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Modular Fischer-Tropsch technologies for decentralized SAF production

G.Corre, R.Dittmeyer, P.Pfeifer, A.Navarette

Topsoe Catalysis Forum – Sustainable Aviation Fuel, 12th of September 2023

Institute for Micro Process Engineering

Outline

- Why Power-to-X and why „decentralized“?
- Evaporation-cooled micro reactors for Fischer-Tropsch synthesis
- Scaling up and integration in process chains
- From FT-crude to SPK
- Outlook

The Guardian, 21 Sep 2019, The best climate strike signs from around the globe in pictures. A sign held by a protester in London depicts global heating. Photograph: Will Oliver/EPA

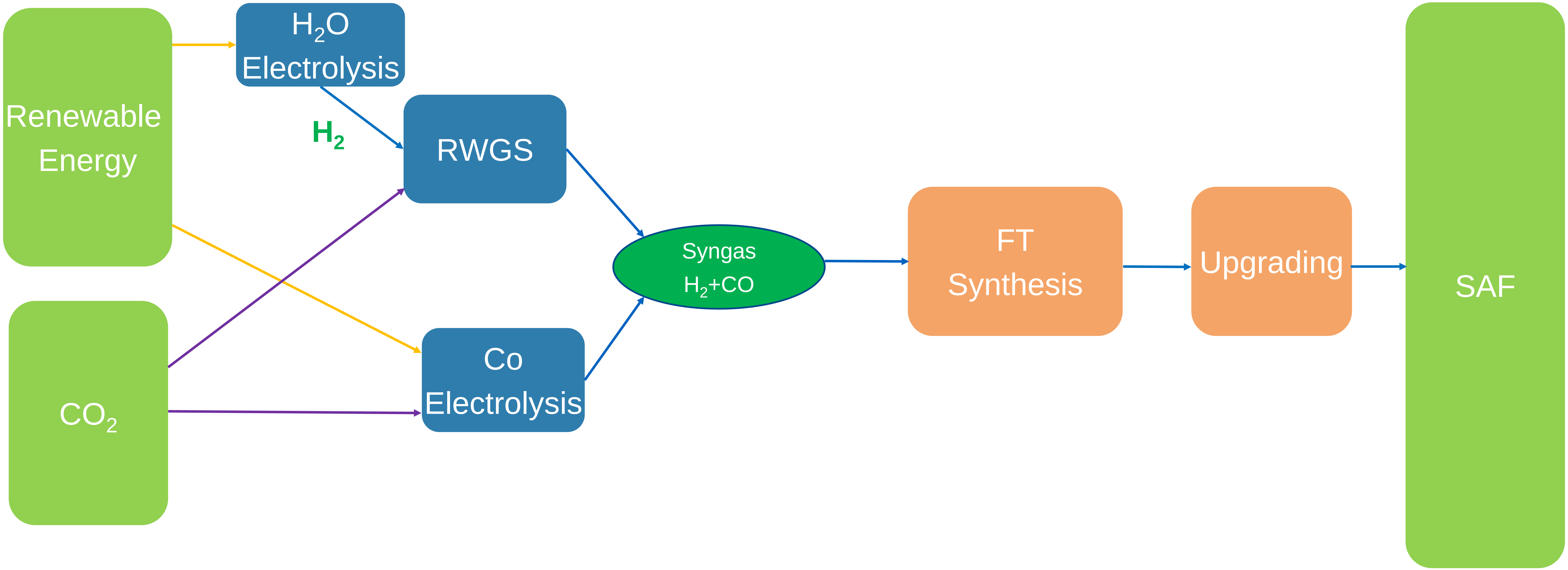
Key priorities for the next decades

- **Reduce GHG (CO_2, CH_4, etc.) emissions quickly and deeply, and prepare for deployment of NETs** to compensate for the unavoidable emissions as well as to clean up the atmosphere (nature-based solutions, BECCS, DACCS)
- **Build up renewable power generation fast(er) and on global scale. Don't forget about energy storage and transport.**
- **Use the „CO_2-free“ electrons as efficient as possible**
  - Direct electrification where possible (heating, engines…)
  - More efficient technologies for „circular carbon“ synthetic fuels and chemicals from air (via Power-to-X); This includes electro and eventually plasma catalysis for CO_2-neutral fuels & chemicals
- **Reduce consumption (where possible) and change habits**

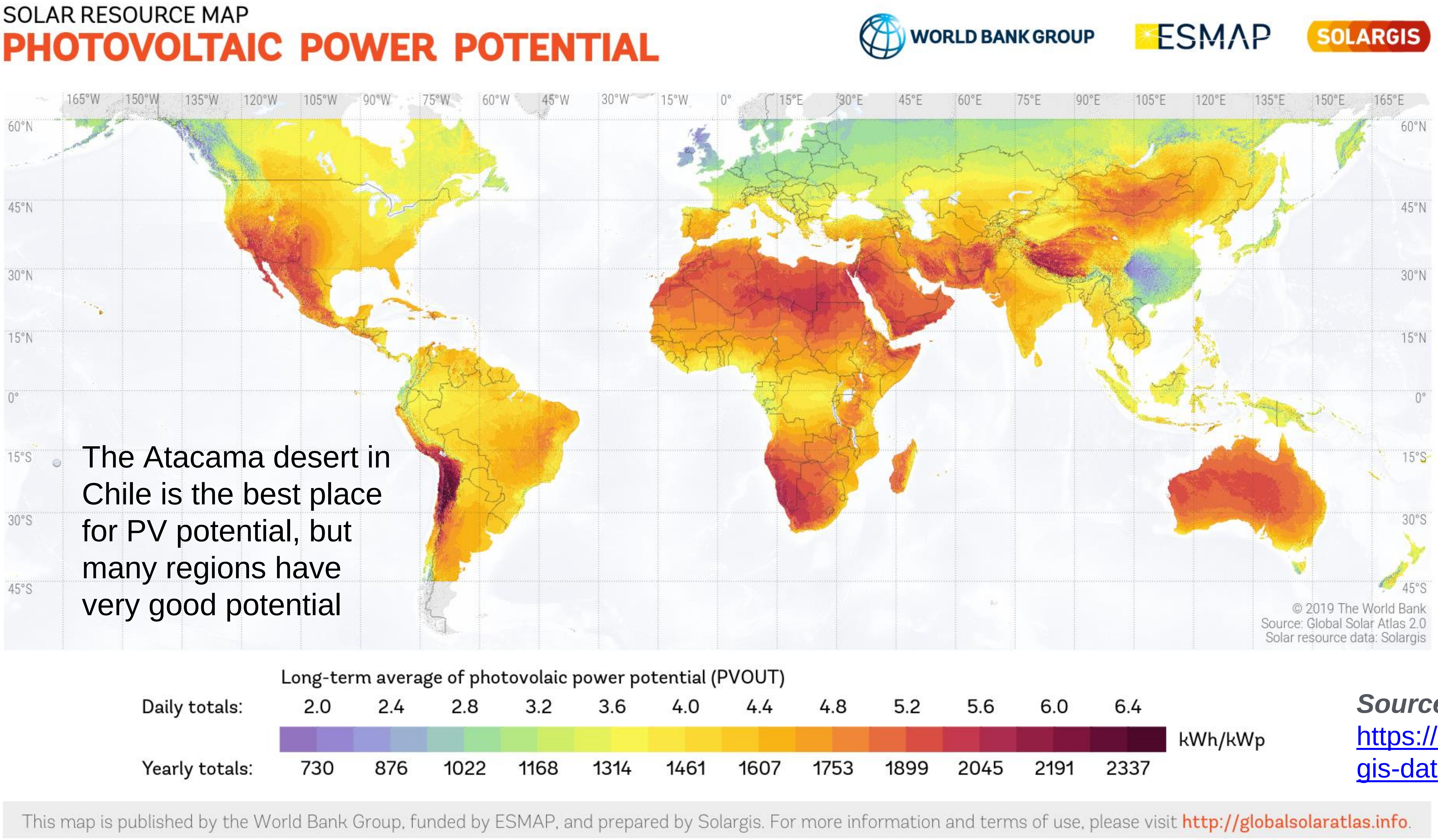
Source: United Nations (https://www.un.org/en/sustainable-development-goals)

BECCS: Bioenergy with Carbon Capture and Storage (CO_2-Capture by biomass and energetic use of that biomass while capturing the produced CO_2 from the effluent for purification and permanent storage)
DACCS: Direct Air Capture and Carbon Storage (CO_2-Capture from the atmosphere with permanent storage)

From CO_2 + renewable electricity to SAF



Potential of renewable energy - Solar

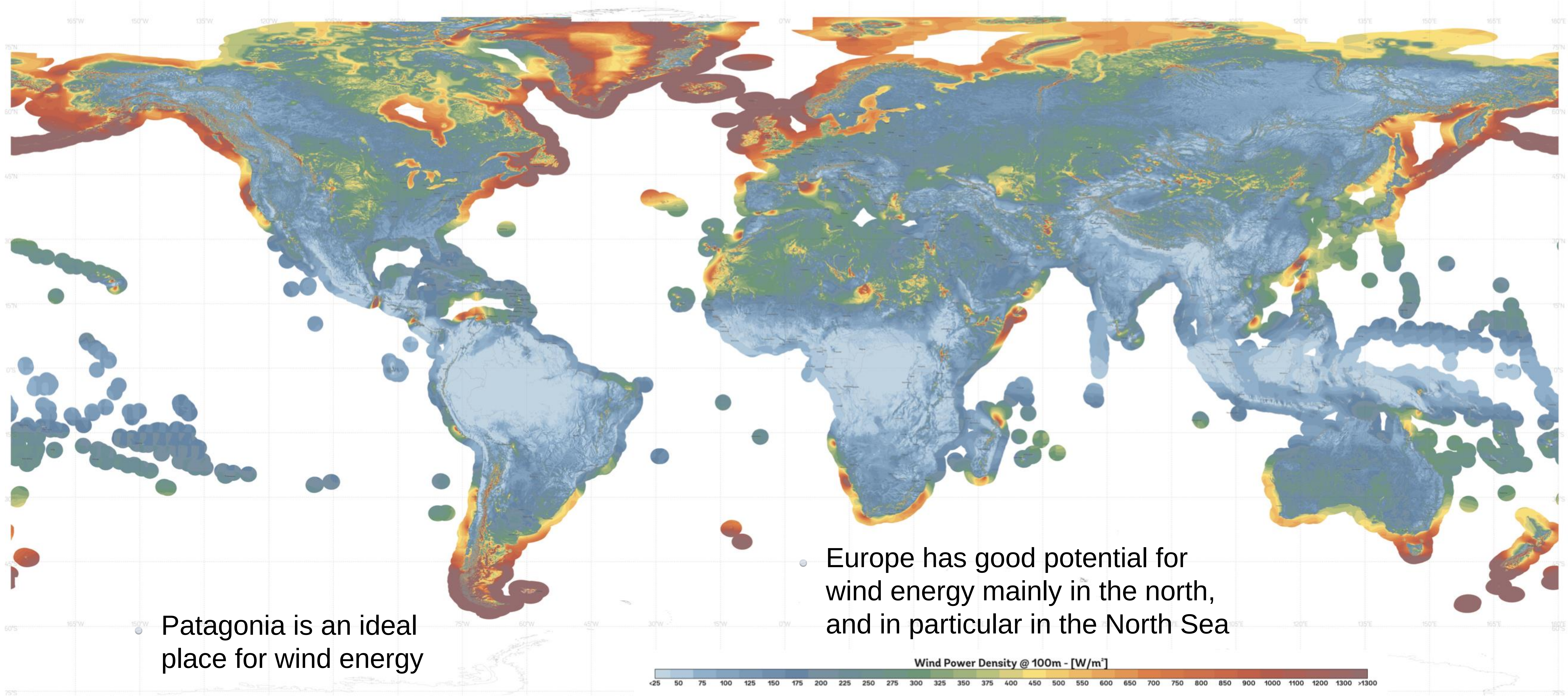


- The Atacama desert in Chile is the best place for PV potential, but many regions have very good potential

- Europe, and even more so Germany, is not privileged when it comes to solar PV potential
- Nevertheless, PV will be massively extended in the south of Germany as well as in the Mediterranean to help decarbonizing the German / European power sector

Source: https://solargis.com/maps-and-gis-data/download/world

Potential of renewable energy - Wind



- Europe has good potential for wind energy mainly in the north, and in particular in the North Sea
- Patagonia is an ideal place for wind energy

Source: https://globalwindatlas.info/download/high-resolution-maps/World

Two types of PtX-plants for different uses

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- **Large plants at sweet spots for renewable energy running 24/7 at high capacity powered by large wind parks and / or solar PV farms**
  - no grid connection
  - high capacity utilization through intermediate storage
  - ideal locations have both, wind and solar radiation, as there is no sun at night :-)

