0446	0.001	1.167	1.069	1.273
%HA indoors						
(Constant term)	-7.671	2.3238	0.001	0.000	0.000	0.044
L_r dB(A)	0.144	0.0674	0.033	1.154	1.012	1.317
%HA outdoors						
(Constant term)	-7.887	1.7422	0.000	0.000	0.000	0.011
L_r dB(A)	0.18	0.0503	0.000	1.197	1.085	1.321

B = regression coefficient, SE = standard error, p = probability of error, OR = odds ratio

Extended models

Parameter	B	SE	p	OR	95% Wald confidence interval for OR	
					Lower limit	Upper limit
%HA overall						
(Constant term)	-8.11	2.19	0.00	0.00	0.00	0.02
Lr dB(A)	0.13	0.06	0.04	1.14	1.01	1.29
Noise sensitivity	-0.04	0.36	0.91	0.96	0.47	1.95
PSS1 Helplessness	-0.29	0.32	0.35	0.75	0.40	1.38
Lack of rest	0.78	0.29	0.01	2.19	1.25	3.84
Negative consequences	0.86	0.52	0.10	2.37	0.86	6.57
Positive consequences	0.17	0.32	0.61	1.18	0.63	2.22
Visual impact	1.09	0.32	0.00	2.96	1.59	5.52

Parameter	B	SE	p	OR	95% Wald confidence interval for OR	
Rumbling	0.34	0.23	0.13	1.41	0.90	2.20
Droning	-0.09	0.25	0.72	0.92	0.56	1.50
Rushing	0.24	0.37	0.52	1.27	0.62	2.63
Humming	-0.05	0.29	0.87	0.96	0.55	1.67
Pulsating	-0.03	0.24	0.89	0.97	0.61	1.54
Whistling	-0.11	0.24	0.64	0.89	0.56	1.44
Whooshing	0.92	0.58	0.11	2.51	0.80	7.85
Fluctuation	0.40	0.37	0.28	1.49	0.73	3.04
%HA indoors						
(Constant term)	-18.69	7.28	0.01	0.00	0.00	0.01
Lr dB(A)	0.33	0.14	0.02	1.39	1.05	1.83
Noise sensitivity	0.34	0.36	0.34	1.41	0.70	2.82
PSS1 Helplessness	0.52	0.36	0.15	1.69	0.84	3.40
Lack of rest	2.70	0.74	0.00	14.92	3.48	63.96
Negative consequences	-1.55	0.75	0.04	0.21	0.05	0.92
Positive consequences	-1.84	1.25	0.14	0.16	0.01	1.84
Visual impact	-0.61	0.55	0.27	0.54	0.18	1.60
Rumbling	0.15	0.31	0.64	1.16	0.63	2.13
Droning	-0.88	0.37	0.02	0.42	0.20	0.86
Rushing	0.29	0.35	0.40	1.34	0.68	2.63
Humming	0.17	0.43	0.69	1.19	0.52	2.73
Pulsating	0.99	0.42	0.02	2.70	1.19	6.12
Whistling	-0.23	0.36	0.52	0.80	0.40	1.60
Whooshing	1.45	1.71	0.40	4.27	0.15	121.92
Fluctuation	1.37	0.74	0.07	3.94	0.92	16.93
%HA outdoors						
(Constant term)	-12.33	3.27	0.00	0.00	0.00	0.00
Lr dB(A)	0.24	0.09	0.01	1.27	1.08	1.50

Parameter	B	SE	p	OR	95% Wald confidence interval for OR	
Noise sensitivity	0.84	0.43	0.05	2.31	0.99	5.40
PSS1 Helplessness	-0.28	0.43	0.51	0.75	0.33	1.75
Lack of rest	0.90	0.40	0.03	2.46	1.12	5.41
Negative consequences	0.34	0.49	0.49	1.40	0.54	3.63
Positive consequences	0.01	0.31	0.97	1.01	0.55	1.87
Visual impact	1.03	0.37	0.01	2.79	1.36	5.74
Rumbling	0.45	0.25	0.07	1.56	0.96	2.55
Droning	-0.19	0.29	0.53	0.83	0.47	1.48
Rushing	0.97	0.36	0.01	2.65	1.31	5.34
Humming	0.11	0.28	0.70	1.11	0.65	1.91
Pulsating	-0.09	0.27	0.73	0.91	0.54	1.54
Whistling	-0.10	0.24	0.68	0.91	0.56	1.46
Whooshing	0.66	0.42	0.12	1.94	0.84	4.45
Fluctuation	0.52	0.35	0.14	1.68	0.84	3.36

B = regression coefficient, SE = standard error, p = probability of error, OR = odds ratio

D.6 In-depth interview: Results of word-pair comparisons

Word-pair comparisons	SA 2	SA 3	Overall
Eventful	1	2	**3**
Uneventful	4	3	**7**
Neither nor	0	0	**0**
Unpleasant	0	1	**1**
Pleasant	1	3	**4**
Neither nor	4	1	**5**
Warm	1	2	**3**
Cold	4	0	**1**
Neither nor	3	3	**6**
Quiet	2	5	**7**
Chaotic	0	0	**0**
Neither nor	3	0	**3**
Dynamic	2	2	**4**
Static	0	3	**3**
Neither nor	3	0	**3**
Lively	1	1	**2**
Lifeless	2	3	**5**
Neither nor	2	1	**3**
Harmonious	0	3	**3**
Disharmonious	2	2	**4**
Neither nor	3	0	**3**
Expressive	0	1	**1**
Expressionless	2	3	**5**
Neither nor	3	1	**4**
Simple	4	2	**6**
Complex	0	3	**3**
Neither nor	1	1	**2**

E Listening tests – details of the stimuli presented

Table 35: Values of amplitude modulations for recording location 1 – static stimuli

Nominal value of AM in the listening test	$L_{HP,05}$-$L_{HP,95}$ in dB	ΔL_{AM} in dB
0 dB	1.4	0.7
2 dB	2.4	2.9
4 dB	4.1	4.6
6 dB	6.0	6.3
8 dB	8.0	9.1

Amplitude modulation values for the individual stimuli presented in a listening test with static AM for recording location 2. In addition to the nominal values of AM used for the evaluation and all further considerations, the $L_{HP,05}$-$L_{HP,95}$ for every stimulus and the ΔL_{AM} specified under the procedure described in Section 4.4 are indicated.

Table 36: Values of amplitude modulations for recording location 2 – static stimuli

Nominal value of AM in the listening test	$L_{HP,05}$-$L_{HP,95}$ in dB	ΔL_{AM} in dB
0 dB	1.4	1.0
2 dB	2.1	2.3
4 dB	3.8	4.5
6 dB	6.1	6.6
8 dB	7.7	8.5

Amplitude modulation values for the individual stimuli presented in a listening test with static AM for recording location 2. In addition to the nominal values of AM used for the evaluation and all further considerations, the $L_{HP,05}$-$L_{HP,95}$ for every stimulus and the ΔL_{AM} specified under the procedure described in Section 4.4 are indicated.

Table 37: Values of amplitude modulations for recording location 1 – dynamic stimuli

Change in AM	**$L_{HP,05}$-$L_{HP,95}$ in dB**		**ΔL_{AM} in dB**	
	Beginning	End	Beginning	End
swelling	3.5	7.7	2.9	8.1
fading	7.9	4.3	5.7	3.9

Amplitude modulation values for the individual stimuli presented in a listening test with dynamic AM for recording location 1. This indicates the trend in change in AM used for the evaluations as well as the $L_{HP,05}$-$L_{HP,95}$ for every stimulus and the ΔL_{AM} specified under the procedure described in Section 4.4. The values were determined separately for the beginning and the end of the stimulus (segments of 10 s each).

Table 38: Values of amplitude modulations for recording location 2 – dynamic stimuli

Change in AM	**$L_{HP,05}$-$L_{HP,95}$ in dB**		**ΔL_{AM} in dB**	
	Beginning	End	Beginning	End
swelling	4.2	5	3.6	4.3
fading	6.4	4.9	5.8	4.6

Amplitude modulation values for the individual stimuli presented in a listening test with dynamic AM for recording location 2. This indicates the trend in change in AM used for the evaluations as well as the $L_{HP,05}$-$L_{HP,95}$ for every stimulus and the ΔL_{AM} specified under the procedure described in Section 4.4. The values were determined separately for the beginning and the end of the stimulus (segments of 10 s each).

F Infrasound measurements

F.1 Measurement systems

F.1.1 Examination of the sound-measurement technology

Studies of amplitude-modulated noise show that it is strongly related to the rotational frequency of the wind turbines. The systems have low rotational frequencies that also generate noise in the infrasound range. This raises the question of whether the occurrence of infrasound relates to the modulation of wind turbine noise. To answer this question, the sound-measurement technology used was examined for its suitability for this task.

A Class-1 microphone on a tripod and an infrasound microphone on a ground plate were provided for the infrasound measurements.

Sound level meters with accuracy class 1 pursuant to DIN EN 61672 (Beuth 2014/2018) are not specified for the frequency range below 10 Hz under this standard. Absent further information from the manufacturer – which in the present case does not exist – the behaviour of a sound level meter with accuracy class 1 in the frequency range below 10 Hz is thus undefined. The sound-measurement technology used in this study, by the deBAKOM company, of the type 'deBAKOM 2014-Q-m' and consisting of measuring computer, matching amplifier and the weatherproof microphone unit B&K 4198 was thus investigated to determine how the frequency response behaves below 250 Hz, but particularly below 10 Hz. For this purpose, a so-called 'bass calibration' was performed in a laboratory of the Norsonic-Tippkemper company.

The following components were used as measurement technology for measuring infrasound on a ground plate in SA 5:

- Sound level meter by Sinus Messtechnik: Soundbook with GFM 212
- Measuring microphone by Microtech Gefell: MK3222 + MV212 with a frequency range from 0.5 Hz to 250 Hz.

The manufacturer Microtechgefell performed a bass calibration for this second measurement system as well.

The calibration method is described by the Norsonic-Tippkemper company as follows:

'To determine the bass frequency response along the entire measuring chain consisting of the microphone type B&K 4189, the impedance converter type 2669-C-001 and the measuring system ImmSound Measurement System, the microphone was mounted in a low-frequency coupler. An adapter is used to insert the microphone vents into the coupler. Prior to measurement, the pre-amplifier attenuation of the reference microphone is measured using the insert voltage measurement. The display on the sound level meter is thus directly tied to the reference microphone.' (Norsonic-Tippkemper GmbH, 2020)

F.1.2 Results of the calibration

The results of the calibrations are presented and discussed below. The focus is on the quantitative evaluation capability of measurement data in the infrasound range.

It should first be noted that these are calibrations of sound-measurement technology carried out under laboratory conditions, and that the measured frequency response is only an orientation guide for use of the measuring device in the field. Factors such as static air pressure, temperature and relative humidity at the place of use influence the frequency response during operation and cannot be investigated in detail in the context of the considerations.