- **Flexible medium-sized plants at good locations for renewable energy**
  - to limit power grid expansion requirements
  - to stabilize power grids
  - to optimize the energy system with regards to economics and/or GHG footprint
  - to reduce the dependency on energy imports and increase resilience

taz archiv 5.4.2022

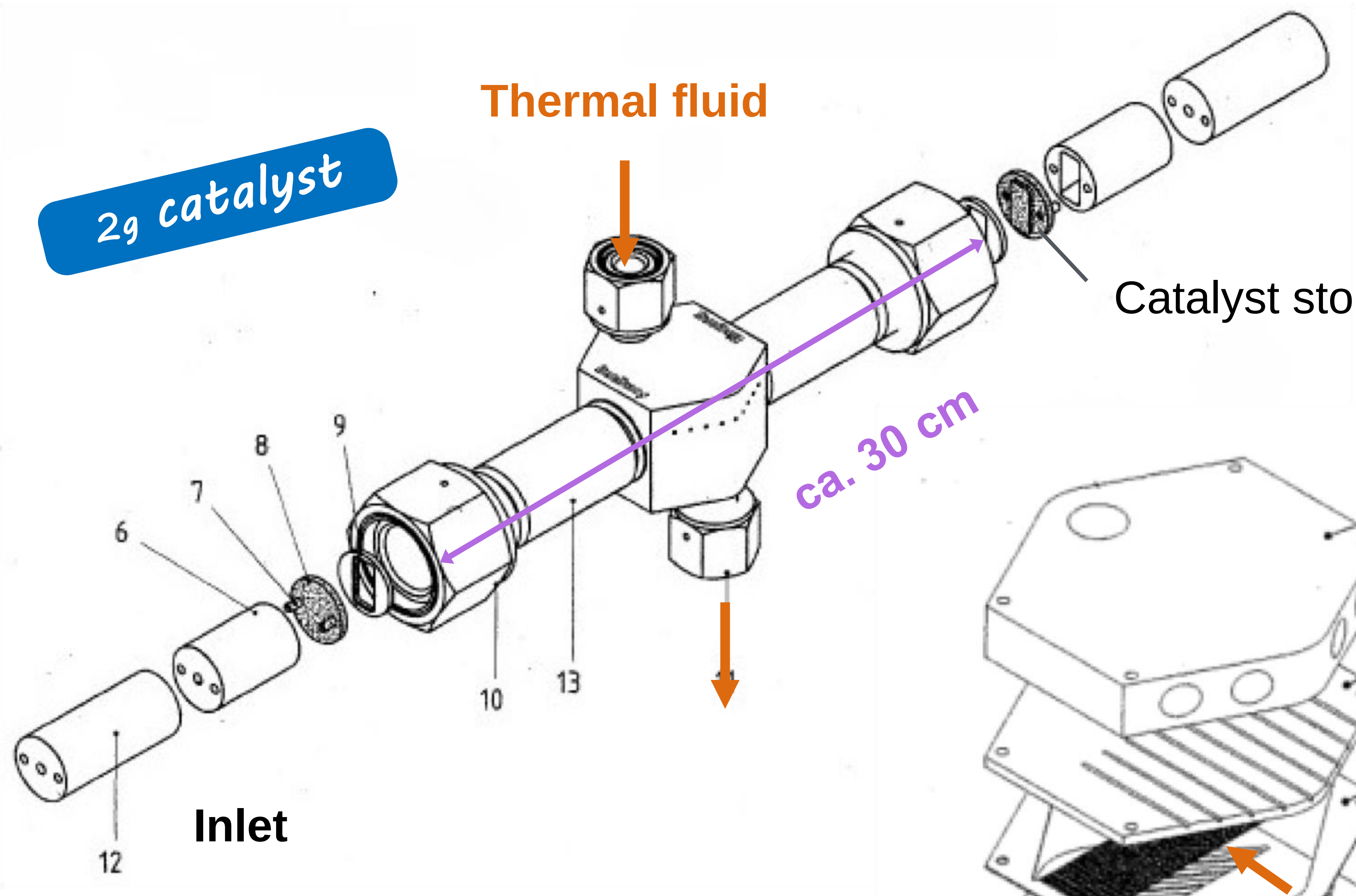
A Windrad a day keeps Putin away

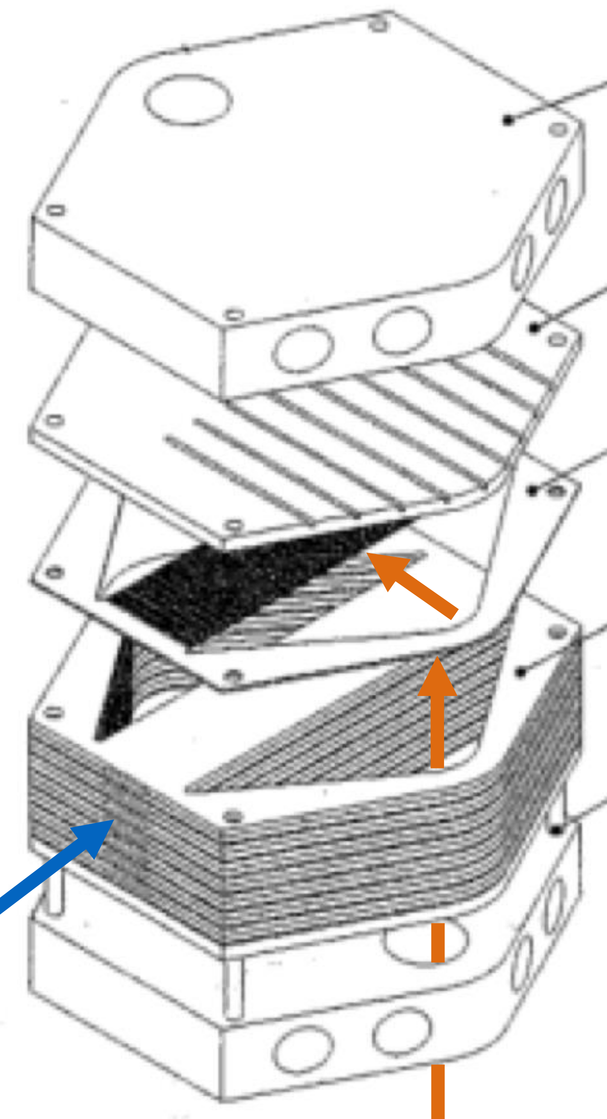
„Eile geboten“: Klimaminister Habeck und Umweltministerin Lemke forcieren den Ausbau der Windkraftanlagen in Deutschland, um schneller unabhängig von russischer Energie zu werden – auch wenn Windräder im Wald neue Probleme schaffen

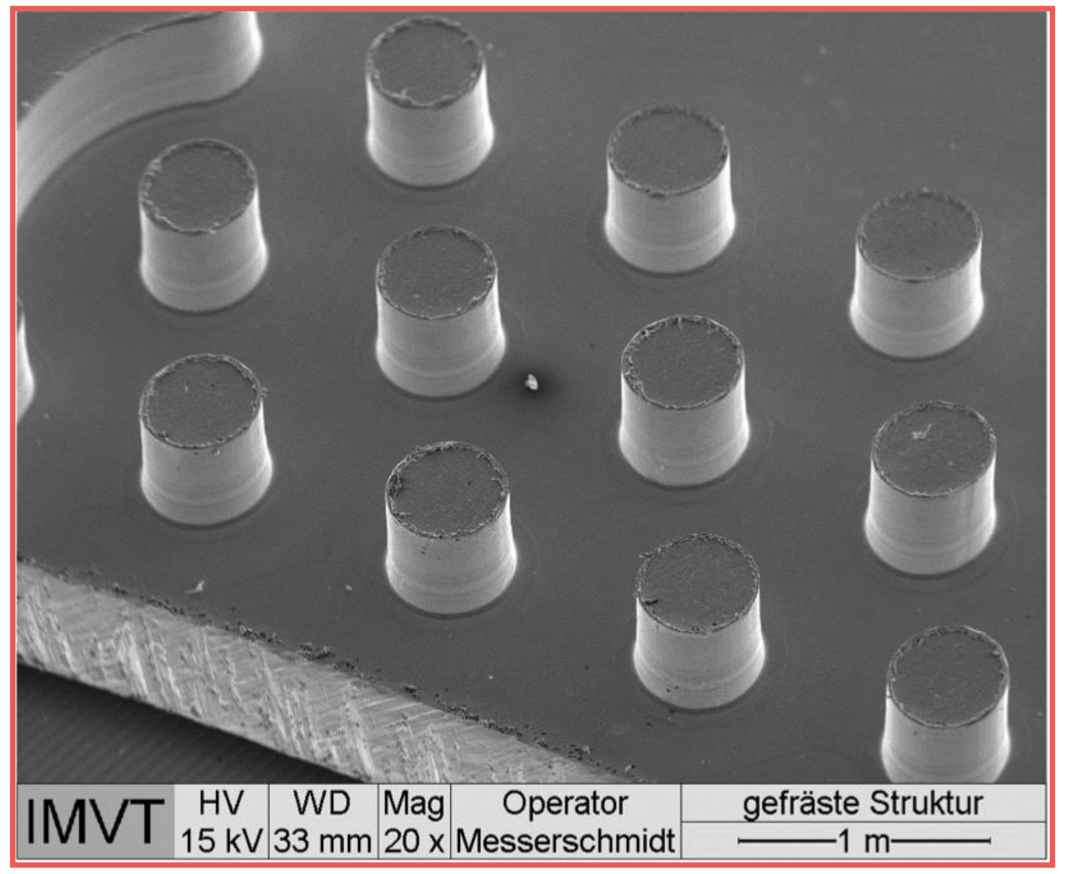
4–5, 8

Microstructured reactors - key technology for gas conversion in PtX

Basic concept - lab system







see also: Myrstad et al., *Catal. Today* **2009**, *1475*, 301-304.

Productivity and Space-Time-Yield

	Productivity (C_{5+} per catalyst mass)	Productivity (C_{5+} per reactor mass)	Space-Time-Yield (C_{5+} per reactor volume)
KIT (IMVT)	2.1 g/gh	16.7 bpd/t	1785 kg/m³h
velocys	-	13 bpd/t [1]	1600 kg/m³h [1]
Oryx GTL - Sasol	-	8 bpd/t [2]	20.6 kg/m³h [1]
Literatur	1.4 - 2 g/gh [3]	-	-

1) S. LeViness, FT Product Manager, Presentation "Velocys Fischer-Tropsch Synthesis Technology – Comparison to Conventional FT Technologies", AIChE Spring Meeting, San Antonio, Texas/USA (30-Apr-2013)

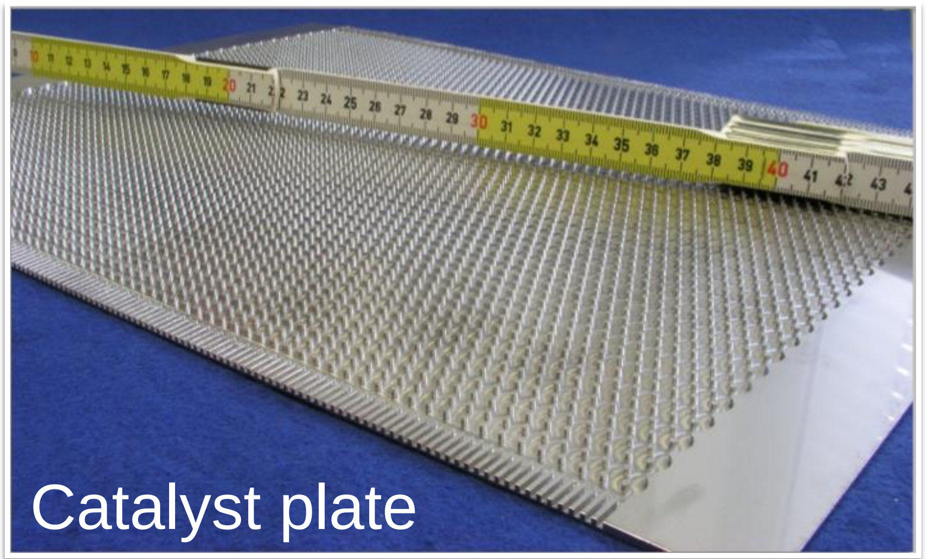
2) "2012 Interim Results", Presentation to analysts of the Oxford Catalysts Group 2012, www.velocys.com

3) C.H. Bartholomew, B. Young, History of Cobalt Catalyst Design for Fischer-Tropsch Synthesis, NGCS, Doha 2013