Serial numbers of components of the measuring chain

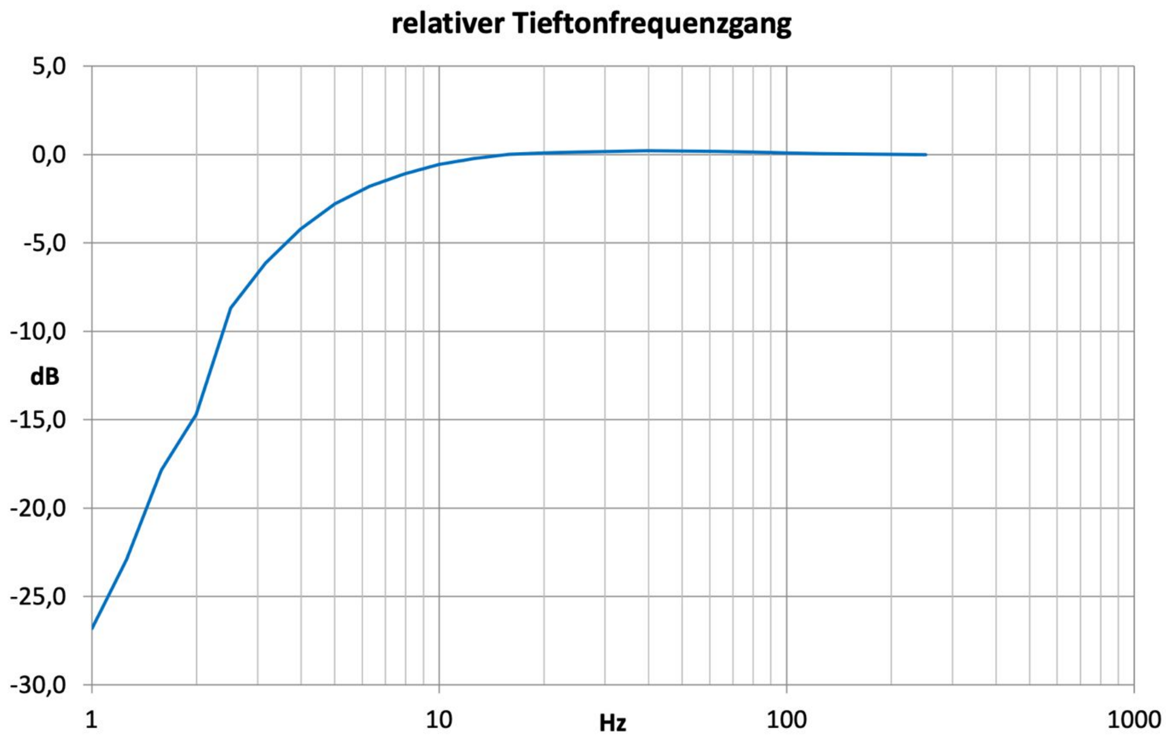
deBAKOM measuring system

Component	Manufacturer	Device type	Serial number
Measuring computer	deBAKOM	deBAKOM 2014-Q-m	1406335
Outdoor microphone unit	Brüel & Kjær	B&K 4198	1946369
Microphone pre-amplifier	Brüel & Kjær	B&K 2669-C	2745477
Microphone capsule	Brüel & Kjær	B&K 4189	2741544
Matching amplifier	deBAKOM	deBAKOM MicV5	1308002

Sinus measuring system

Component	Manufacturer	Device type	Serial number
Measuring computer	Sinus	Soundbook MK2_2LG	07398
Microphone pre-amplifier	MTG	MV212	0002
Microphone capsule	MTG	MKS222	38657

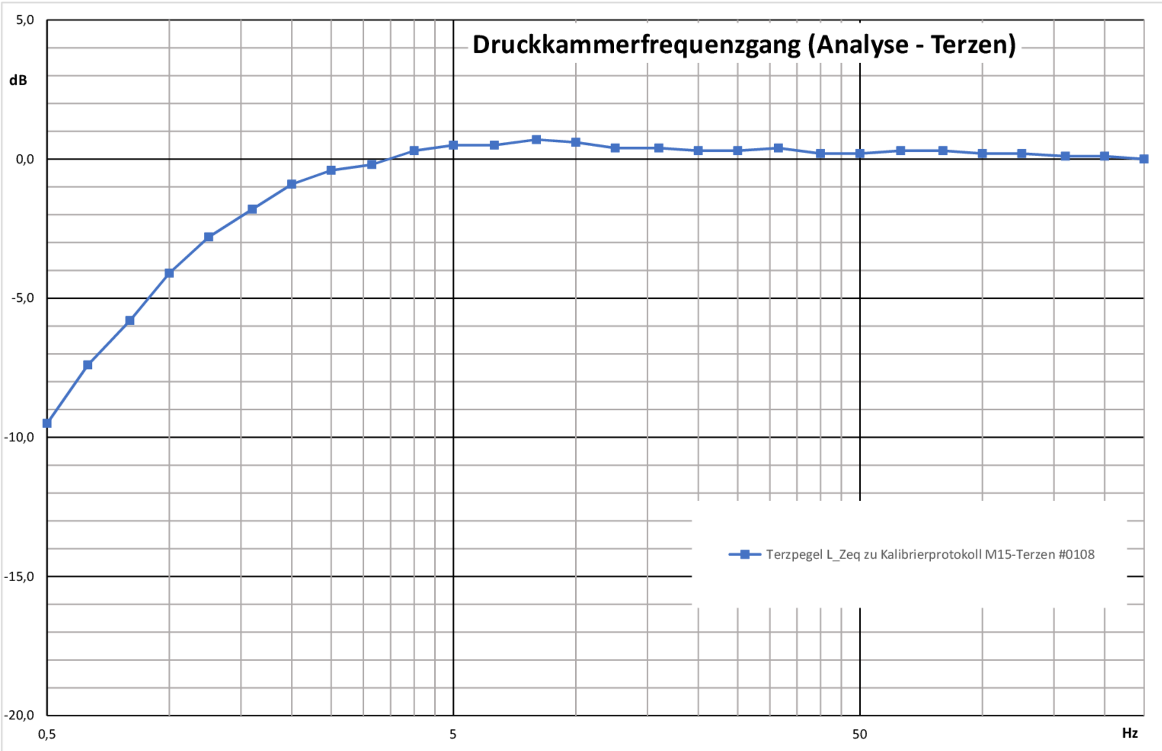
Figure 130 Relative bass frequency response (excerpt from deBAKOM 2014-Q-m calibration protocol)



Source: own presentation, deBAKOM GmbH

relativer Tieftonfrequenzgang = Relative bass frequency response

Figure 131 Bass frequency response (excerpt from deBAKOM 2014-Q-m calibration protocol)



Source: own presentation, deBAKOM GmbH

Druckkammerfrequenzgang (Analyse – Terzen) = Pressure-chamber frequency response (analysis – third-octaves); Terzpegel L_Zeq zu Kalibrierprotokoll M15-Terzen #0108 = Third-octave level L_Zeq to calibration protocol M15-Third-octaves #0108

The measured frequency response shows that the lower limiting frequency (-3 dB base frequency) of the Sinus Messtechnik measuring system is approximately 1.25 Hz, while the deBAKOM measurement system has a lower limiting frequency of approximately 5 Hz. The Sinus measuring system has an attenuation at 1Hz which is about 20dB lower than that of the deBAKOM measuring system.

Since the requirements for Class-1 sound level meters at 10 Hz set at +3/-∞ dB (see Table 3, p.21) are used as a basis in DIN EN 61672 (Beuth 2014), both of the sound measuring systems examined operate in the frequency range from 1 Hz to 10 Hz, in keeping with the acceptance limits for the lowest frequency of 10 Hz specified in DIN EN 61672 (Beuth 2014). Considerations of level shares in this frequency range can therefore be made with a quality based on Accuracy Class 1 under DIN EN 61672 (Beuth 2014).

When considering the acceptance limits of DIN EN 61672 (Beuth 2014), it is striking that an error of -∞ dB is tolerated for Accuracy Class 1, even at frequencies below 16 Hz. In addition, the linear detection of (infra-)sound, continuing right through to static air pressure, by means of measuring microphones, represents an increased requirement for the construction of sound-measurement technology with high-pass character in terms of the physical properties involved.

An ideal infrasound measurement would thus require sound-measurement technology with an ideal linear frequency response of less than 20 Hz.

Which errors are acceptable in the detection of the sound pressure level essentially depends on the purpose of the measurement conducted. In the present study, the aim was to examine the audio signal for the presence of individual tones in the infrasound range. For this purpose, the accuracy of the level is initially of secondary importance. Only a strong attenuation, down to the range of background noise, would render the desired consideration impossible. As expected, individual tones in the infrasound range, consideration of which is of interest in terms of human perceptibility, have levels in excess of 60 dB; this would give them a minimum margin of 49.5 dB to the background-noise level (which manufacturer states as 10.5 dB) for the measuring system. Attenuation of 26.8 dB at 1 Hz in the overall measuring system would still leave a 'residual' margin of 22.7 dB to the background noise level.

With a minimum level margin of at least 20 dB between individual tones and background noise, frequency response-corrected levels can thus also be determined with the aid of the results of the bass calibration above 1 Hz. Although the levels determined in this way cannot replace measurement with a frequency response for all components designed to be as linear as possible, they do make it possible to consider the levels in the infrasound range with defined, finite measurement errors.

Below 1 Hz, the slope of the frequency response of 12 dB/octave is expected to continue. Under this assumption, attenuations of 38 dB to 63 dB result for the octave middle frequencies 0.5 Hz, 0.25 Hz and 0.125 Hz.

The following pages list the calibration protocols for the sake of completeness.

Figure 132 Calibration protocol, Sinus measuring system

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Kalibrierprotokoll M15-Terzen **Werkskalibrierung** ***Factory Calibration***	**Prot.-Nr.: 0108** **Seite: 1 von 4**
Frequenzgang-Kalibrierung Druckkammerverfahren **Mikrofonkapsel Kondensatortyp mit Vorverstärker und Schallpegelmesser**	

Gegenstand *Object*	Messmikrofonkapsel + Vorverstärker, stromgesp. + Schallpegelmesser
Hersteller *Manufacturer*	Microtech Gefell GmbH + Sinus Messtechnik GmbH
Typ *Type*	MKS222 + MV212 + Soundbook MK2_2LG
Fabrikate/Serien/Nr. *Serial number*	38657 + 0002 + 07398
Prüfmittelnummer *PM number*	-
Equipmentnummer *Equipment number*	-
Auftraggeber *Customer*	Umweltamt Dessau 06844 Dessau
Auftragsnummer *Order No.*	zu DK21-028
Anzahl der Seiten des Zertifikats *Number of pages of the certificate*	4
Datum der Kalibrierung *Date of calibration*	14.07.2021

Microtech Gefell kalibriert die physikalischen Größen Schalldruck und Beschleunigung mit Werkszertifikat.

Die Normale für Schalldruck und Referenzmikrofone sind rückführbar auf PTB-Normale. (Physikalisch Technische Bundesanstalt).

Die Normale für Beschleunigung und Referenzbeschleunigungssensoren sind rückführbar auf DKD-Normale. (Deutscher Kalibrierdienst)

Microtech Gefell calibrates the physical quantities sound pressure and acceleration with factory certificate.

The standards for sound pressure and reference microphones conform to PTB standards (Physikalisch Technische Bundesanstalt).

The standards of acceleration and reference accelerometers conform to DKD standards (Deutscher Kalibrierdienst).

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Stempel *Seal*	Datum *Date*	Laborleiter *Head of laboratory*	Bearbeiter *Person responsible*
	23.07.2021	Udo Wagner	Stephan Patzer

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Kalibrierprotokoll M15-Terzen **Werkskalibrierung** ***Factory Calibration***	**Prot.-Nr.:** **0108** **Seite:** **2 von 4**
Frequenzgang-Kalibrierung Druckkammerverfahren **Mikrofonkapsel Kondensatortyp mit Vorverstärker und Schallpegelmesser**	

Kalibriergegenstand:

Messmikrofonkapsel Kondensatortyp:	MKS222,	Seriennummer: 38657
Wandlertyp:	kapazitiver Druckempfänger	
Nomineller Druckleerlaufübertragungskoeffizient:	50,0 mV/Pa +/-1,5 dB (@ 250Hz)	
Frequenzbereich (+/-2 dB):	0,5 Hz bis 250 Hz (zu prüfender Messbereich)	
Messmikrofonverstärker stromgespeist:	MV212,	Seriennummer: 0002
Schallpegelmesser:	Soundbook MK2_2LG,	Seriennummer: 07398

Kalibrierverfahren:

Das Messmikrofon (Messmikrofonkapsel + Messmikrofonverstärker) des zu kalibrierenden Schallpegelmessers wird zusammen mit dem Referenzmikrofon in der Messkammer für Druckkammermessungen installiert. Die größte Kammerinnenausdehnung ist kleiner als ca. 10% der kleinsten Wellenlänge, die bei der Druckkammermessung an der oberen Grenze des Frequenzbereichs auftritt (f<=250Hz). Umgebungsgeräusche werden durch die massive Kammerwand um ca. 40dB gedämpft. Die Messanordnung wird schwingungsisoliert aufgestellt. Über einen elektrodynamischen Lautsprecher wird das Erregersignal eingespeist.
Erregersignal: Sinus 0,5Hz bis 250Hz mit Schrittweite von 1/3-Oktave
Messdauer: jeweils 20sec
Die Kalibrierung erfolgt durch Bestimmung des Frequenzganges von Messmikrofonkapsel mit Messmikrofonvorverstärker und Schallpegelmesser. Die Übertragungsfunktion der zu kalibrierenden Kombination aus Messmikrofonkapsel, Messmikrofonvorverstärker und Schallpegelmesser wird aus dem Vergleich ihres gemessenen Frequenzganges mit dem rückgeführten Frequenzgang des Referenzmikrofons (Frequenzgang des Druckbetriebsübertragungsmaßes) bestimmt.