Microstructured reactors - key technology for gas conversion in PtX

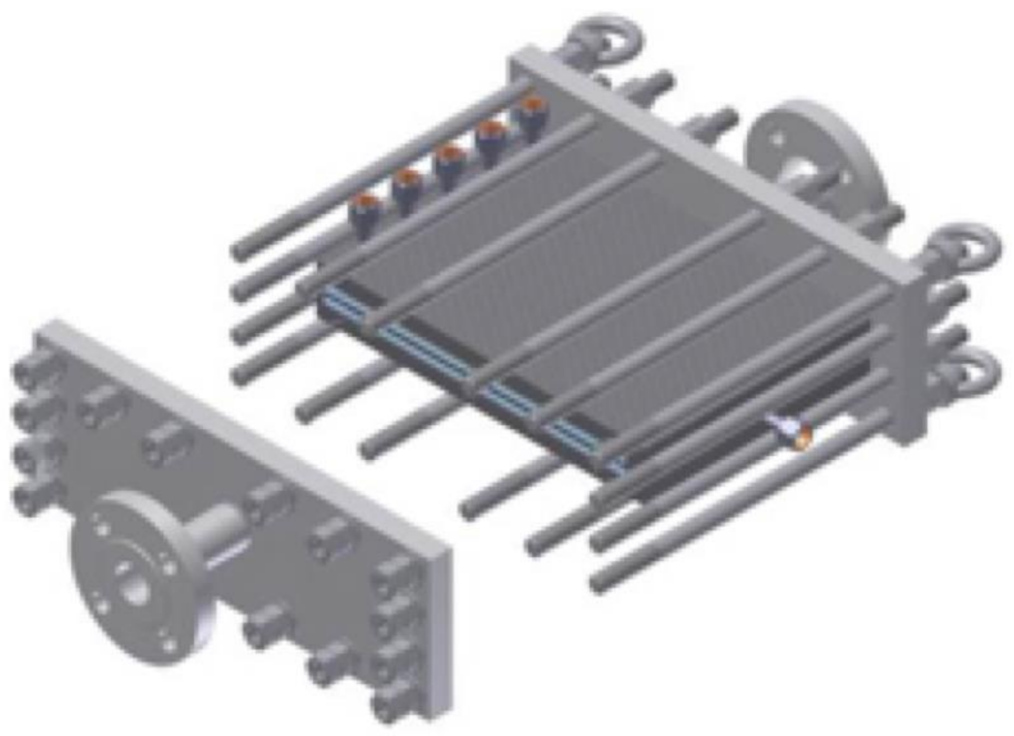
Validation and Scale-up

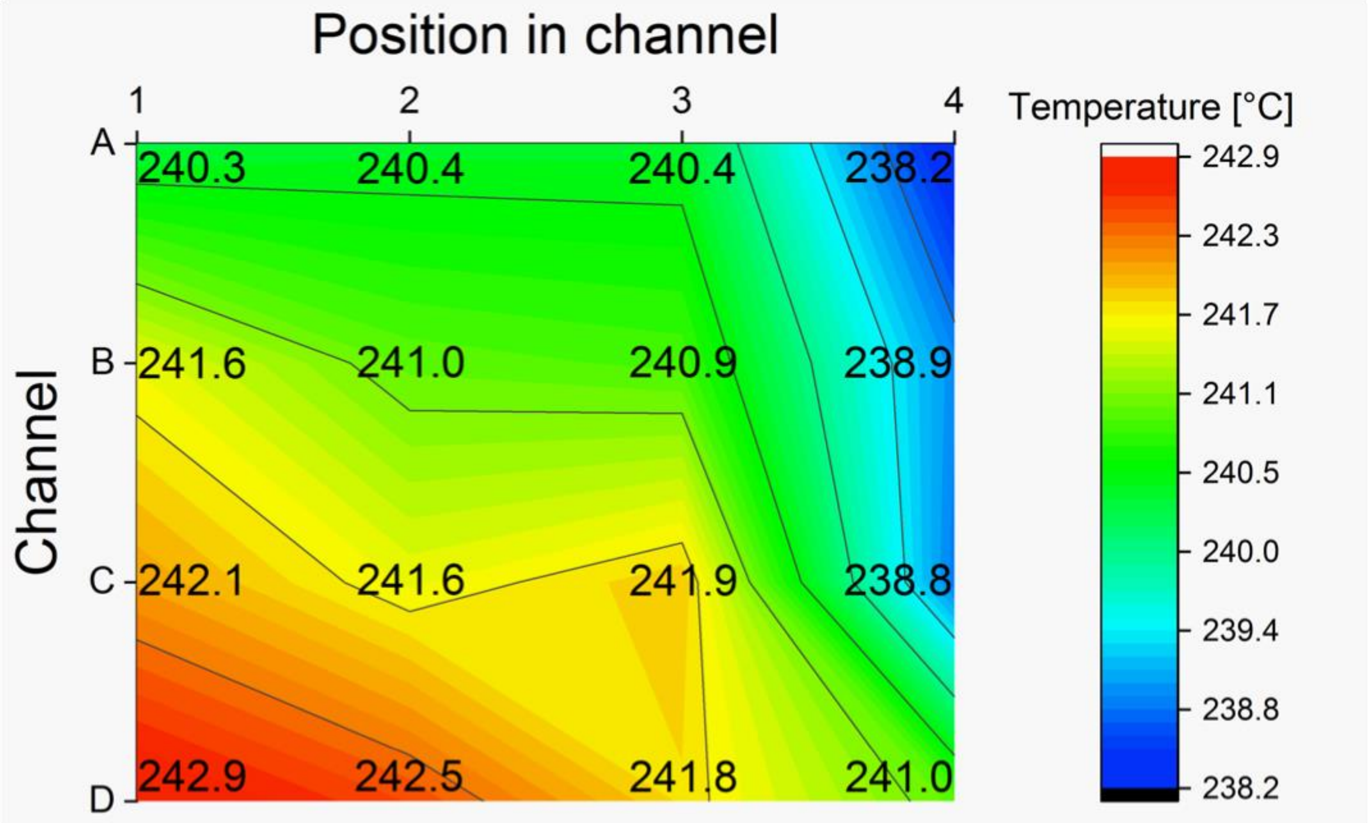
IMVT / INERATEC



Catalyst is applied as powder(50 - 200 µm) and is not diluted with inerts

- Cooling by closed water/steam-cycle (20-40 bar)
- 30-40 l/min Synthesis gas
- 5 kg/d FT Products





see also: www.ineratec.com

R. Dittmeyer et al., *Curr. Opin. Chem. Eng.* **2017**, *17*, 108-125. doi:10.1016/j.coche.2017.08.001

Process development

FTS - HC Pilot plant

FTS Pilot plant

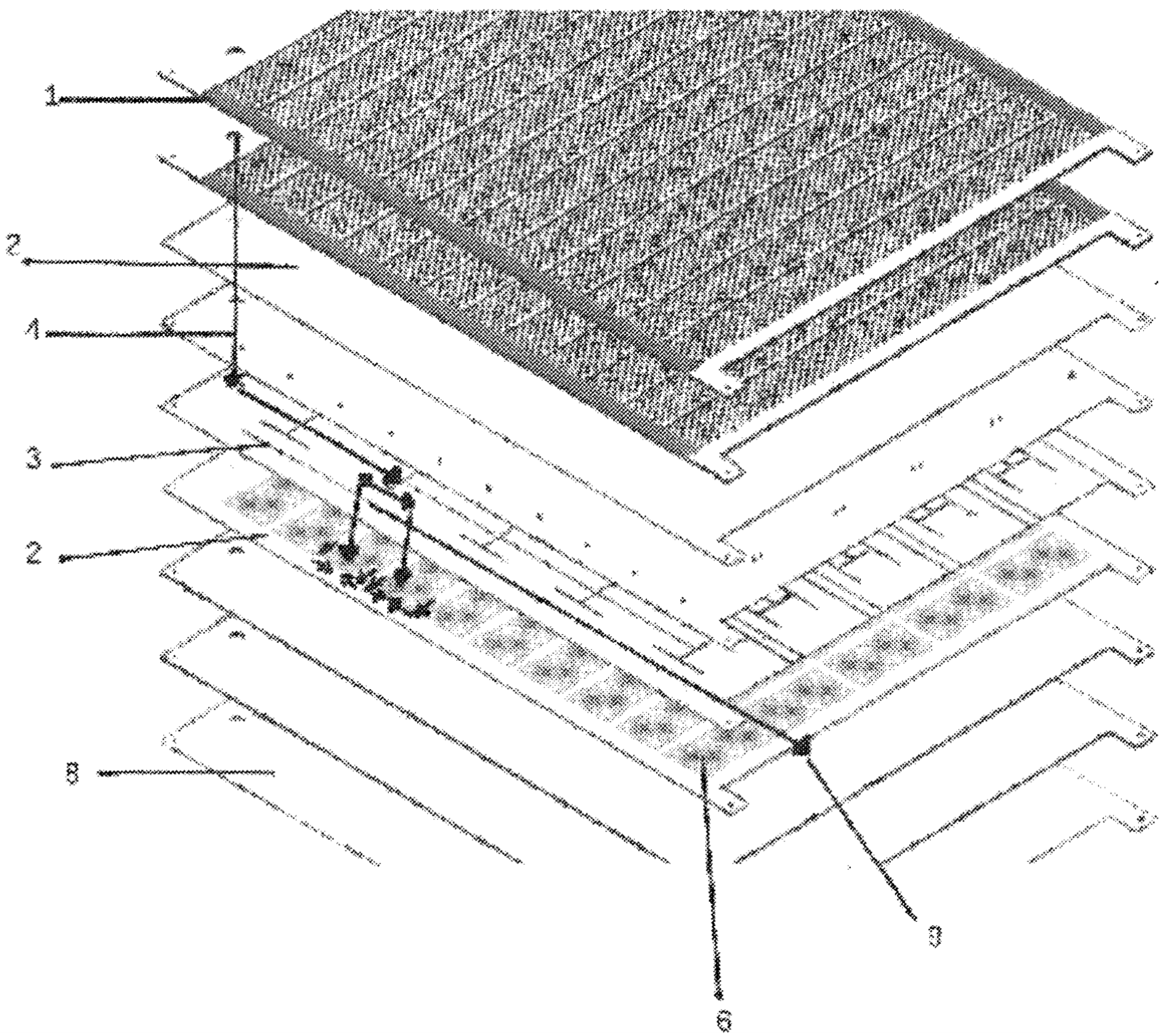
RWGS Pilot plant

Complete process chain from CO_2 to synthetic fuel (5 kg per day)

Combustion tests performed at DLR Stuttgart

Design principle of the evaporation-cooled microreactor

Basic stacking scheme



2 stacked reaction sheets (packed bed)