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Kalibrierprotokoll M15-Terzen **Werkskalibrierung** ***Factory Calibration***	**Prot.-Nr.: 0108** **Seite: 3 von 4**
Frequenzgang-Kalibrierung Druckkammerverfahren **Mikrofonkapsel Kondensatortyp mit Vorverstärker und Schallpegelmesser**	

Bestandteile der Kalibriereinrichtung:

Messkammer:	MTG		Tieftonmesskammer	
Referenzmesskette:				
Mikrofon:	MTG	Typ:	MK222	S.-Nr.: 26826
			mit MV203	S.-Nr.: 0125
Soundbook:	Sinus	Typ:	CF18 Quadro plus G	S.-Nr.: 6128
Frequenzgenerator:	Agilent	Typ:	33210A	S.-Nr.: MY48015289

Kalibrierbedingungen:

Das Messmikrofon des zu kalibrierenden Schallpegelmessers ist in der Druckkammer montiert.
Die Druckkammer ist gegenüber der Messumgebung abgedichtet.
Die Druckkammer ist mit weichem Dämmmaterial auf einer massiven Arbeitsplatte installiert, um Rückwirkungen der Umgebung weitgehend auszuschließen.

Erregersignal: Sinus 0,5Hz bis 250Hz mit Schrittweite von 1/3-Oktave

Soundbook: Analyse - Terzen, L_{Zeq} mit Mittelungszeit = 20s

Umgebungsbedingungen:

Temperatur des Prüflings: 22,5 °C
Relative Luftfeuchtigkeit: 56,2 %
Luftdruck: 948,1 hPa
Speisung: 200V (Polarisationsspannung)

Messergebnisse:

(siehe beiliegender Messschrieb)

Kalibrierintervall (nicht bindende Empfehlung): **jährlich**

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Kalibrierprotokoll M15-Terzen Werkskalibrierung *Factory Calibration*	Prot.-Nr.: 0108 Seite: 4 von 4
Frequenzgang-Kalibrierung Druckkammerverfahren **Mikrofonkapsel Kondensatortyp mit Vorverstärker und Schallpegelmesser**	

Messunsicherheit:

Messunsicherheit: siehe Bemerkung

Bemerkung: siehe Physikalisch-Technische Bundesanstalt bzw. DKD

	Kalibriermittel:	Seriennummer:	kalibriert am:	durch:
Kalibrierschein für	B&K 4180	2787479	13.04.2021	PTB
	mit B&K 2673	2966562		
Kalibrierschein für	MTG MK221	37532	10.03.2020	PTB
	mit MTG MV203	0125		
Kalibrierschein für	MTG MK222	26826	25.06.2015	DKD
	mit MTG MV203	0125		
Kalibrierschein für	B&K 4231	2528549	06.10.2020	PTB
Kalibrierschein für	MTG 4000	30840	07.10.2020	PTB
Kalibrierschein für	MTG 4010	10010	19.04.2021	PTB
Kalibrierschein für	B&K 4228	1742031	06.10.2020	PTB
Kalibrierschein für	MTG 5002	0102	14.05.2020	PTB
Kalibrierschein für	Ahlborn FHAD 46-C2	19080150 & 11708263	04.09.2019	DKD
Kalibrierschein für	Agilent 33210A	MY48015289	07.08.2019	DKD

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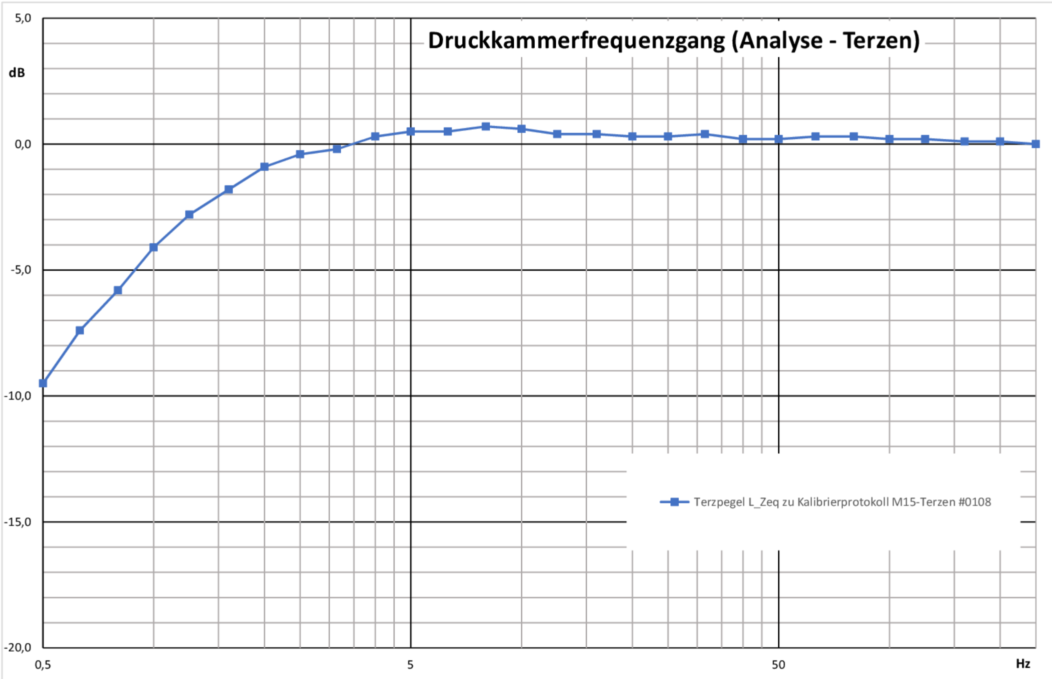

Source: own presentation, deBAKOM GmbH

Druckkammerfrequenzgang (Analyse – Terzen) = Pressure-chamber frequency response (analysis – third-octaves); Terzpegel L_Zeq zu Kalibrierprotokoll M15-Terzen #0108 = Third-octave level L_Zeq to calibration protocol M15-Third-octaves #0108

Figure 133 Calibration certificate, deBAKOM measuring system

Norsonic Tippkemper

Werkskalibrierschein

Calibration certificate

Kalibrierschein-Nr.: 25040/20

Certificate-No.:

Gegenstand *Object*	**Schallpegelmesser mit Außenmikrofon**
Hersteller *Manufacturer*	**deBAKOM**
Typ *Type*	**ImmSound Measurement System**
Serien-Nr. *Serial number*	**1406335**
Ident-Nr. *Ident No.*	---
Auftraggeber *Customer*	**deBAKOM Gesellschaft für sensorische Messtechnik mbH Bergstraße 36 51519 Odenthal**
Anzahl der Seiten *Number of pages*	**3**
Kalibrierdatum *Date of Calibration*	**24.09.2020**

Die Kalibrierung erfolgt durch Vergleich mit Bezugsnormalen bzw. Bezugsnormal-messeinrichtungen, die kalibriert und damit rückgeführt sind auf die nationalen Normale, mit denen die Physikalisch-Technische-Bundesanstalt (PTB) die physikalischen Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI) darstellt. Für die Kalibrierung und deren Dokumentation trägt der Aussteller dieses Kalibrierscheins die alleinige Verantwortung. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

The calibration is performed by comparison with reference standards or standard measuring equipment which are calibrated and thus traceable to the national measurement standards maintained by the PTB for the realization of the physical units according to the International System of Units (SI). The issuing company is solely responisble for the performance and the documentation of the calibration. The user is obliged to have the

Auswertung
Evaluation

Datum *Date*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person in charge*
24.09.2020	W. Thomann	P. Hanebrink

Norsonic-Tippkemper GmbH
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Tippkemper norsonic

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Kalibriernummer: 25040/20

1. Verwendete Messgeräte

Referenzmikrofon Typ:	B&K 4180	Seriennr.:	2564071	Kalibrierscheinnr.:	PTB-1.61-4099091/19
Generator Typ:	Standfort DS360	Seriennr.:	149069	Kalibrierscheinnr.:	25024/20
Calibration unit Typ:	Norsonic 483B	Seriennr.:	25750	Kalibrierscheinnr.:	24052/19
Voltmeter Typ:	Keysight 34401A	Seriennr.:	SG53001511	Kalibrierscheinnr.:	1-11111939237-1
Tieftonkuppler Typ:	G.R.A.S. 42AE	Seriennr:	95644		

2. Kalibriergegenstand

Messmikrofon Typ:	B&K 4189	Seriennr.:	2564071
Impedanzwandler Typ:	B&K 2669-C-001	Seriennr.:	2745477
Wetterschutzmodul Typ:	B&K 4198	Seriennr.:	1946369
Schallpegelmesser Typ:	ImmSound Measurement System V2.0.1	Seriennr.:	1406335
Kabel Typ:	B&K-AO0414-D-100-2018W05		

3. Kalibrierverfahren

Zur Bestimmung des Tieftonfrequenzganges der gesamten Messkette bestehend aus dem Mikrofon Typ B&K 4189, dem Impedanzwandler Typ 2669-C-001 und dem Messsystem ImmSound Measurement System wurde das Mikrofon in einem Tieftonkuppler montiert. Mit einem Adapter wird die Entlüftung des Mikrofons in den Kuppler geführt. Vor der Messung wird über die Insert-Voltage Messung die Vorverstärkerdämpfung des Referenzmikrofons gemessen. Die Anzeige des Schallpegelmessers wird so direkt auf das Referenzmikrofon bezogen.

4. Messbedingungen

Die Messeinrichtung wurde mindestens eine Stunden vor Messbeginn aufgebaut und in Betrieb genommen, um eine ausreichende Stabilisierungszeit zu erhalten.

Umgebungsbedingungen zur Zeit der Messung

Temperatur:	24,5 °C
rel. Luftfeuchtigkeit:	33 %
Luftdruck:	986,54 hPa

5. Messergebnisse auf Umgebungsbedingungen bezogen

Angabe des relativen Frequenzganges der gesamten Messkette auf 250 Hz bezogen.

Numerische Werte

Frequenz	Pegel
dB	dB
1,000	-26,8
1,259	-22,9
1,585	-17,8
1,995	-14,7
2,512	-8,7
3,162	-6,1
3,981	-4,2
5,012	-2,8
6,310	-1,8
7,943	-1,1
10,00	-0,6
12,59	-0,2
15,85	0,0

Frequenz	Pegel
dB	dB
19,95	0,1
25,12	0,2
31,62	0,2
39,81	0,2
50,12	0,2
63,10	0,2
79,43	0,1
100,0	0,1
125,9	0,1
158,5	0,0
199,5	0,0
251,2	0,0

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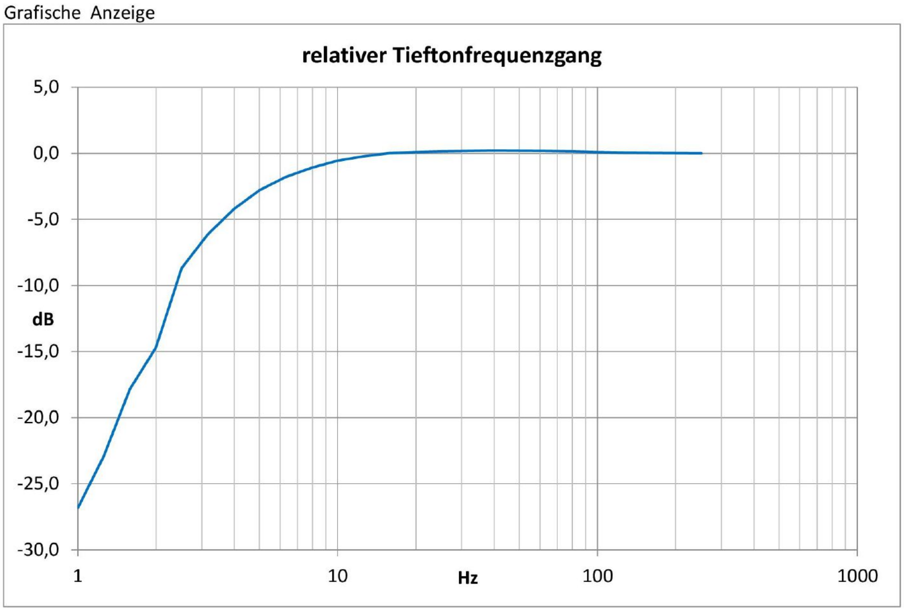
Kalibriernummer: **25040/20**

Grafische Anzeige



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F.2 Evaluation of the measurements from the ground plate

F.2.1 Measurement times

All times between 11:00 p.m. and 5:00 a.m. were taken into account, provided it was not raining and the wind speed at a height of 6 m was less than 6 m per second.

Equivalence levels were formed for 1-minute intervals in each case.

F.2.2 G-weighting and auditory threshold

The ratio of a G-weighted level to the auditory threshold depends on the frequency of the sound.

At 20 Hz, G-weighting increases the level by 9 dB; as the DIN 45680 (Beuth 1997) auditory threshold is 71 dB, the G-weighting for a tone at 20 Hz must exceed 80 dB in order to be above the auditory threshold. Accordingly, at 25 Hz, the result is 3.7 dB + 63 dB = 63.7 dB, and at 31.5 Hz -4.0 dB + 55 dB = 51 dB.

F.2.3 Frequency bands

The bands

- $L_{Zeq,<3Hz}$ very low frequencies
- $L_{Zeq,4-7Hz}$ the extended infrasound range
- $L_{Zeq,8-20Hz}$ the classic infrasound range
- $L_{Zeq,25-80Hz}$ low frequency above the infrasound range

are constituted by aggregating the corresponding one-third-octave bands.

Because A-weighting is unsuitable for very low frequencies, either no frequency weighting or Z-weighting (IEC 61672-1) is used, which is equal to zero at all frequencies.

F.2.4 Determining the rotational speed of the wind turbines in Section 5.4.2 5.4.2

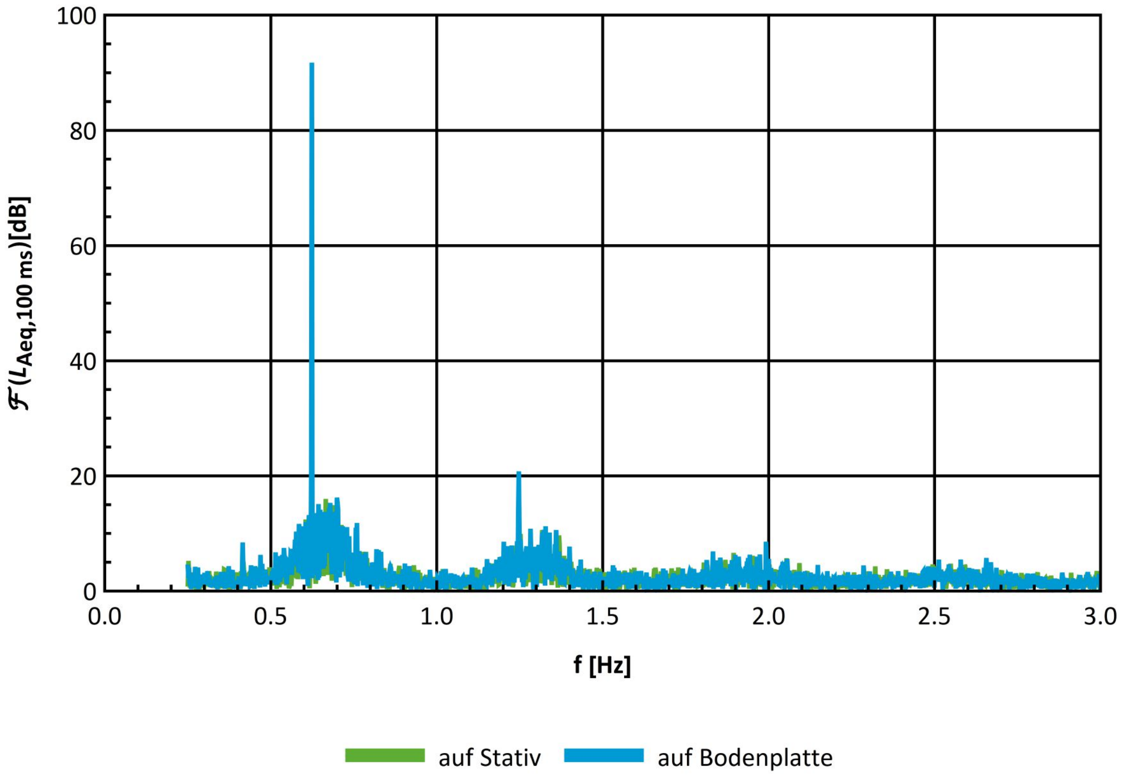
Section 5.4.2 shows a line spectrum for a time segment of the measurement in SA 5.

There are no operating data available for the wind turbines in SA 5; since it is not possible to compare wind turbine speeds with the frequencies of the lines in the spectrum, the speed must be determined acoustically. If the same wind turbine that causes the infrasound spectrum also causes amplitude modulations, then its rotational speed can be determined by means of the frequency of the amplitude modulations (cf. sections 4.4 and C.1).

Figure 134 shows the Fourier transform of the $L_{Aeq,100ms}$ in the time segment. The maximum corresponding to the rotational speed of the wind turbine is very clearly visible.

A large number of the wind turbines in SA 5 cause immissions at the measuring location. It is not possible to ascertain whether the immissions in the selected time segment were caused by exactly one turbine, or whether several turbines were running at the same precise speed. With frequency determination so acute, wind turbines would also be a proven source if the AM were caused by one turbine and the infrasound by the other turbine.

Figure 134: Fourier transform of the $L_{Aeq,\ 100ms}$



Source: own presentation, Dr. Kühner GmbH

auf Stativ = On tripod; auf Bodenplatte = On ground plate

F.3 Comparison of measurements with Class-1 microphone on tripod and infrasound microphone on ground plate

Measurements in SA 1 to 4 were performed using only a Class-1 microphone mounted on a tripod. The disadvantage that this poses for the study of infrasound is that microphone sensitivity decreases significantly at very low frequencies – with the measuring system measuring frequencies at levels lower than they actually are – and that the microphone is exposed to more wind and turbulence due to the greater altitude, which can expose the microphone to signals not caused by the wind turbines.

To estimate infrasound levels in SA 1 to 4 in spite of this, the two measuring systems, infrasound microphone on a ground plate and Class-1 microphone on a tripod, were extensively compared with one another. The approx. 8-week long-duration measurements conducted in SA 5 were used for the comparison. In SA 5, both measuring systems could be used and operated simultaneously for the entire measurement period. The two measuring systems were also compared under laboratory conditions.

F.3.1 Influence of local wind on measurement results

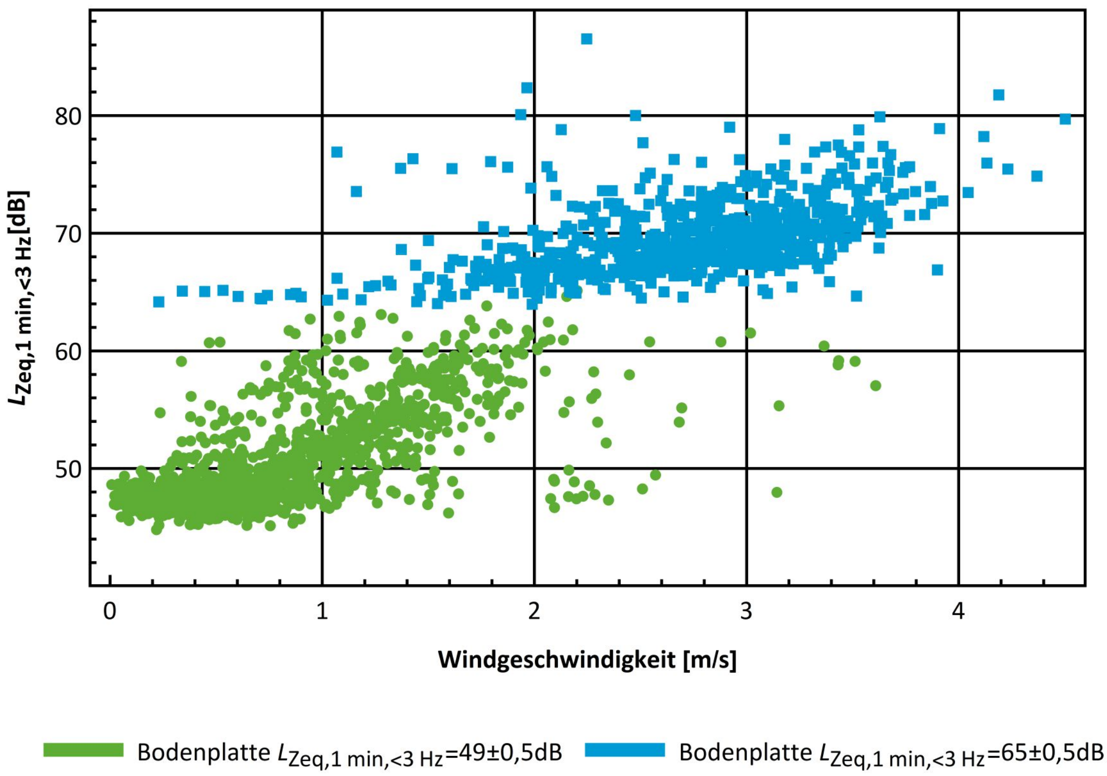
At wind speeds of up to 6 m/s near the microphone, there is practically no wind noise in the frequency range of audible sound that would contribute to an A-weighted level. At higher wind speeds, noise occurs directly at the microphone due to air vortices. The deBAKOM microphones are equipped with secondary wind baffles to minimise disturbance due to wind noise as much as possible, even at high wind speeds.

The situation is somewhat different When measuring very low-frequency noise. Atmospheric vortices connected with fluctuating wind fields and their turbulences play a greater role here. The pressure fluctuations that this causes cannot be suppressed by wind baffles.

To investigate the influence of local wind on measurements taken with a Class-1 microphone mounted on a tripod and measurements with an infrasound microphone on a ground plate, measurement times were selected in which the level on the ground plate was within a small time window. Then the levels measured simultaneously on the tripod were plotted against local wind speeds at microphone height for these time segments. Figures 124 to 127 show these levels for four frequency bands and for two constant levels on the ground plate. If not for the influence of the wind, ideally all points would lie on horizontal lines. Indeed, the trend that emerges is that the level increases in line with increases in local wind speed. As the level measured on the ground plate is constant at the same time, this is a clear indication that local wind creates a disturbance of the measurement and leads to high levels.

Figure 127 shows the level for the frequency band of 25-80 Hz. In this frequency range, the dependency on local wind speed of up to 3 m/s is small. The influence of local wind on the measurement result is thus problematic, particularly at very low frequencies. Extrapolation to windless local conditions is nevertheless possible as part of an effort to conduct measurements with the microphone on the tripod in this frequency range as well. By way of example, L_{Geq} levels are plotted in Figure 128 for times when the wind speed at hub height was in the 6-8 m/s range. As can be seen, the levels increase with local wind speed. Local wind speeds were divided into intervals for this purpose. In each interval, the lower data points were carried out as the basis for an extrapolation to zero local wind speed.