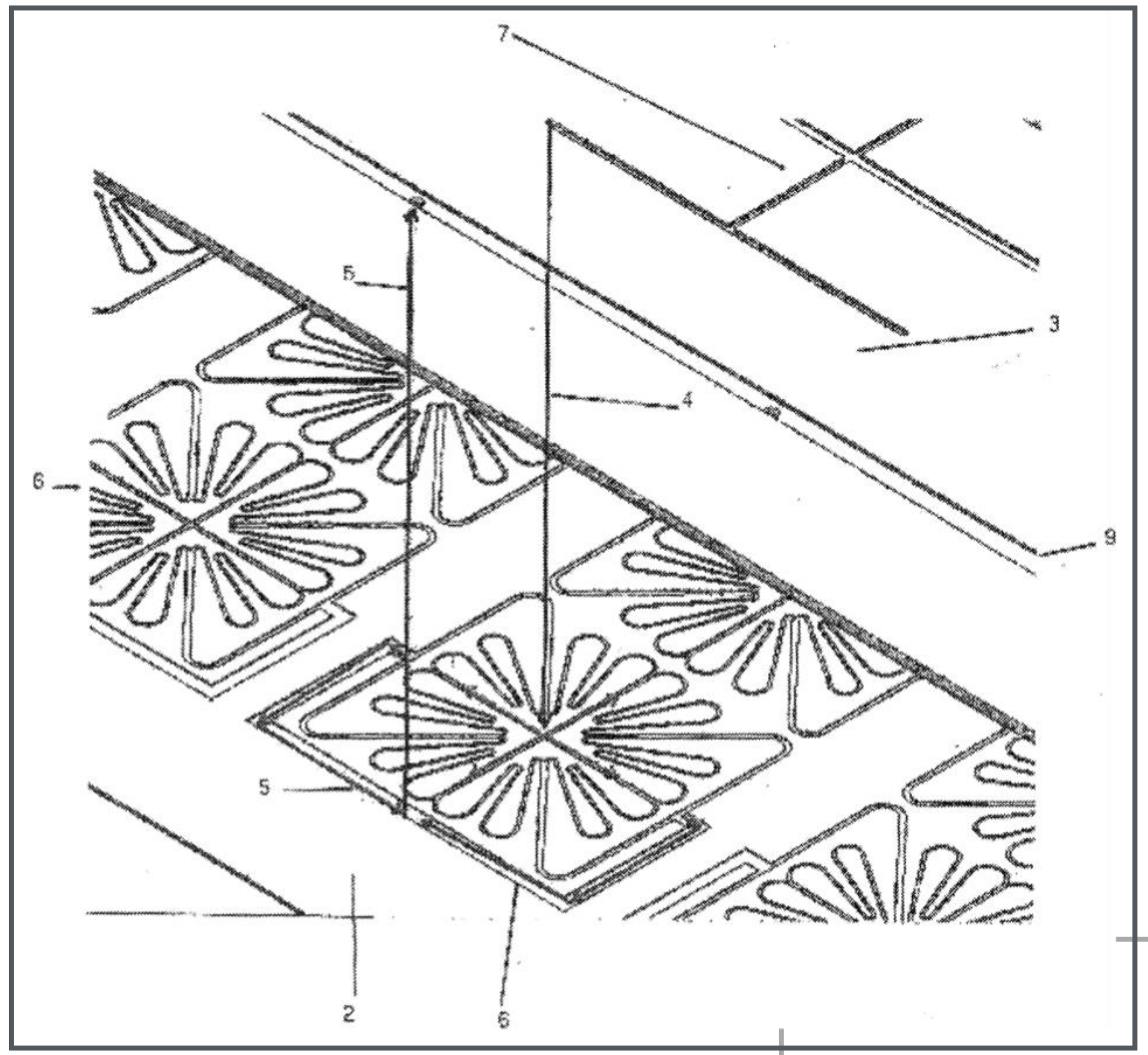
cooling sheet

2 stacked coolant distribution sheets

cooling sheet

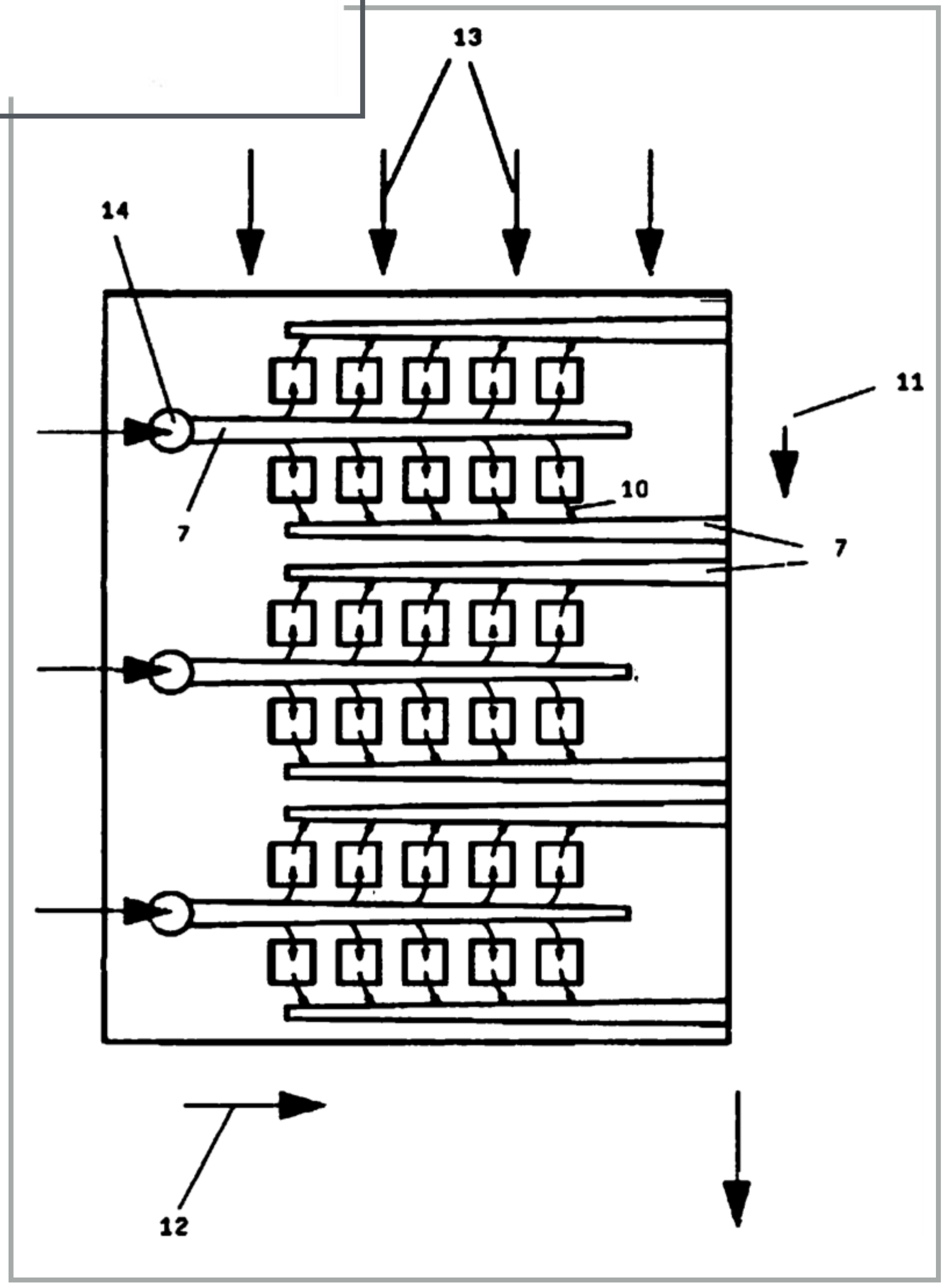
2 stacked reaction sheets

termination sheet



Detail of evaporation section

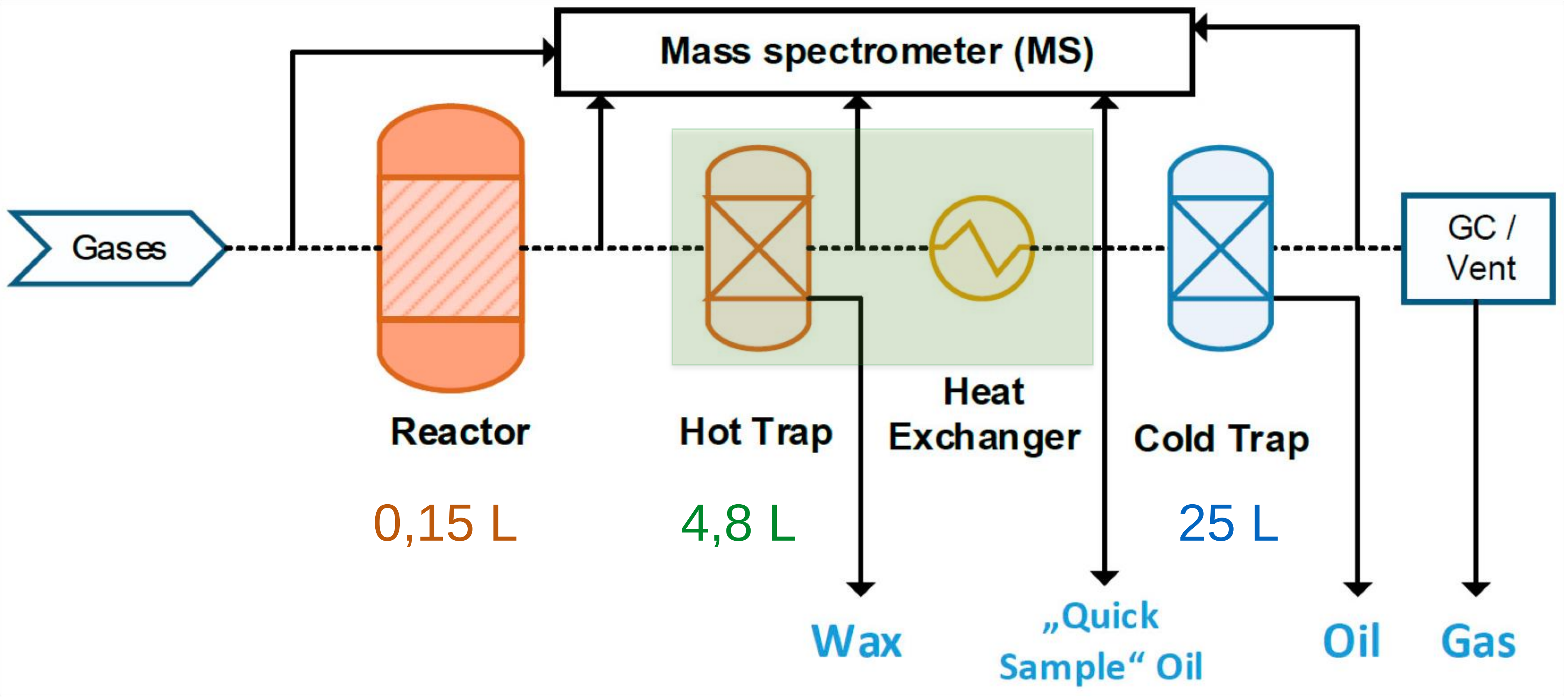
Arrangement of reactant and coolant flows in the stack



P. Pfeifer, P. Piermartini, A. Wenka, **2017**, *DE 10 2015 111 614 A1*

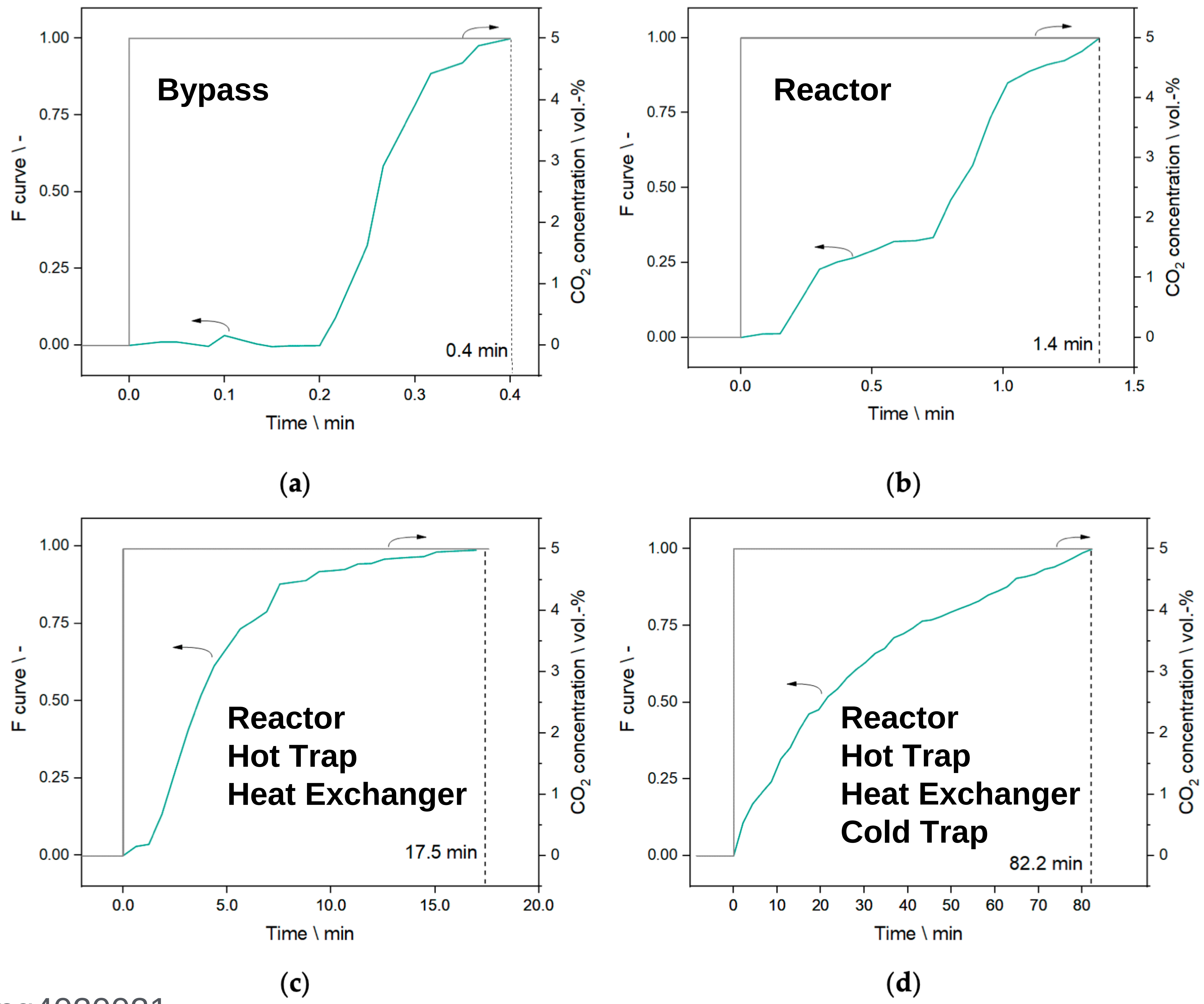
Studies on transient operation of the bench-scale FTS unit

Lab setup



Dissertation
Marcel Löwert,
KIT, 2021

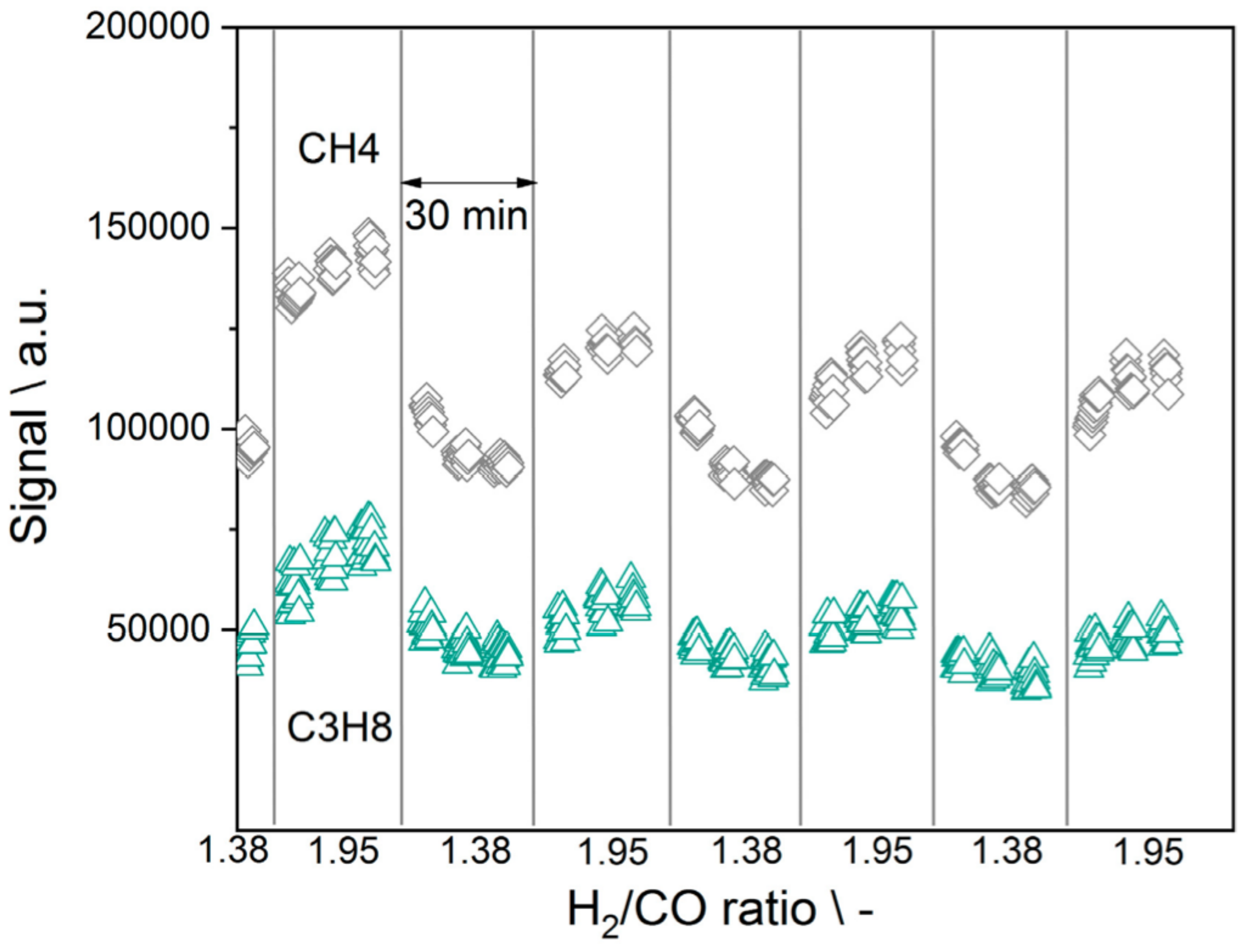
RTD in non-reactive mode - F curves

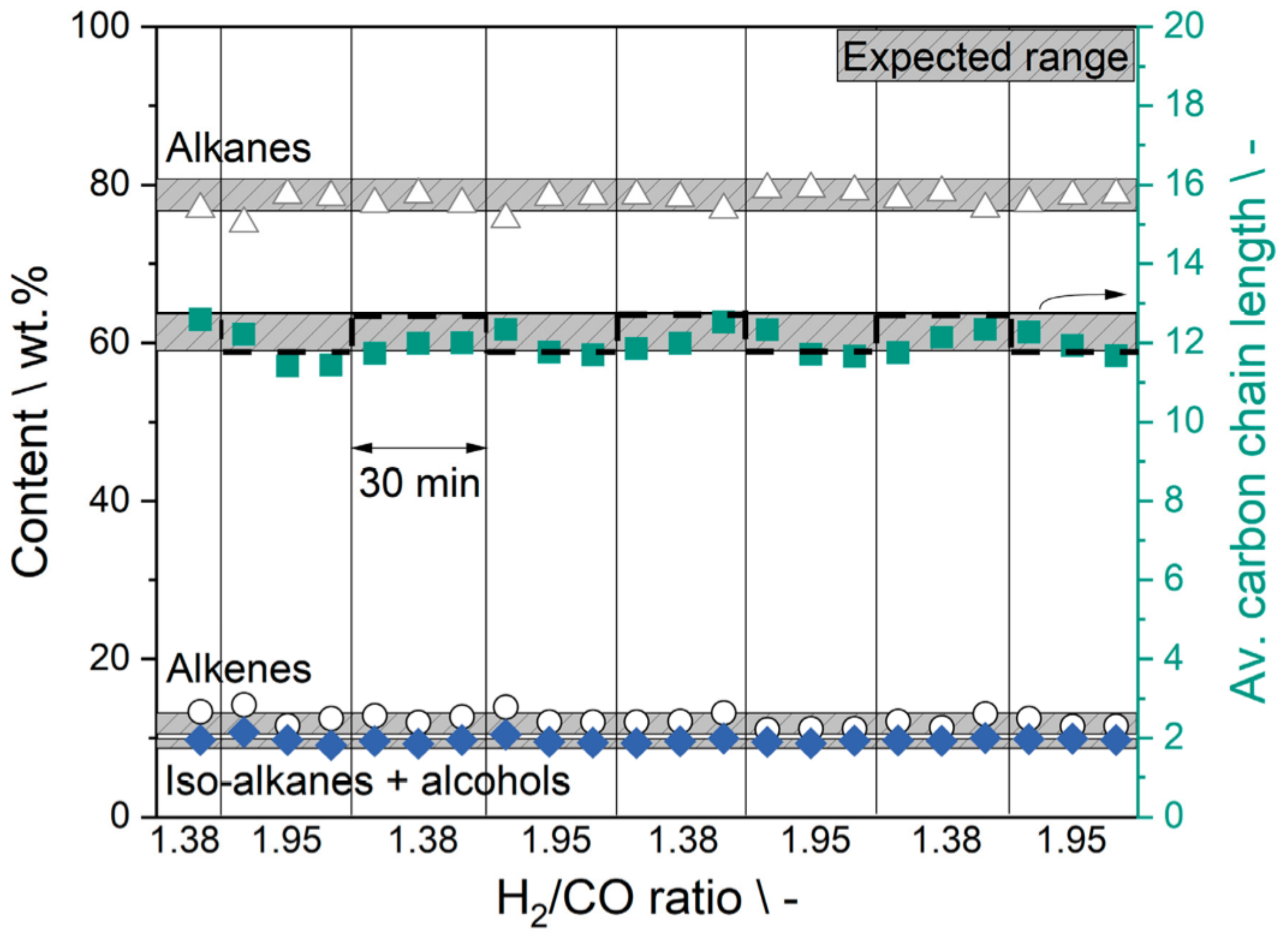


M. Löwert, P. Pfeifer, *ChemEngineering* **2020**, *4*, 21; doi:10.3390/chemengineering4020021

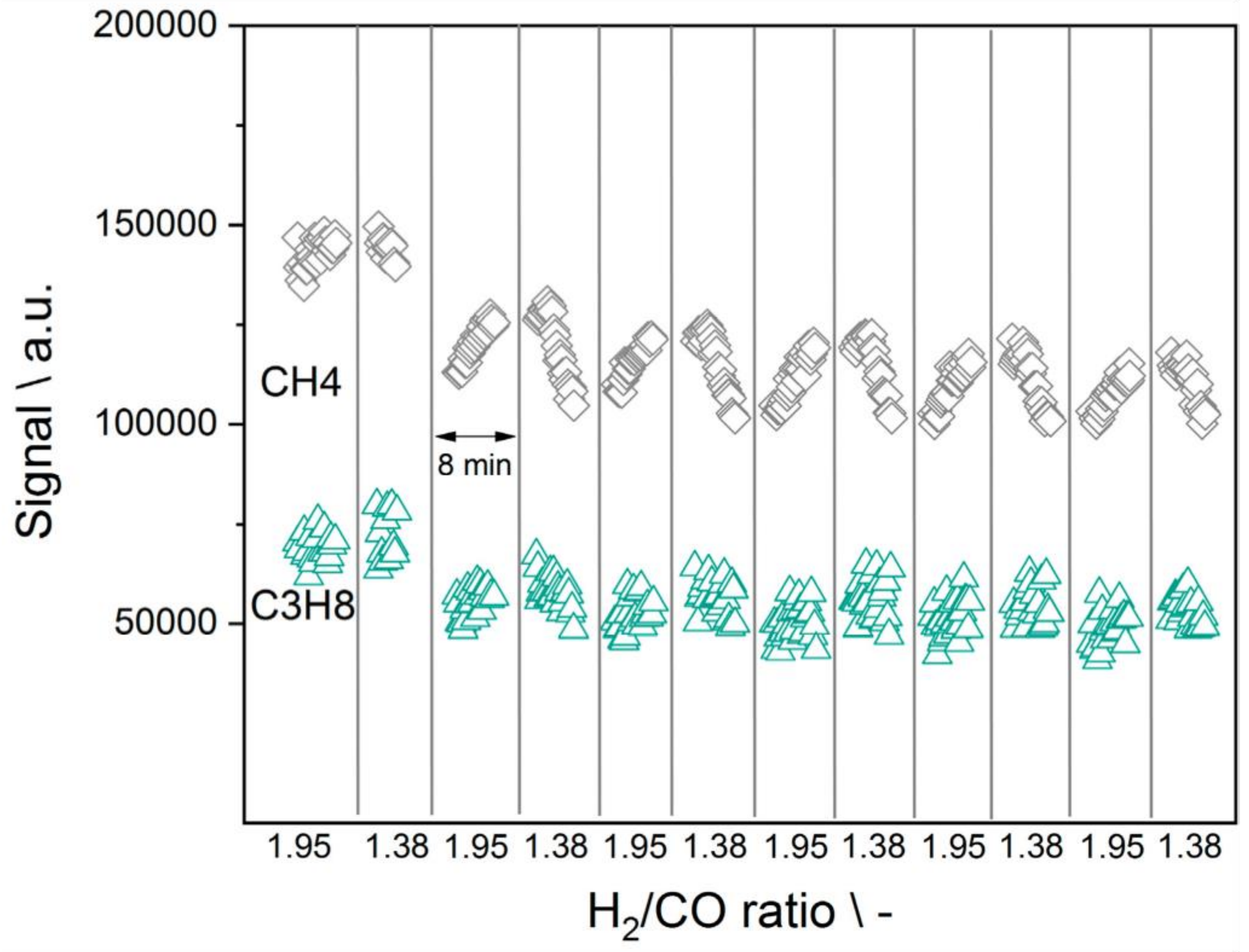
Studies on transient operation of the bench-scale FTS unit