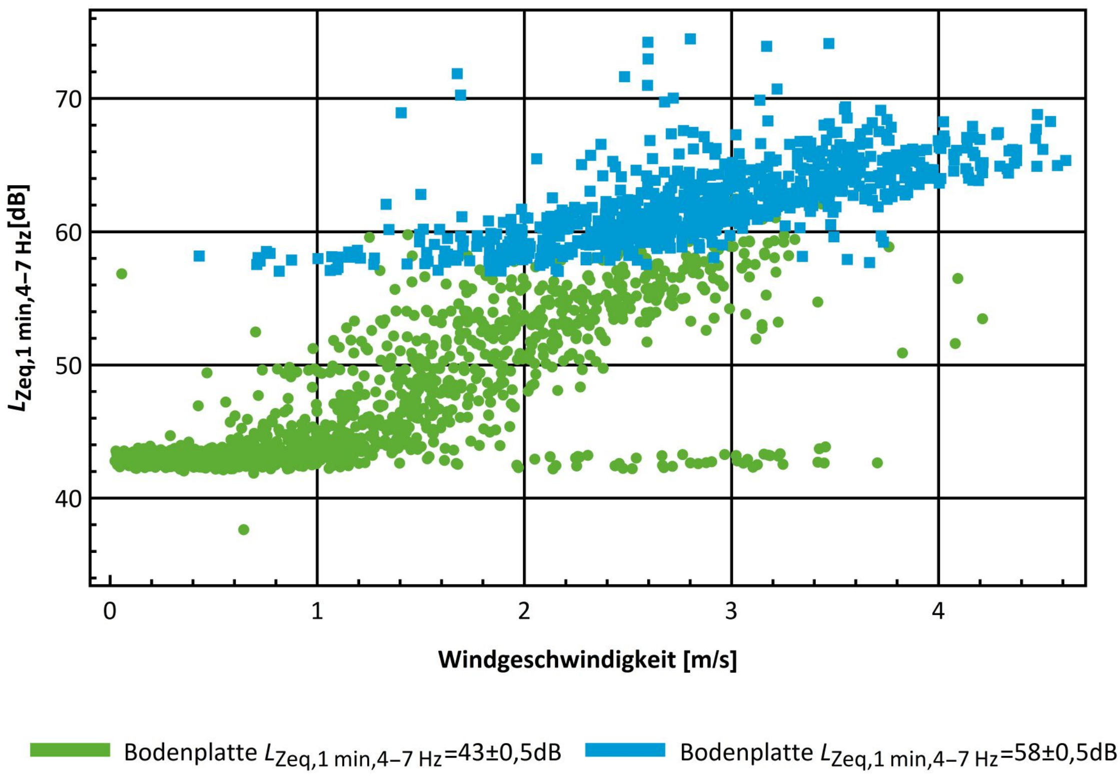
Figure 135: $L_{Zeq,1min,<3Hz}$ on tripod vs. wind speed for fixed $L_{Zeq,1min,<3Hz}$ on ground plate



Source: own presentation, Dr. Kühner GmbH

Windgeschwindigkeit [m/s] = Wind speed [m/s]; Bodenplatte = Ground plate

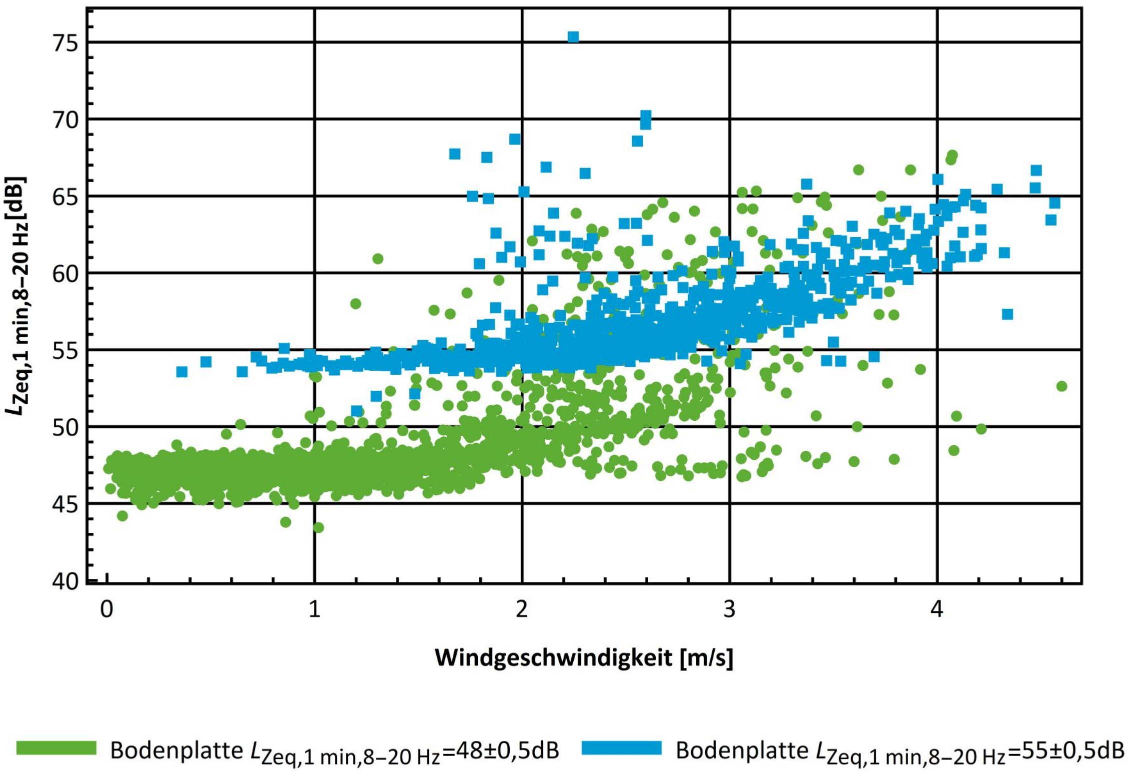
Figure 136: $L_{Zeq,1min,4\text{-}7Hz}$ on tripod vs. wind speed for fixed $L_{Zeq,1min,4\text{-}7Hz}$ on ground plate



Source: own presentation, Dr. Kühner GmbH

Windgeschwindigkeit [m/s] = Wind speed [m/s]; Bodenplatte = Ground plate

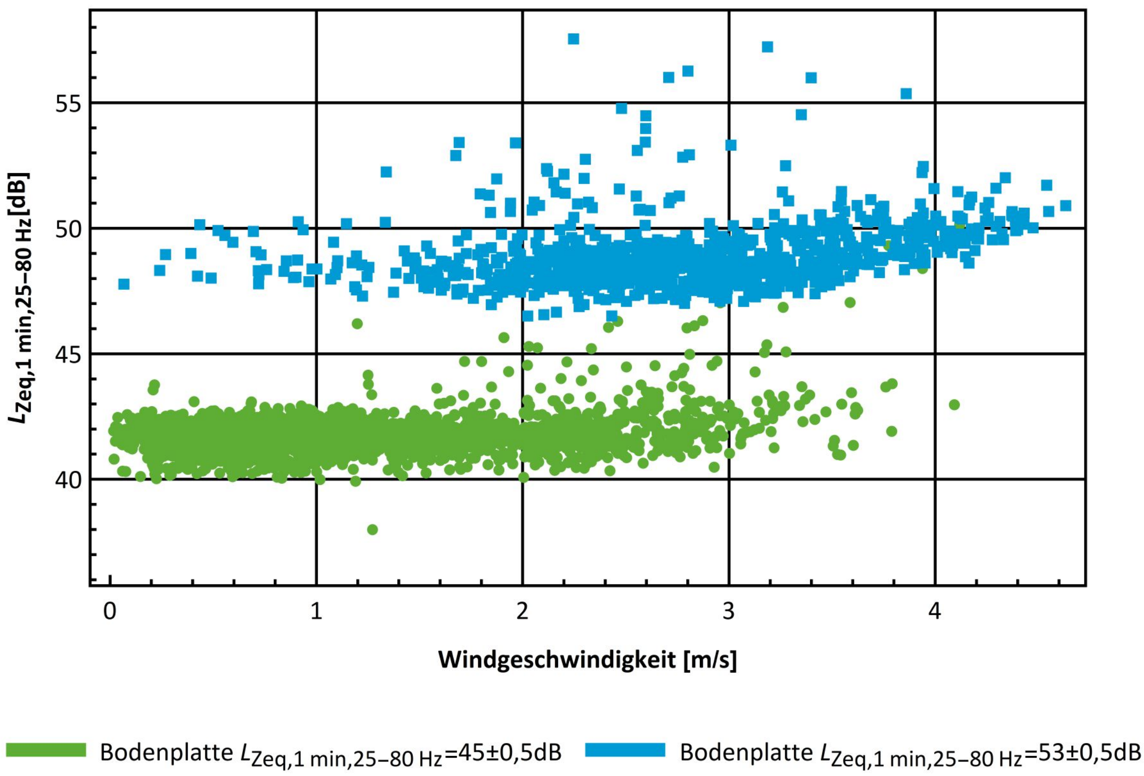
Figure 137: $L_{Zeq,1min,8\text{-}20Hz}$ on tripod vs. wind speed for fixed $L_{Zeq,1min,8\text{-}20Hz}$ on ground plate



Source: own presentation, Dr. Kühner GmbH

Windgeschwindigkeit [m/s] = Wind speed [m/s]; Bodenplatte = Ground plate

Figure 138: $L_{Zeq,1min,25\text{-}80Hz}$ on tripod vs. wind speed for fixed $L_{Zeq,1min,25\text{-}80Hz}$ on ground plate

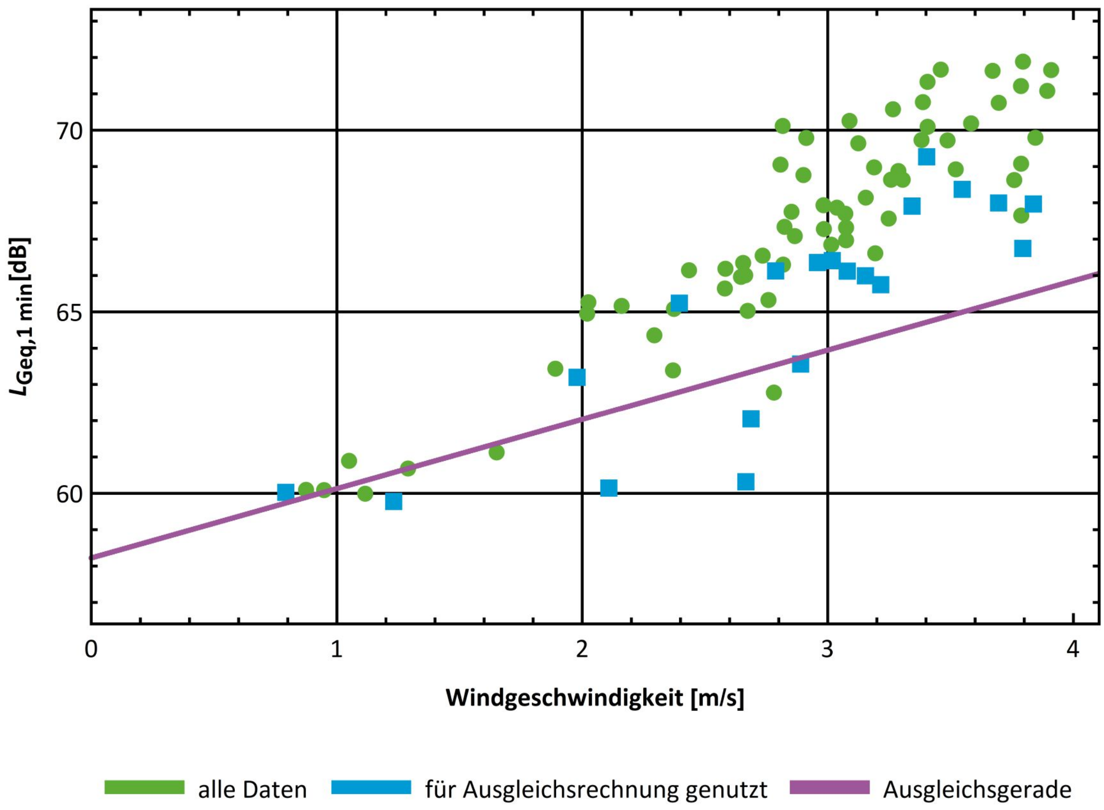


Source: own presentation, Dr. Kühner GmbH

Windgeschwindigkeit [m/s] = Wind speed [m/s]; Bodenplatte = Ground plate

Figure 139: $L_{Geq\ ,1minagainst}$ against wind speed at microphone height

Measured in SA 2 and limited to times when wind speed at the wind turbine hub height is 6-8 m/s and the wind turbines are producing power. Local wind speeds were divided into intervals. In each interval, the lower data points were carried out as the basis for an extrapolation to zero local wind speed.