Concentration cycles - Variation of H_2/CO

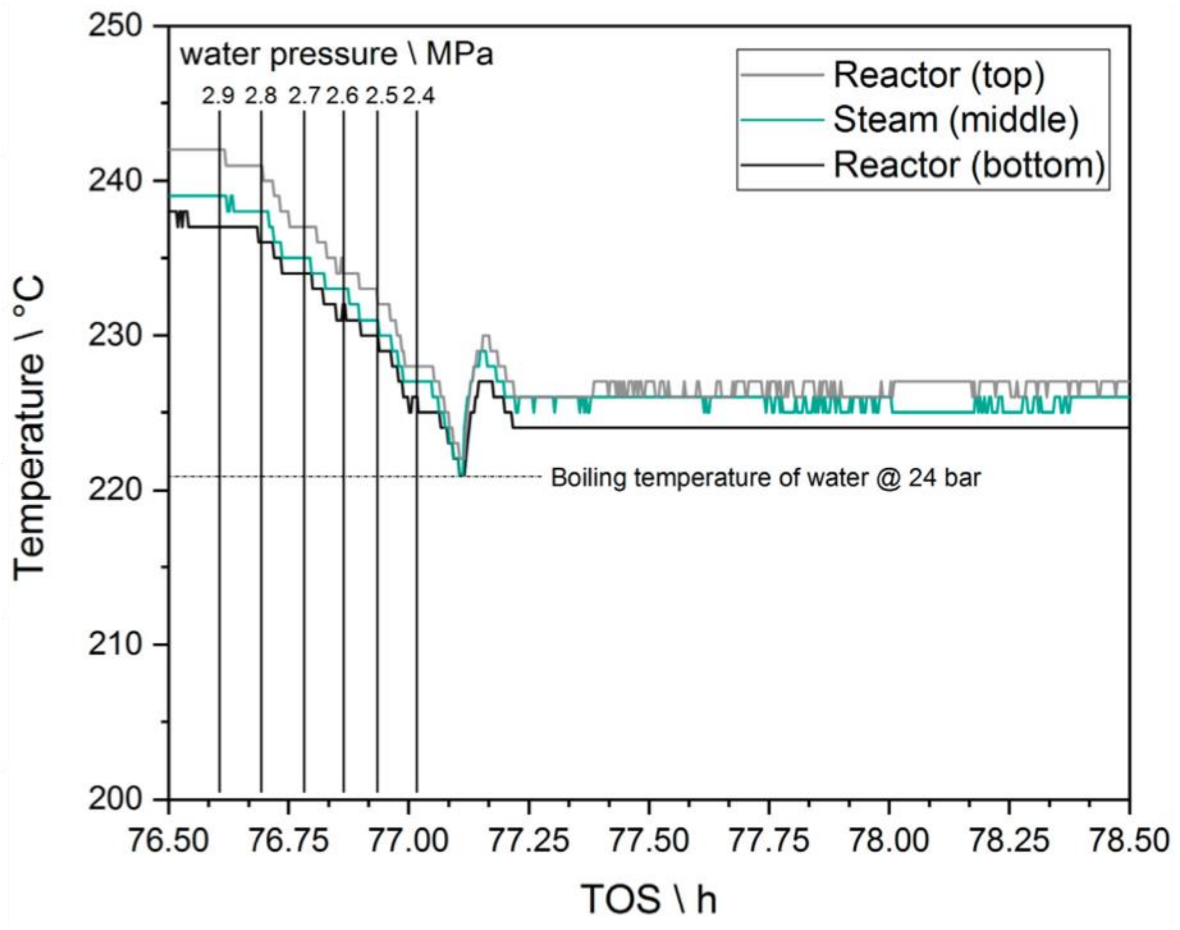


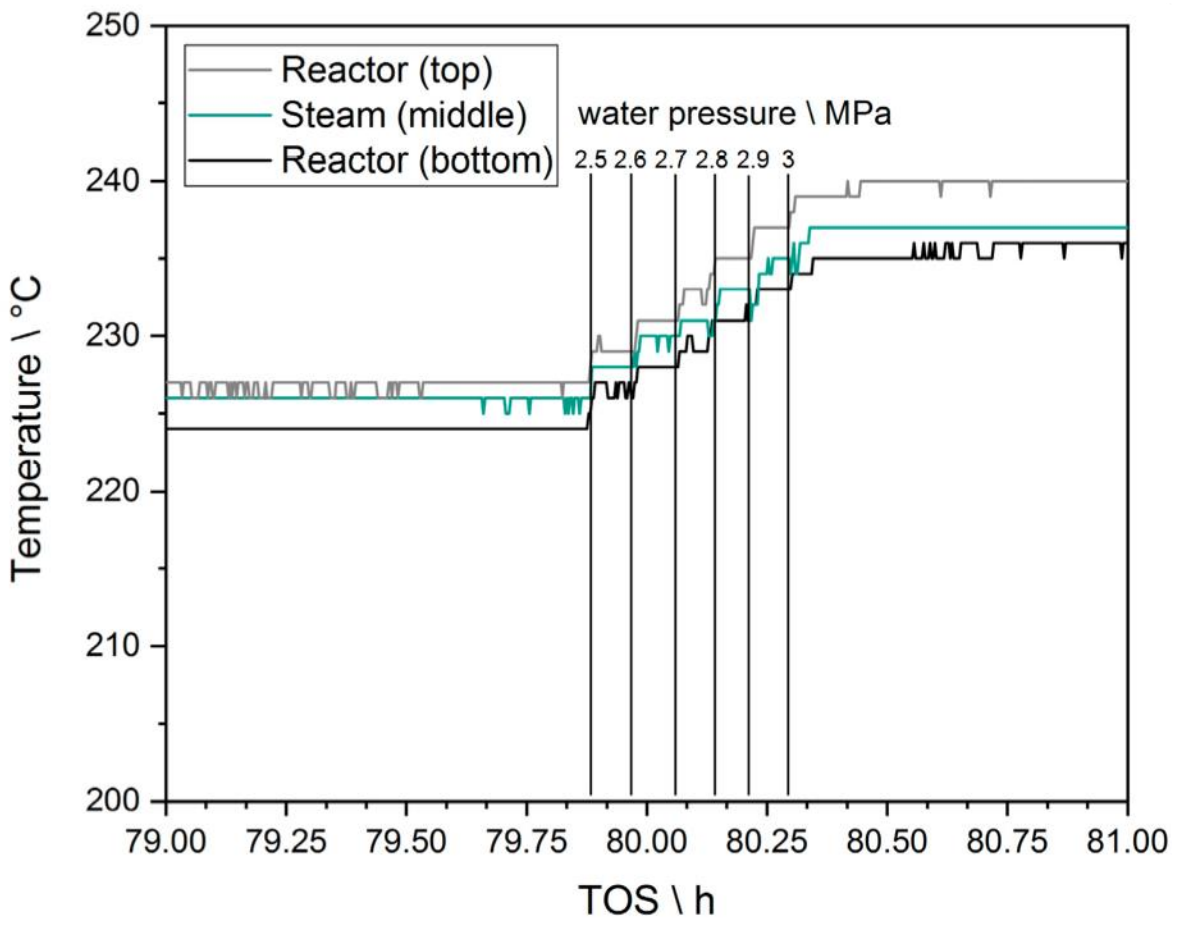


Shorter cycle time



Temperature switching - Adjustment of the coolant pressure



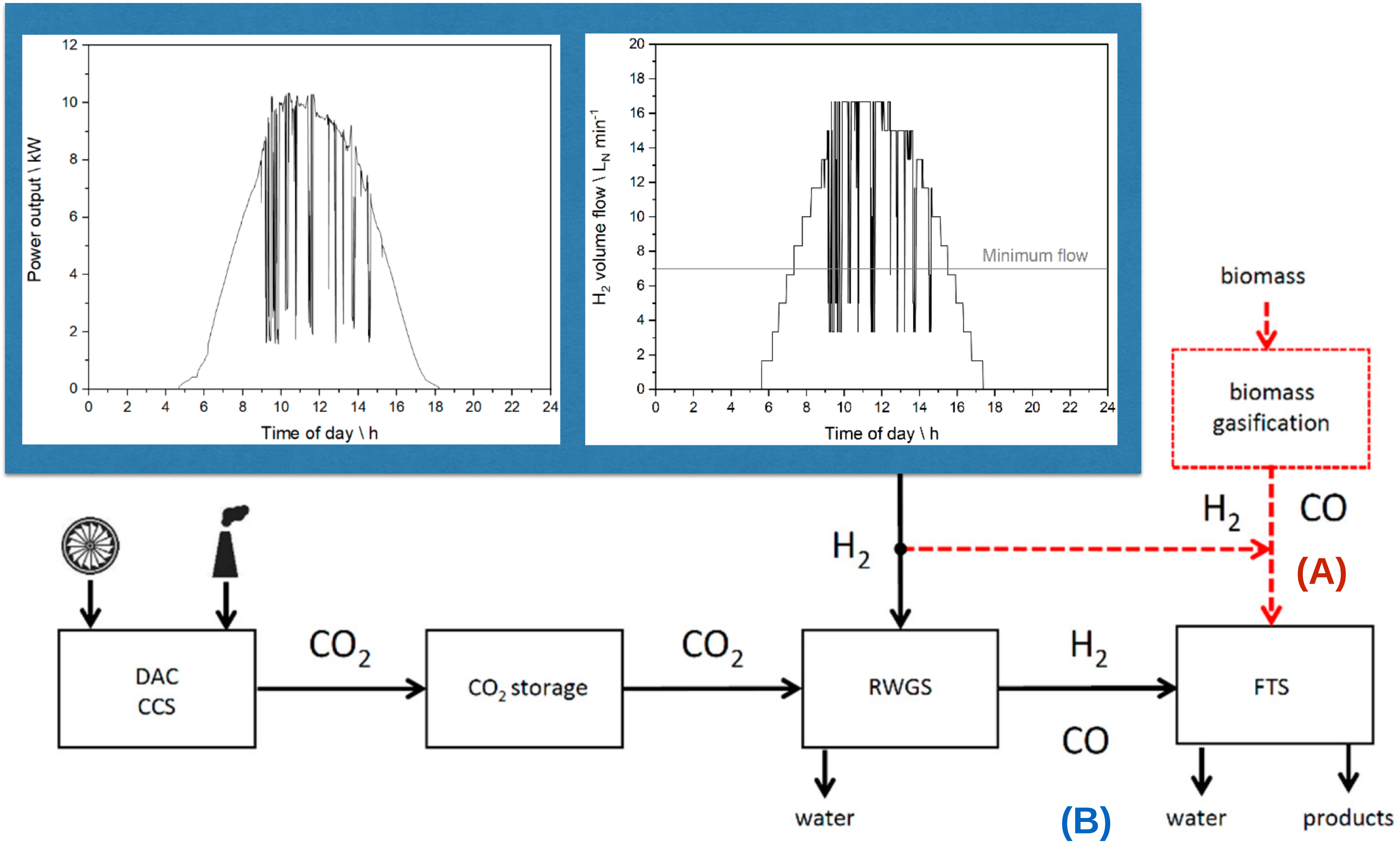


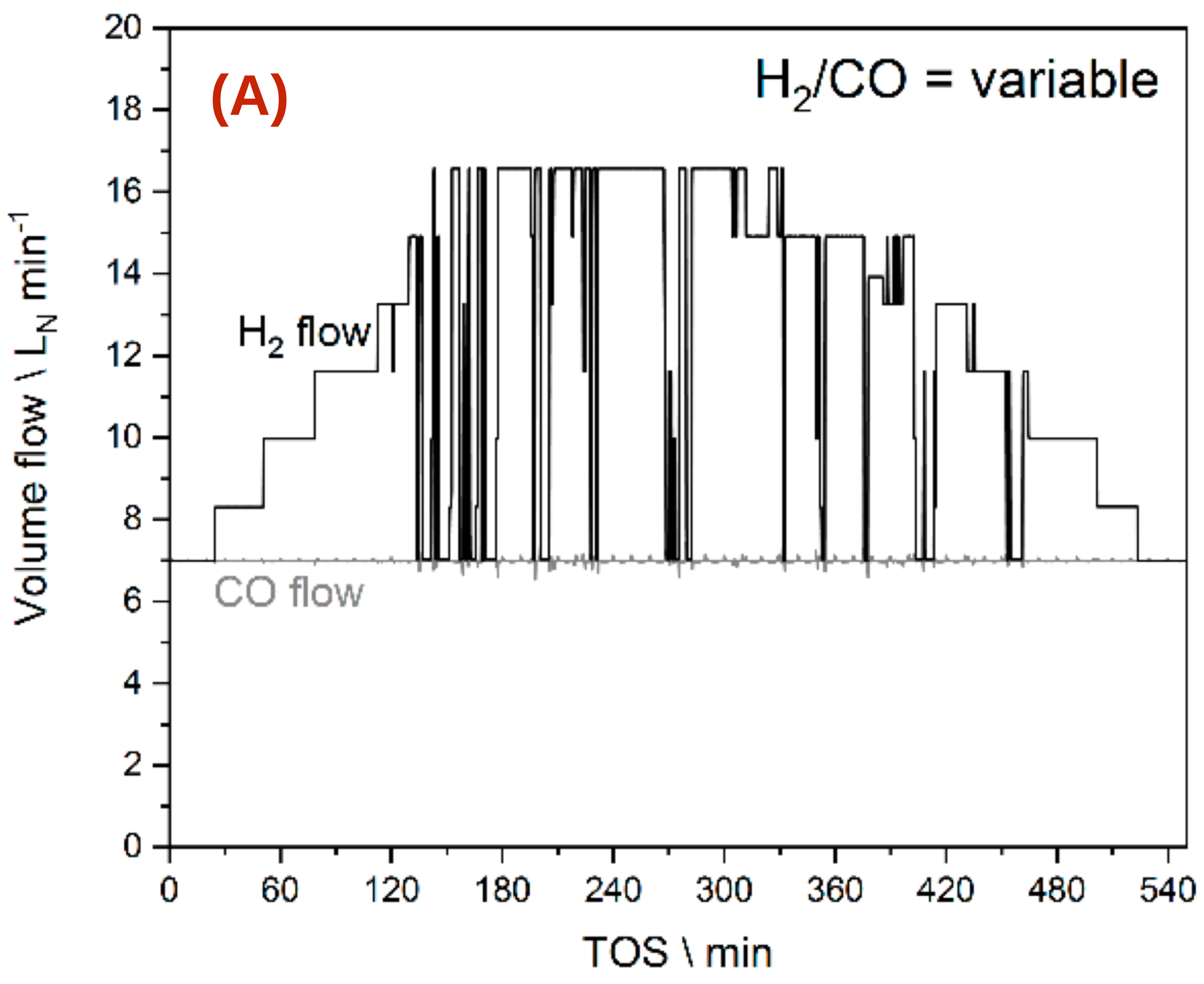
(Level of H_2 conversion ca. 50-70%)

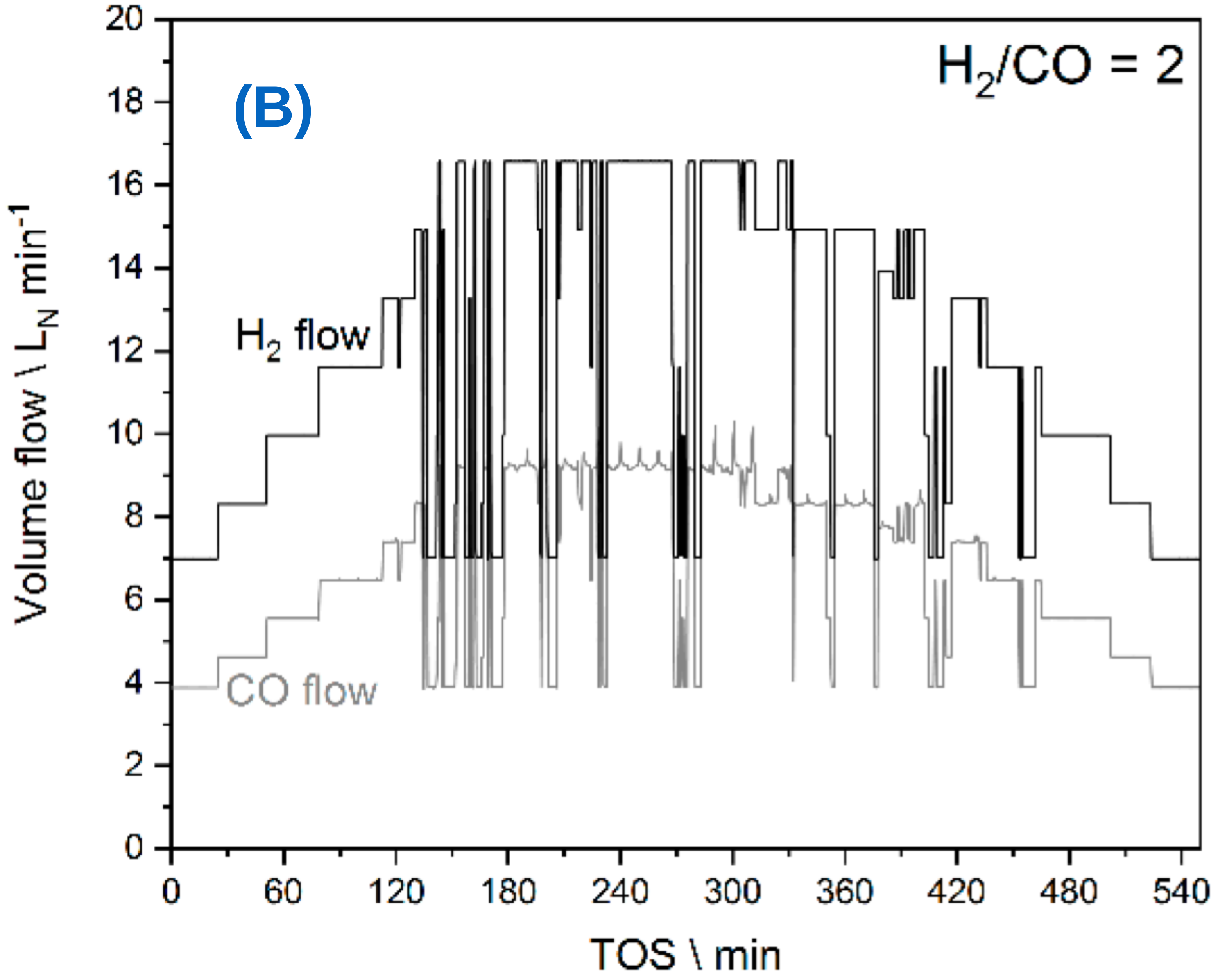
M. Löwert, P. Pfeifer, *ChemEngineering* **2020**, *4*, 21; doi:10.3390/chemengineering4020021

Transient operation of the bench-scale FTS unit

Transient operation assuming a H_2 generation profile determined by fluctuating power from PV for electrolysis



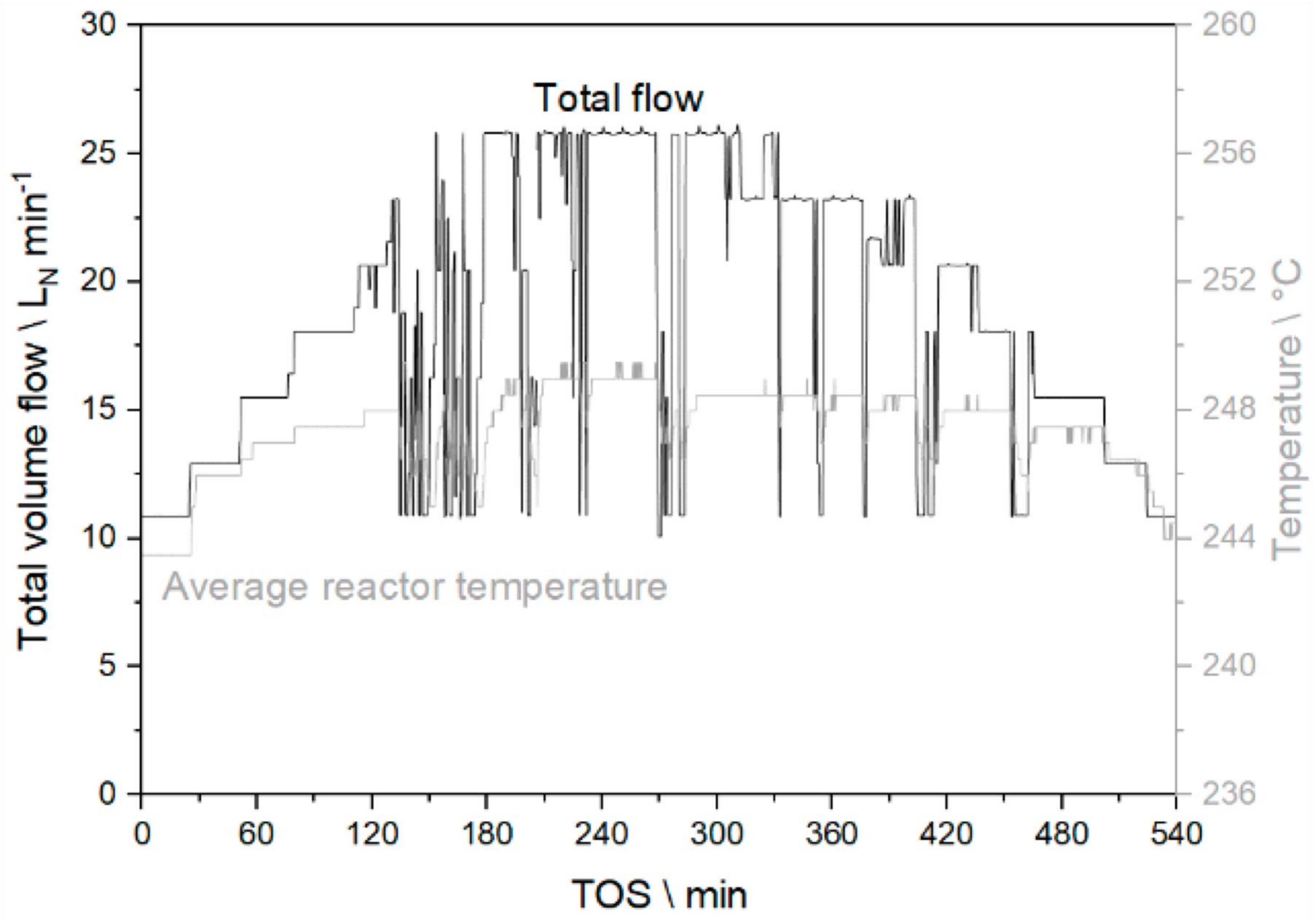


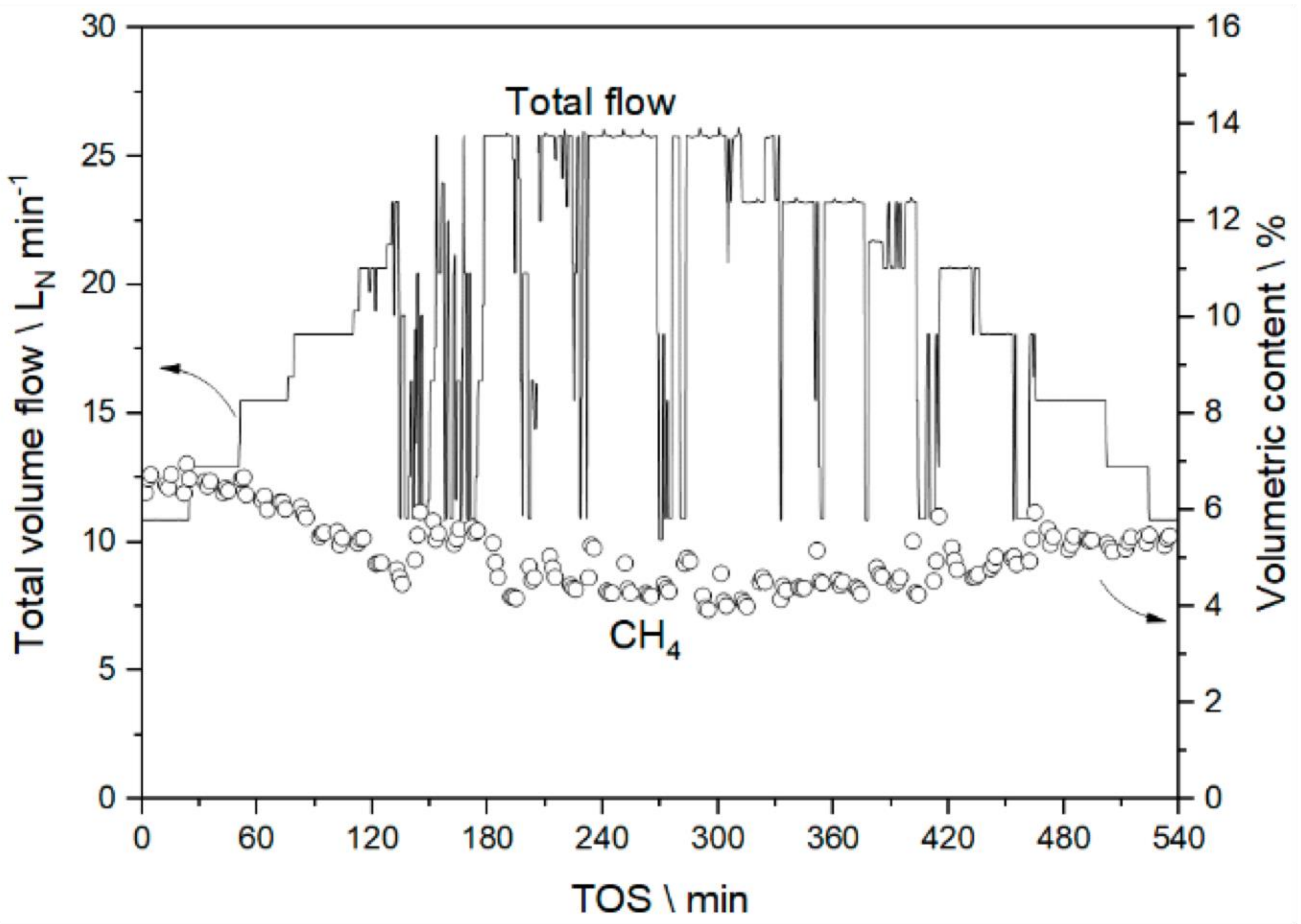


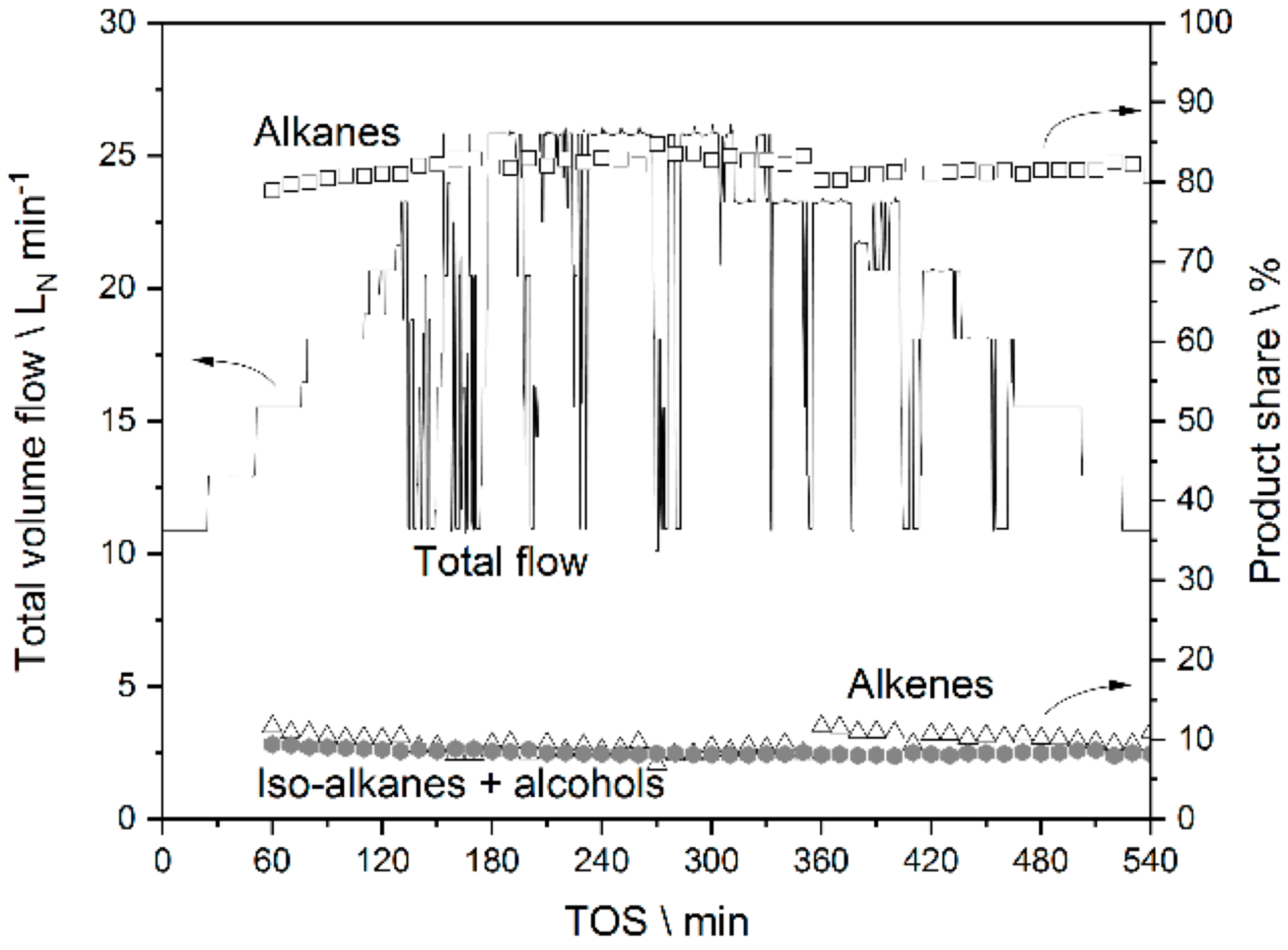
M. Löwert, M. Riedinger, P. Pfeifer, *ChemEngineering* **2020**, *4*, 27; doi:10.3390/chemengineering4020027

Transient operation of the bench-scale FTS unit

System response - case (B)







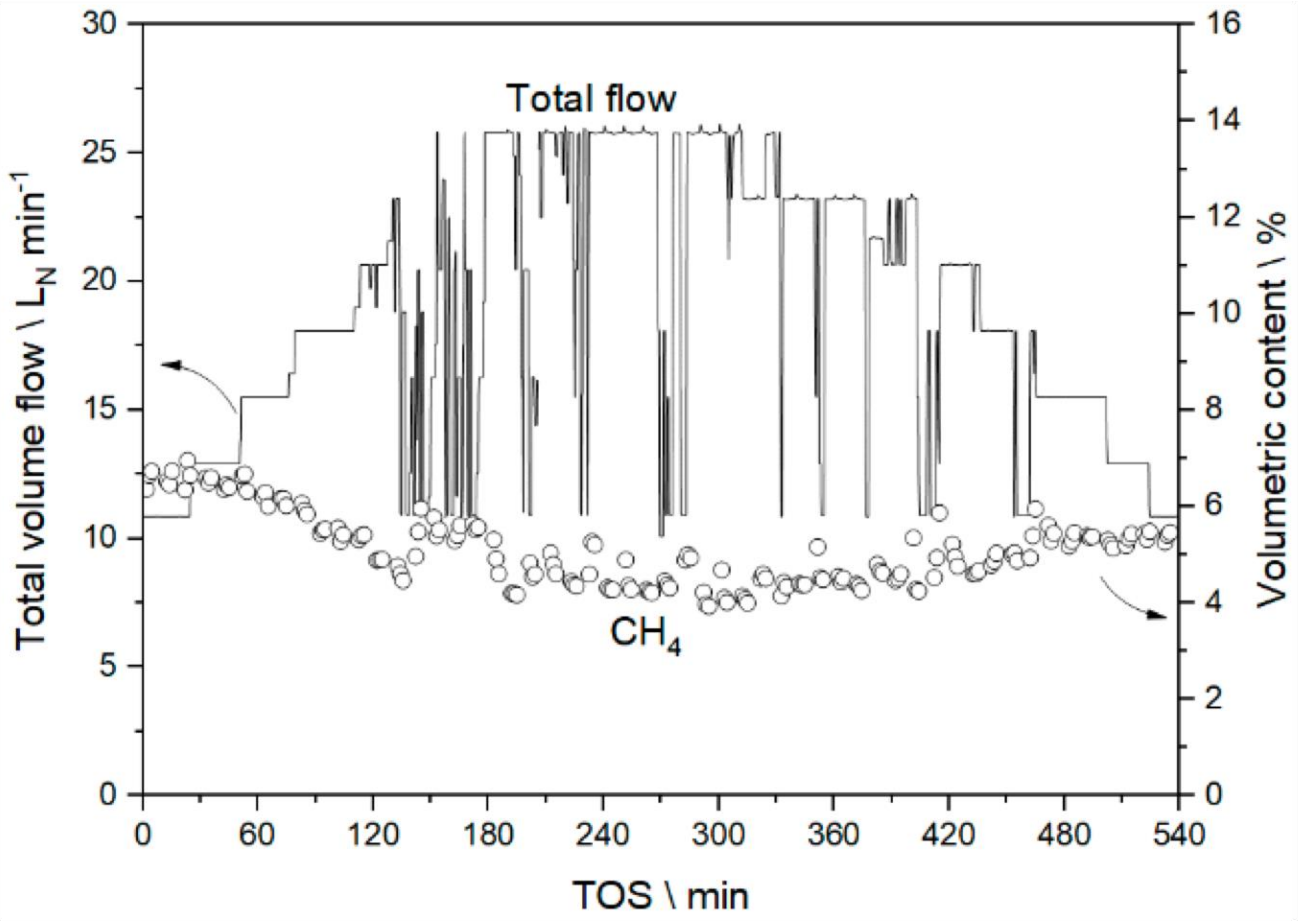
M. Löwert, M. Riedinger, P. Pfeifer, *ChemEngineering* **2020**, *4*, 27; doi:10.3390/chemengineering4020027