Source: own presentation, Dr. Kühner GmbH

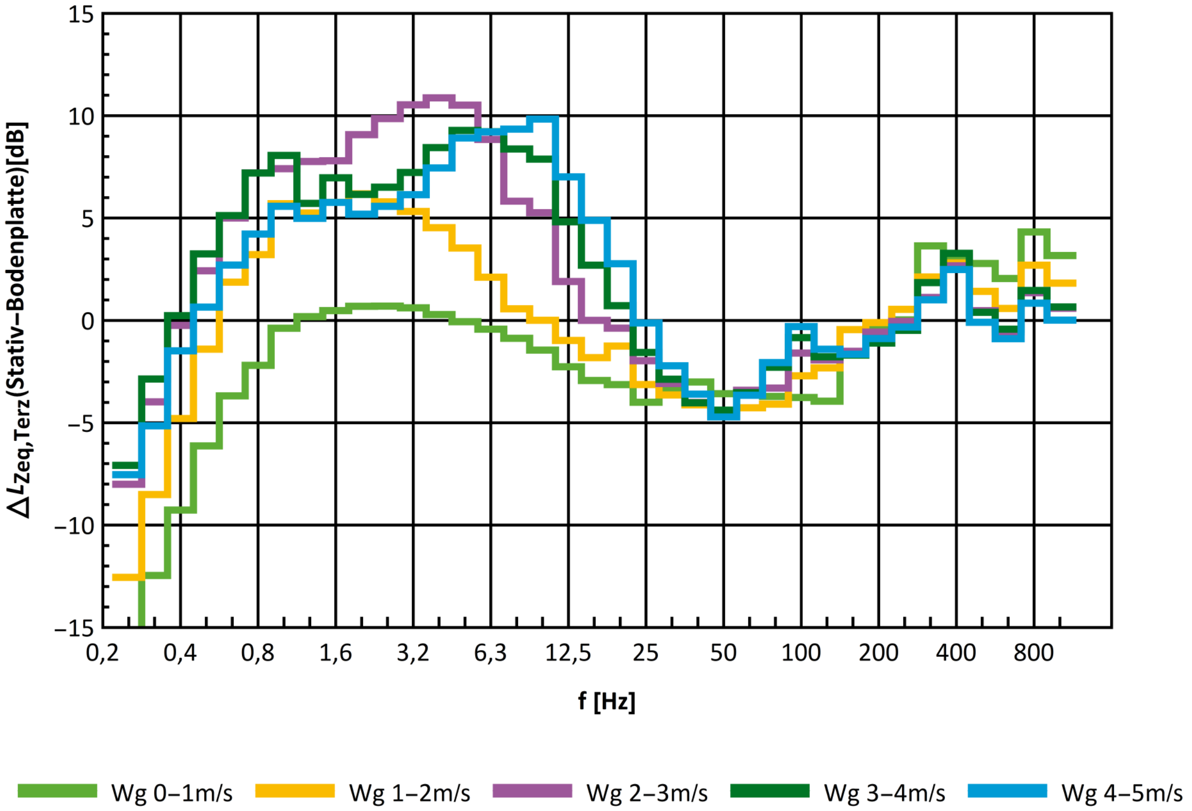
Windgeschwindigkeit [m/s] = Wind speed [m/s]; alle Daten = All data; für Ausgleichsrechnung genutzt = used for curve fitting; Ausgleichsgerade = Best-fit line

F.3.2 Difference spectra between measurements on ground plate and tripod

In addition to the influence of local wind, measurements made with a microphone on a tripod differ from those with an infrasound microphone on the ground in that the infrasound microphone is more sensitive at low frequencies and is lying on a ground plate. To compare the two microphones, the spectra for both are respectively formed for time periods of one minute and a spectrum determined based on the difference. In, Figure 140 the 70% percentile of the difference spectrum is presented as a one-third-octave spectrum. The classification is based on different wind speeds at the tripod-mounted microphone. Positive values mean that the level at the microphone on the tripod is higher, and negative values indicate that higher levels were measured on the ground plate.

As is to be expected, local wind conditions have a significant effect on the shape of the difference spectrum. But a frequency dependence of the difference function of several dB is even discernible for times when local wind speeds were less than 1 m/s. At low frequencies, it can be seen that the sensitivity of the infrasound microphone is greater than that of the Class-1 microphone. The difference spectrum is negative here.

Figure 140: Differential spectrum (tripod-ground plate) vs. wind speed



Source: own presentation, Dr. Kühner GmbH

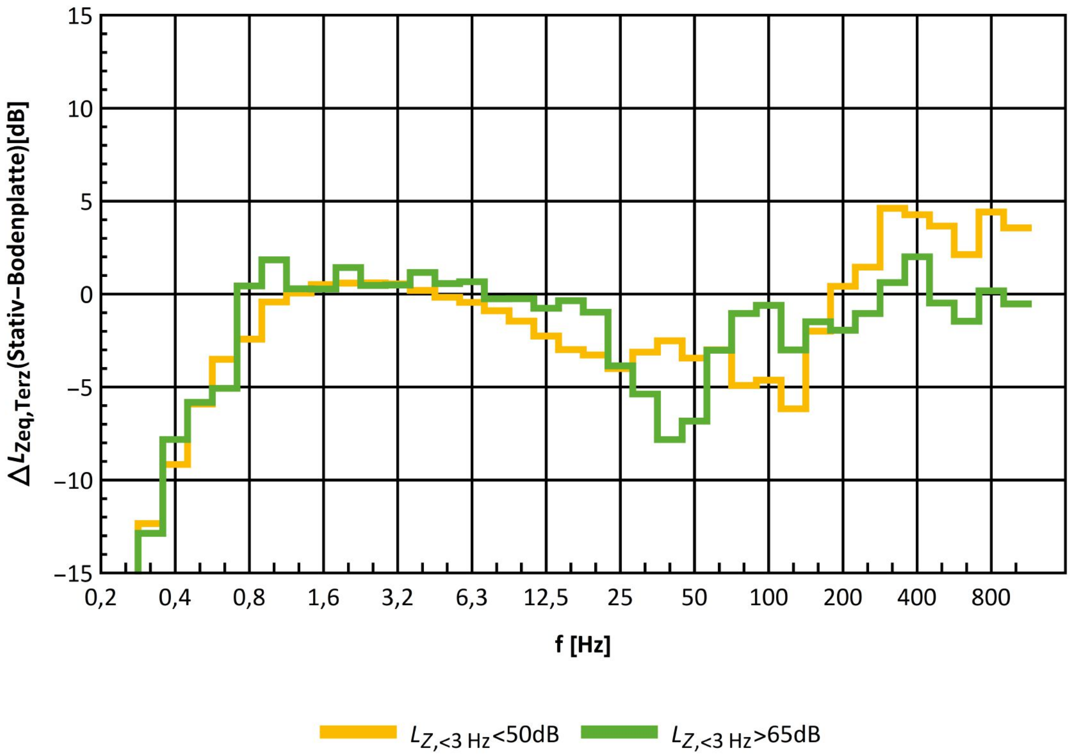
(Stativ–Bodenplatte) = (Tripod–Ground plate); Wg = Wind speed

F.3.3 Further difference spectra when using different microphones

As part of the comparison of the tripod-mounted Class-1 microphone and the infrasound microphone on the ground, a variety of difference spectra were created for purposes of an in-depth analysis. In Figure 141 and Figure 142, the difference spectra are classified based on the level $L_{Zeq,<3Hz}$ on the ground plate. The transfer function is scarcely dependent on the level at a very low local wind speed (Figure 141). In Figure 142, it can be seen that if local wind speed is somewhat higher, the spectra respond more sensitively to wind at low levels than they do at high levels. The contributions due to wind are thus energetically additive to the actual infrasound present; these contributions do not have a blanket amplifying effect.

In Figure 143 to Figure 147, different percentiles in the difference spectra are presented for different classes of local wind speed.

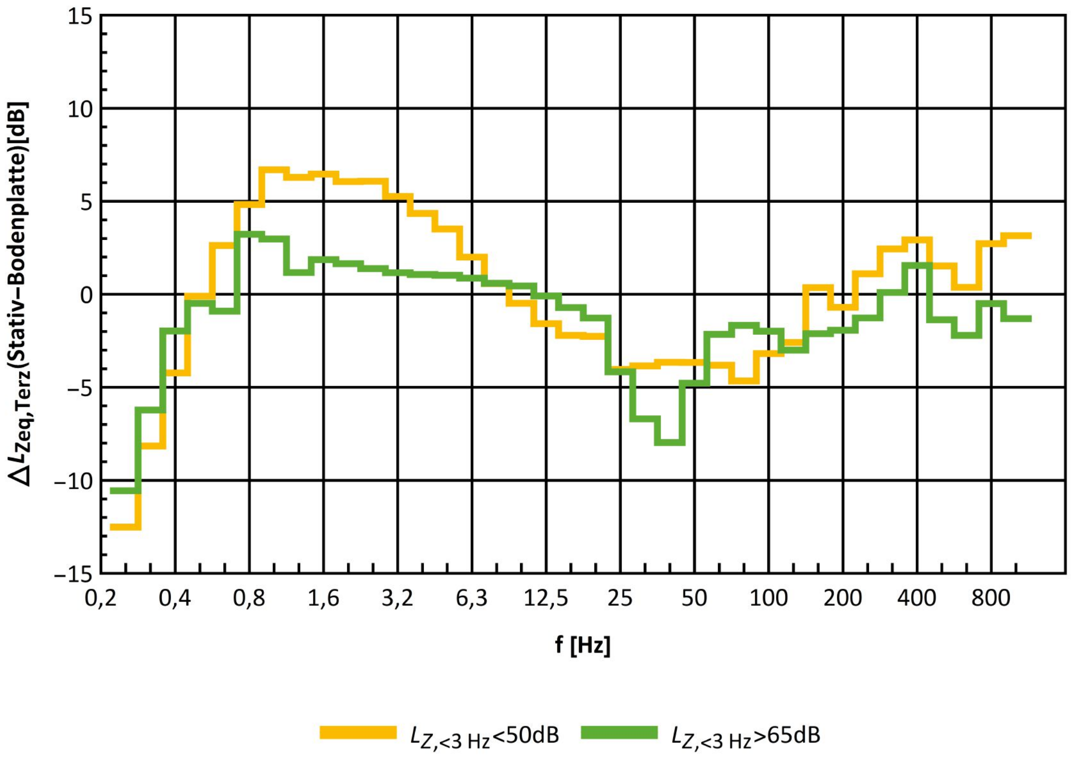
Figure 141: Difference spectrum (tripod-ground plate) for small and large levels at wind speed of 0-1m/s



Source: own presentation, Dr. Kühner GmbH

(Stativ–Bodenplatte) = (Tripod–Ground plate)

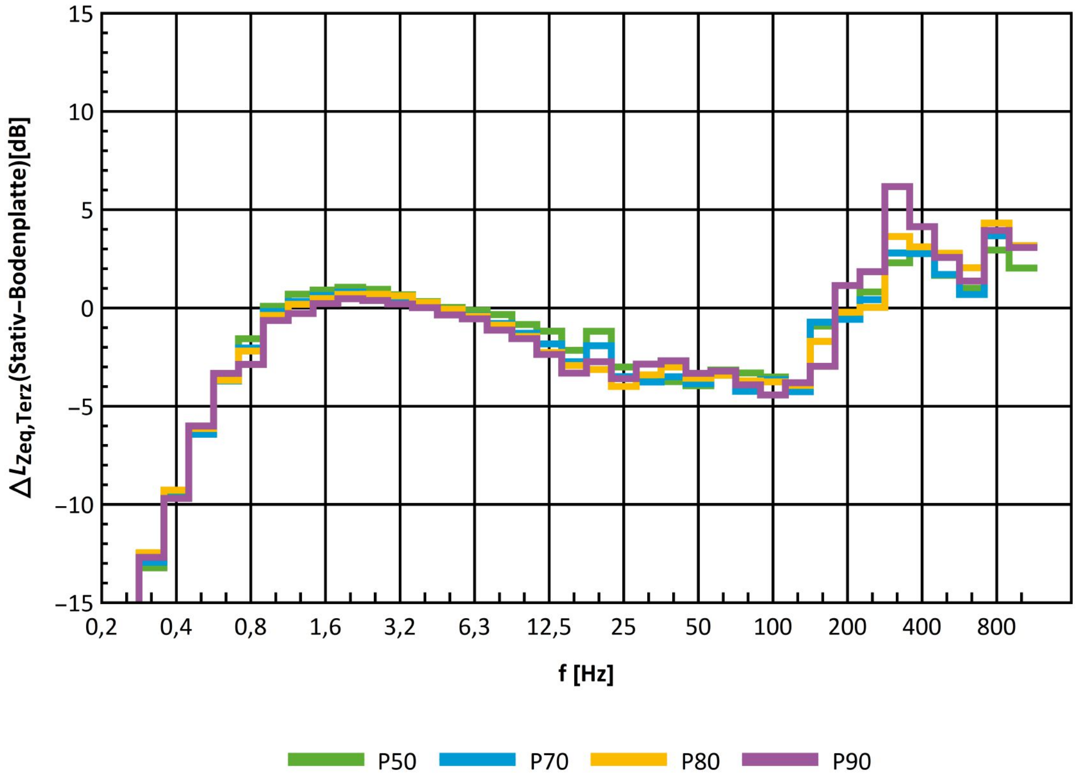
Figure 142: Difference spectrum (tripod-ground plate) for small and large levels at wind speed of 1-2 m/s



Source: own presentation, Dr. Kühner GmbH

(Stativ–Bodenplatte) = (Tripod–Ground plate)

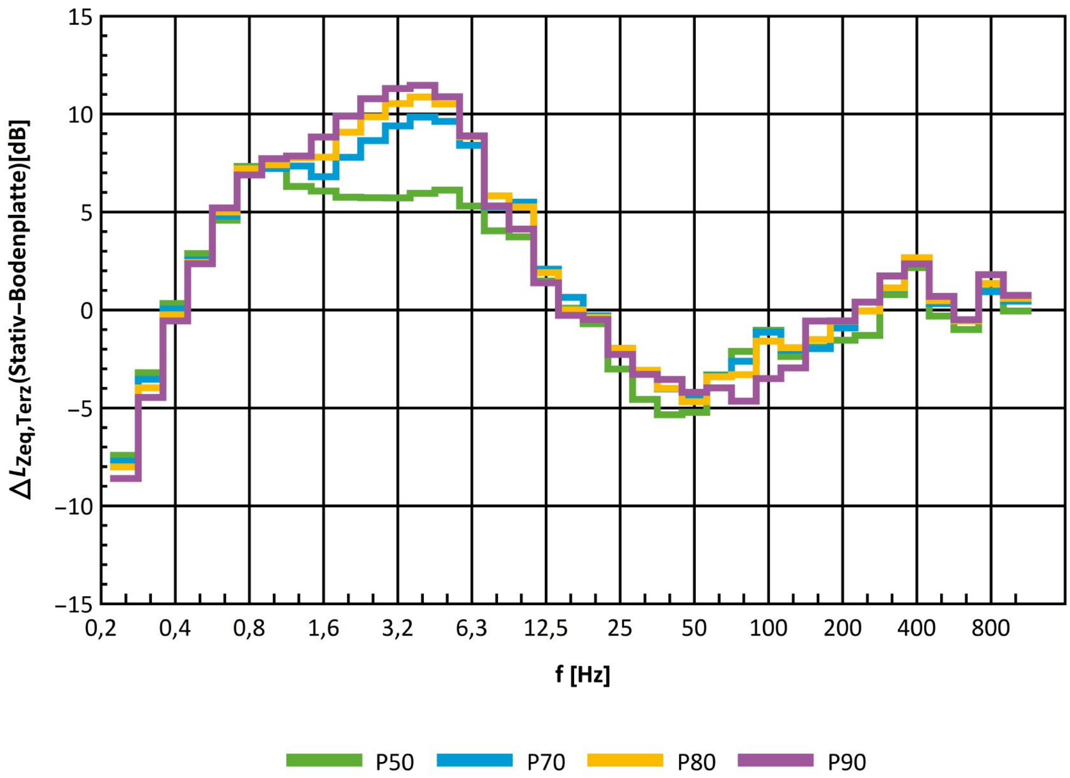
Figure 143: Difference spectrum (tripod-ground plate), wind speed 0-1 m/s



Source: own presentation, Dr. Kühner GmbH

(Stativ–Bodenplatte) = (Tripod–Ground plate)

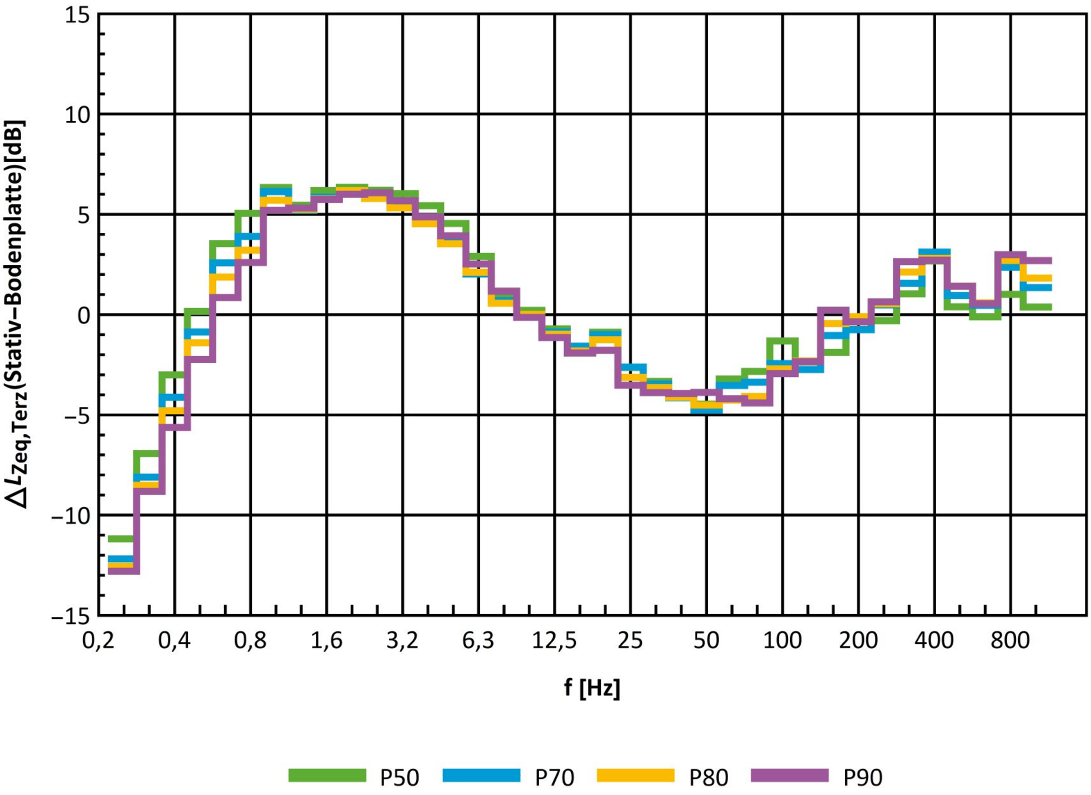
Figure 144: Difference spectrum (tripod-ground plate), wind speed 1-2 m/s



Source: own presentation, Dr. Kühner GmbH

(Stativ–Bodenplatte) = (Tripod–Ground plate)

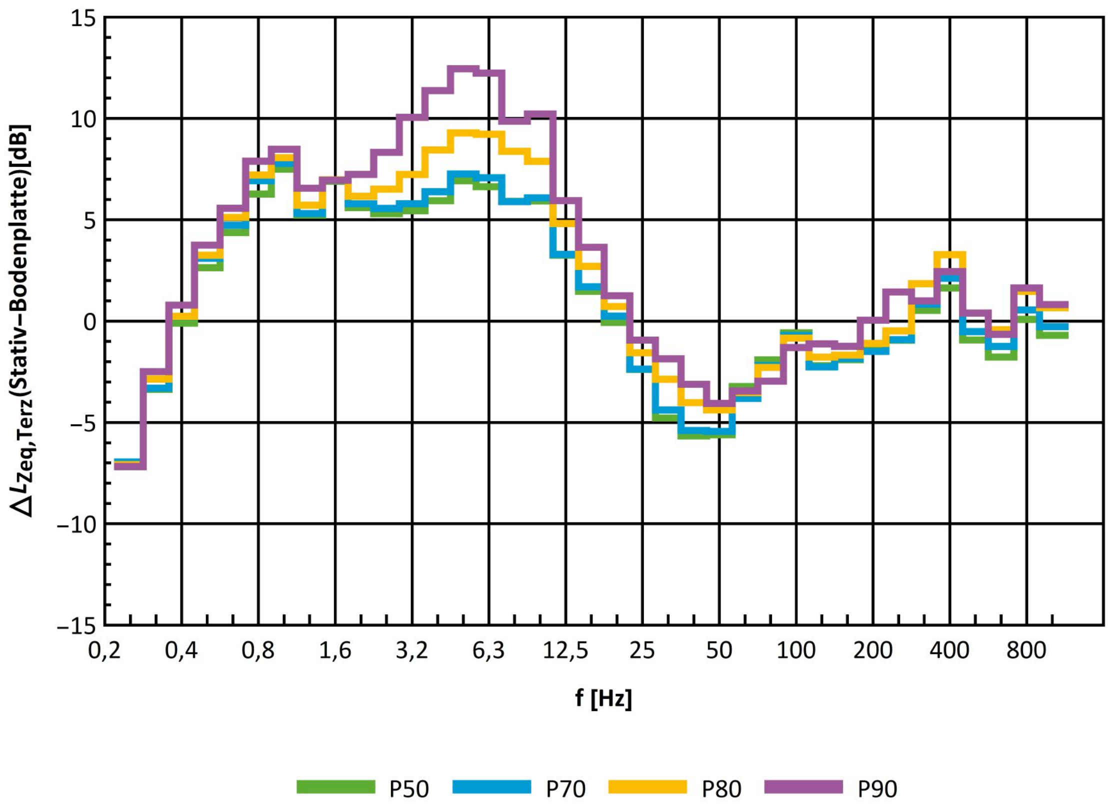
Figure 145: Difference spectrum (tripod-ground plate), wind speed 2-3 m/s



Source: own presentation, Dr. Kühner GmbH

(Stativ–Bodenplatte) = (Tripod–Ground plate)

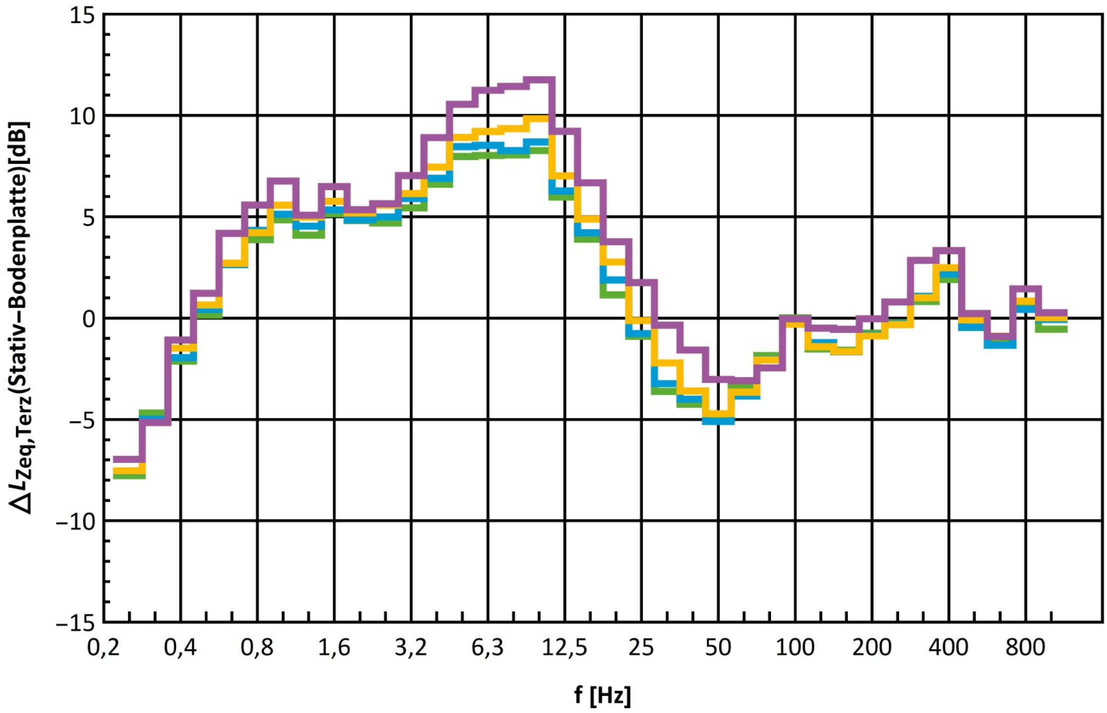
Figure 146: Difference spectrum (tripod-ground plate), wind speed 3-4 m/s



Source: own presentation, Dr. Kühner GmbH

(Stativ–Bodenplatte) = (Tripod–Ground plate)

Figure 147: Difference spectrum (tripod-ground plate), wind speed 4-5 m/s



Source: own presentation, Dr. Kühner GmbH

(Stativ–Bodenplatte) = (Tripod–Ground plate)

F.3.4 Uncertainties and confidence intervals

There are two methods available for use in determining the frequency response of the measurement with a Class-1 microphone on a tripod; their result is presented in Figure 148:

Based on the comparative measurements with the infrasound microphone on the ground plate.

The comparison of parallel measurements with a Class-1 microphone on a tripod and an infrasound microphone on a ground plate in SA 5 can be used here. The frequency response of the infrasound microphone is known based on pressure-chamber measurement; additionally, the difference spectrum for the smallest wind strengths from

- Figure 52 (or one of the other percentiles in Figure 143) can be used in the manner of a transfer function.

- Based on pressure-chamber measurement of the Class-1 microphone.

  A second way to account for the frequency response of the tripod-mounted Class-1 microphone is to use the result of the pressure-chamber measurement (see Appendix F.1.2).

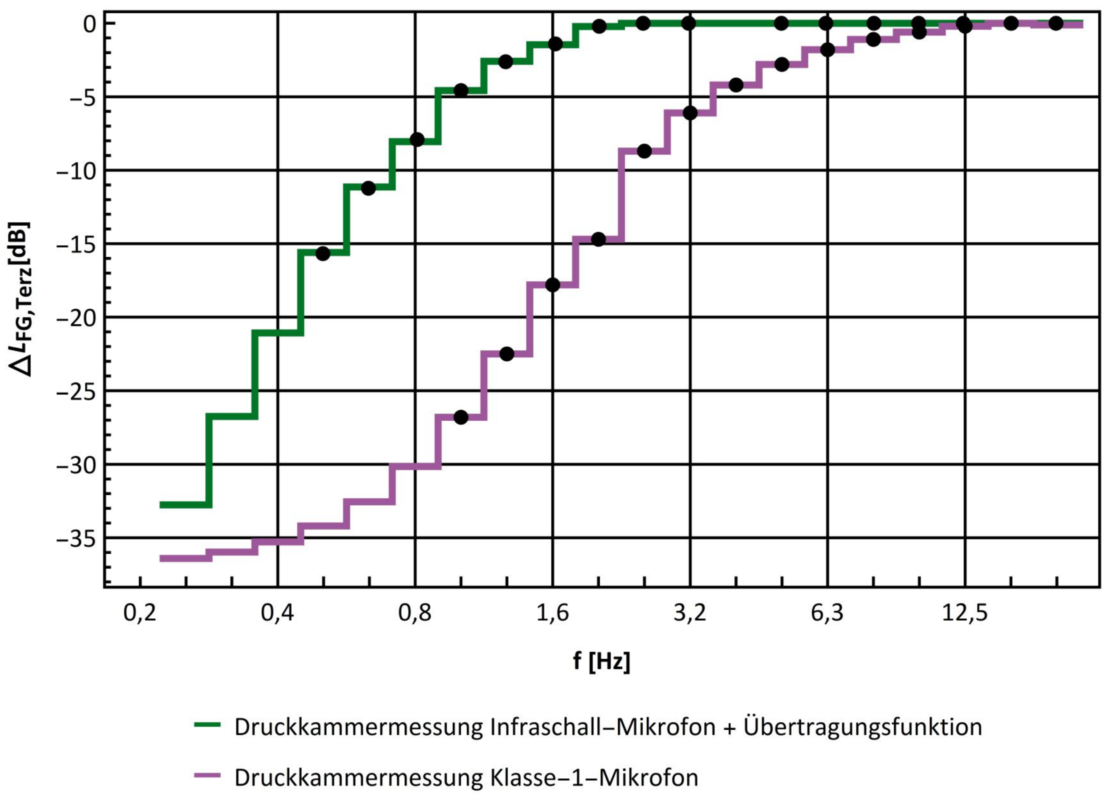
The results for the possible frequency response using both approaches are presented in Figure 148. Obviously, there is a considerable difference between the frequency responses determined using the two approaches. This discrepancy extends the confidence interval for measurement results obtained with the Class-1 microphone, as shown in Figure 149.

Because the cause of the discrepancy between the two methods for determining the frequency response of the Class-1 microphone is unclear, a corresponding uncertainty must also be assumed for measurements taken using the ground plate. The corresponding confidence intervals are presented in Figure 150.

Since no bass calibration is available for the smallest frequency bands, and since the frequency responses are only extrapolated, the data on confidence intervals for frequencies of less than 1 Hz are only rough reference values.

Figure 148: Effective frequency response, Class-1 microphone on tripod

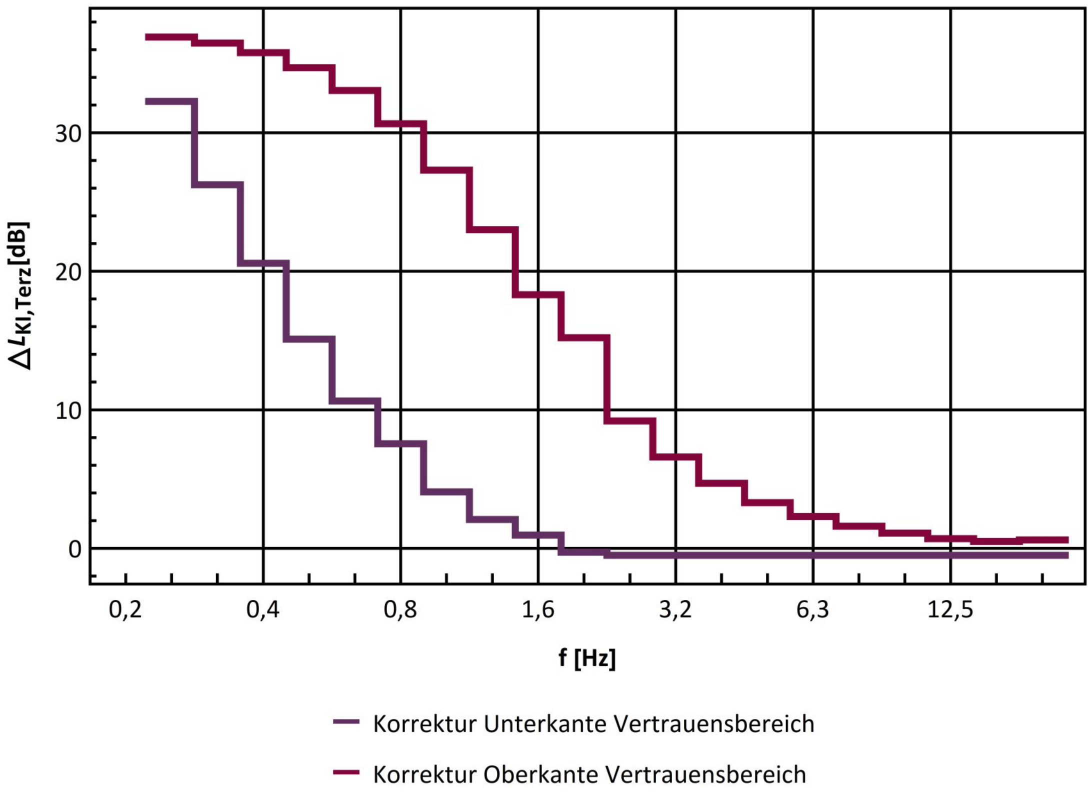
Data from pressure-chamber measurements exist for one-third-octaves with a black dot; one-third-octaves shown without a black dot are extrapolated.



Source: own presentation, Dr. Kühner GmbH

Terz = One-third-octave; Druckkammermessung Infraschall-Mikrofon + Übertragungsfunktion = Pressure-chamber measurement infrasound microphone + transfer function; Druckkammermessung Klasse-1-Mikrofon = Pressure-chamber measurement Class-1 microphone

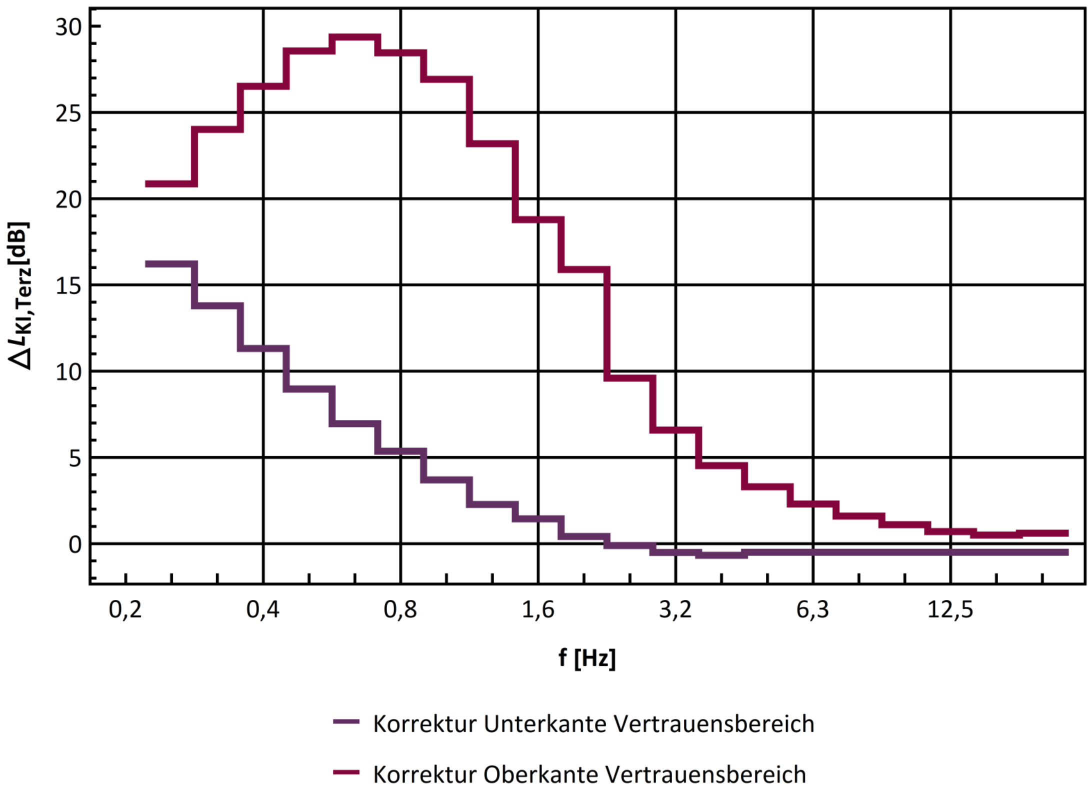
Figure 149: Confidence interval, Class-1 microphone on tripod



Source: own presentation, Dr. Kühner GmbH

Terz = One-third-octave; Korrektur Unterkante Vertrauensbereich = Correction lower limit confidence interval; Korrektur Oberkante Vertrauensbereich = Correction upper limit confidence interval

Figure 150: Confidence interval, infrasound microphone on ground plate



Source: own presentation, Dr. Kühner GmbH

Terz = One-third-octave; Korrektur Unterkante Vertrauensbereich = Correction lower limit confidence interval; Korrektur Oberkante Vertrauensbereich = Correction upper limit confidence interval