Transient operation of the bench-scale FTS unit

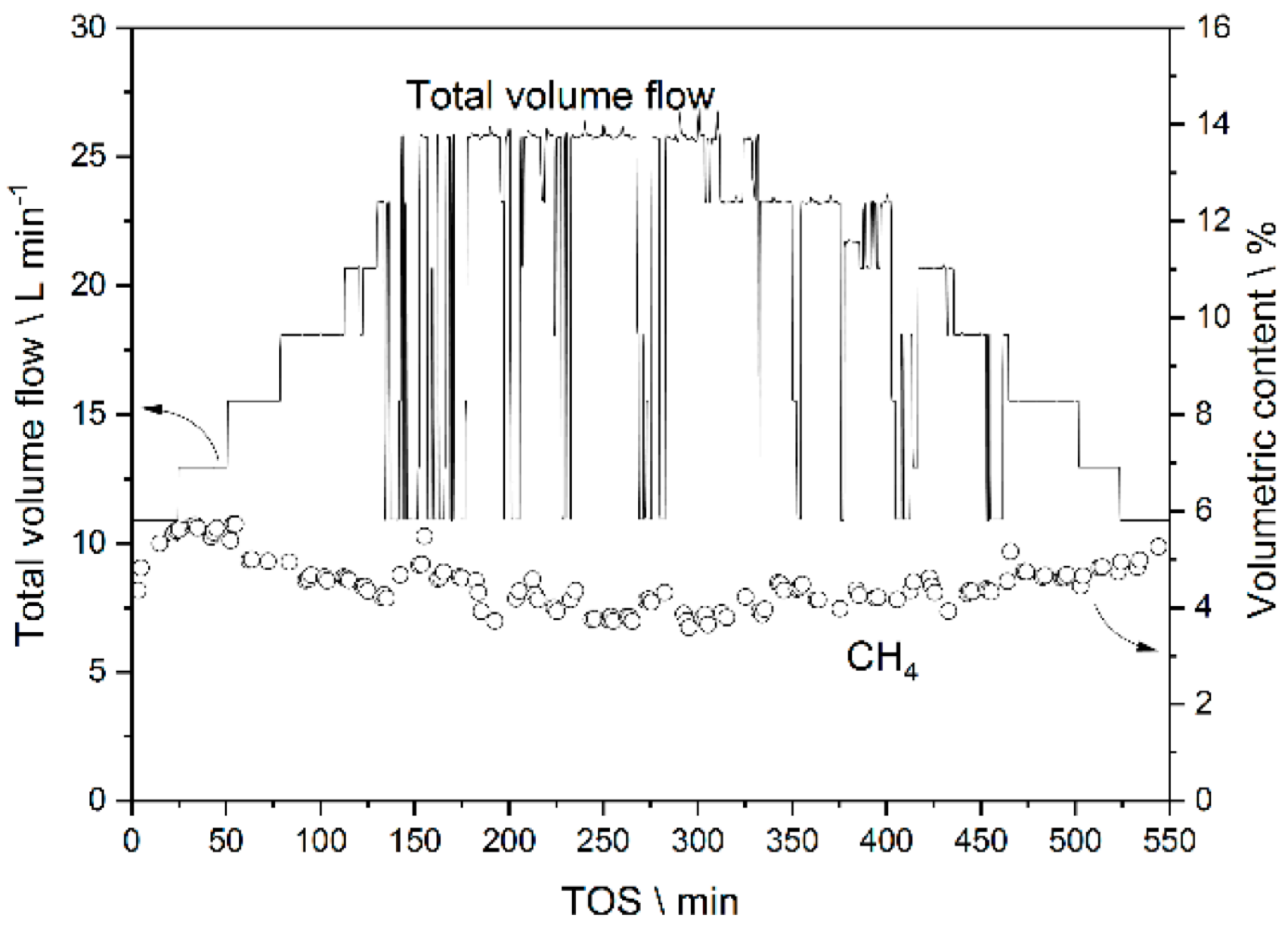
Transient operation assuming a H_2 generation profile determined by fluctuating power from PV for electrolysis.
Case B: Variable flow rate at constant CO/H_2 ratio (assuming an upstream RWGS unit reaching equilibrium).

Reactor temperature varies depending of flow rate

Reactor temperature was adjusted by setting the coolant pressure / temperature as to reach a conversion of 70% despite varying flow rate (interpolation of kinetic data)



Varying H_2 conversion



H_2 conversion 70%

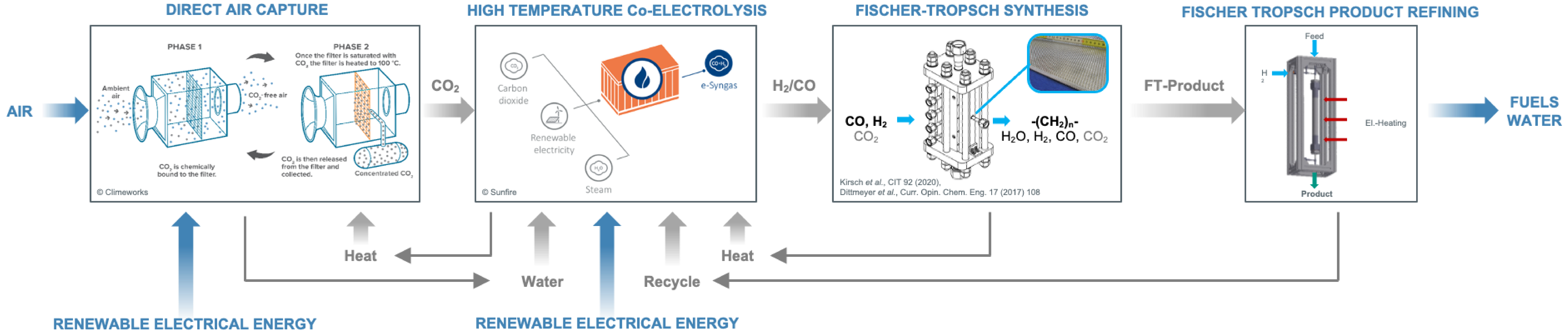
M. Löwert, M. Riedinger, P. Pfeifer, *ChemEngineering* **2020**, *4*, 27; doi:10.3390/chemengineering4020027

Copernicus project P2X - Synthetic fuels from CO_2 from thin air

Key features:

- High efficiency through process integration
- Compact design of the synthesis unit enabled by micro process engineering
- Modular plant concept scalable over a wide range of capacity

Project start in September 2016



Funded partners:

CLIMEWORKS, sunfire, INERATEC, KIT Karlsruhe Institute of Technology, DLR, Linde

Associated partners:
Audi AG, AVL List GmbH, Ford Werke GmbH, Volkswagen AG,
DB Energie GmbH, International Association for Sustainable Aviation IASA e.V.

Copernicus project P2X - Outcome of Phase I (2016-2019)

World premiere 2019: Entire process operated in 30 ft container

https://www.kopernikus-projekte.de/projekte/p2x

May/June 2019

Copernicus P2X integrated PtL plant in May 2019
©KIT

Targets reached

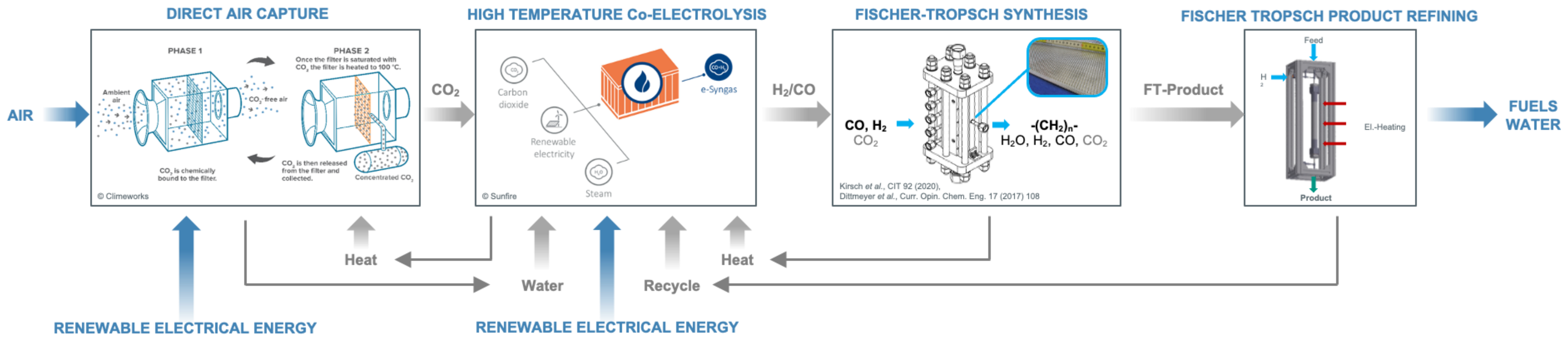
- Validation of the four individual components and their connection
- 100 Litres of fuel produced in 2 campaigns (both FT product and hydrocracked FT product)
- Roadmap 1.0 to 4.0 available showing ranges, uncertainties and potential of the technical, economic, and ecological key performance indicators

Copernicus project P2X - Activities in Phase II (2019-2023/2024)

ENERGY LAB 2.0

pdf download, 18 MB

Modular integrated container plants



- Reactor design optimization for FT synthesis
- Modular technologies for FT product upgrading
- Process synthesis and analysis
- Proposal for further scale-up to MW range in Phase III (2024-2027)

Copernicus project P2X - Activities in Phase II (2019-2023/2024)

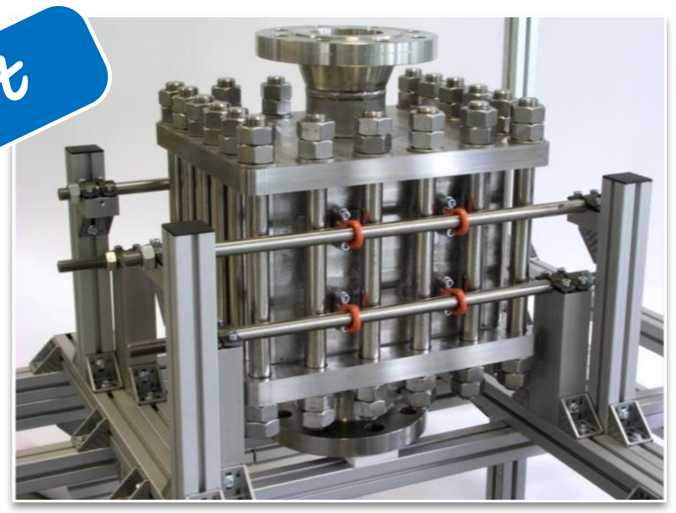
250 kW System

SG

compressed SG

RWGS Stage

‚10.000g' catalyst



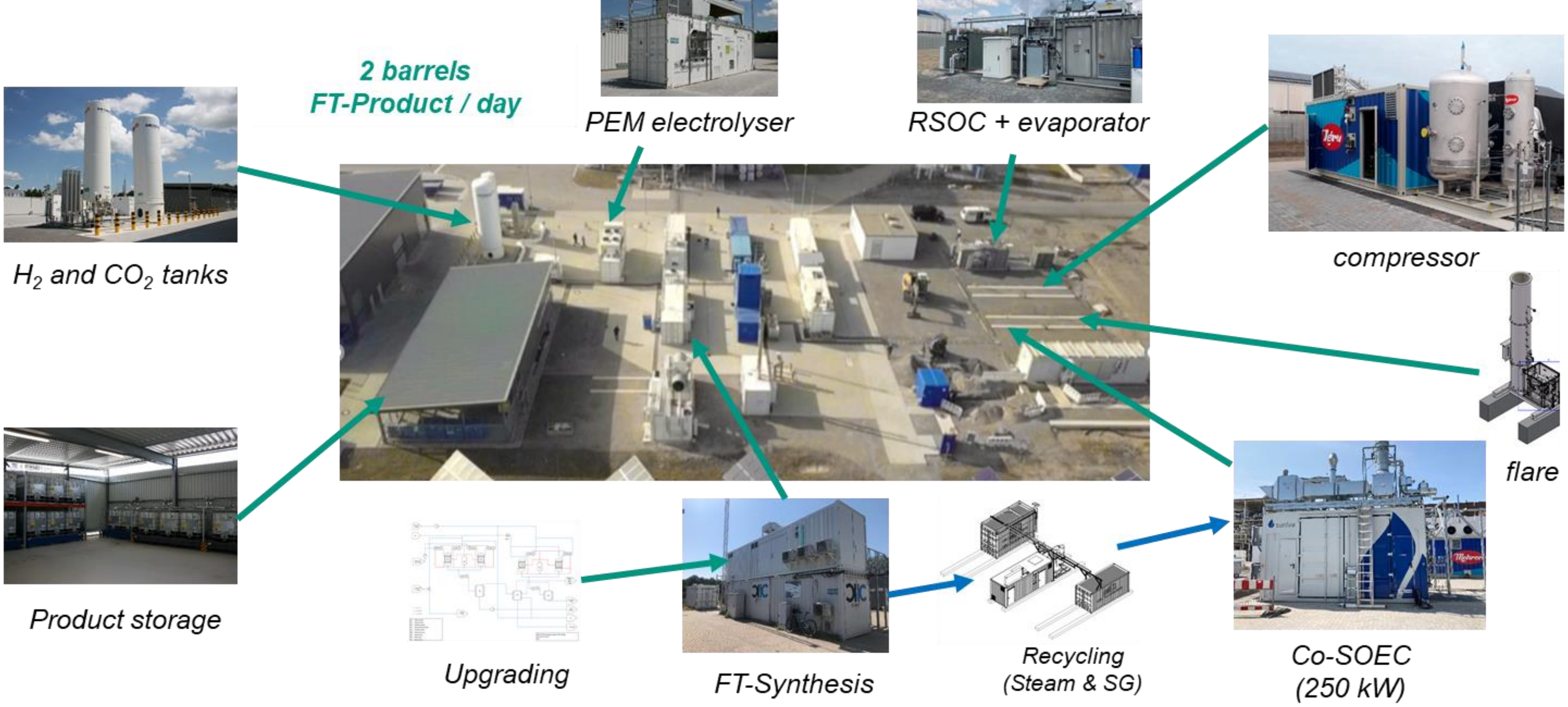
FT-crude

- 2nd FTS module

Ongoing

- *Separate PEC on top for FT crude refining to SPK*

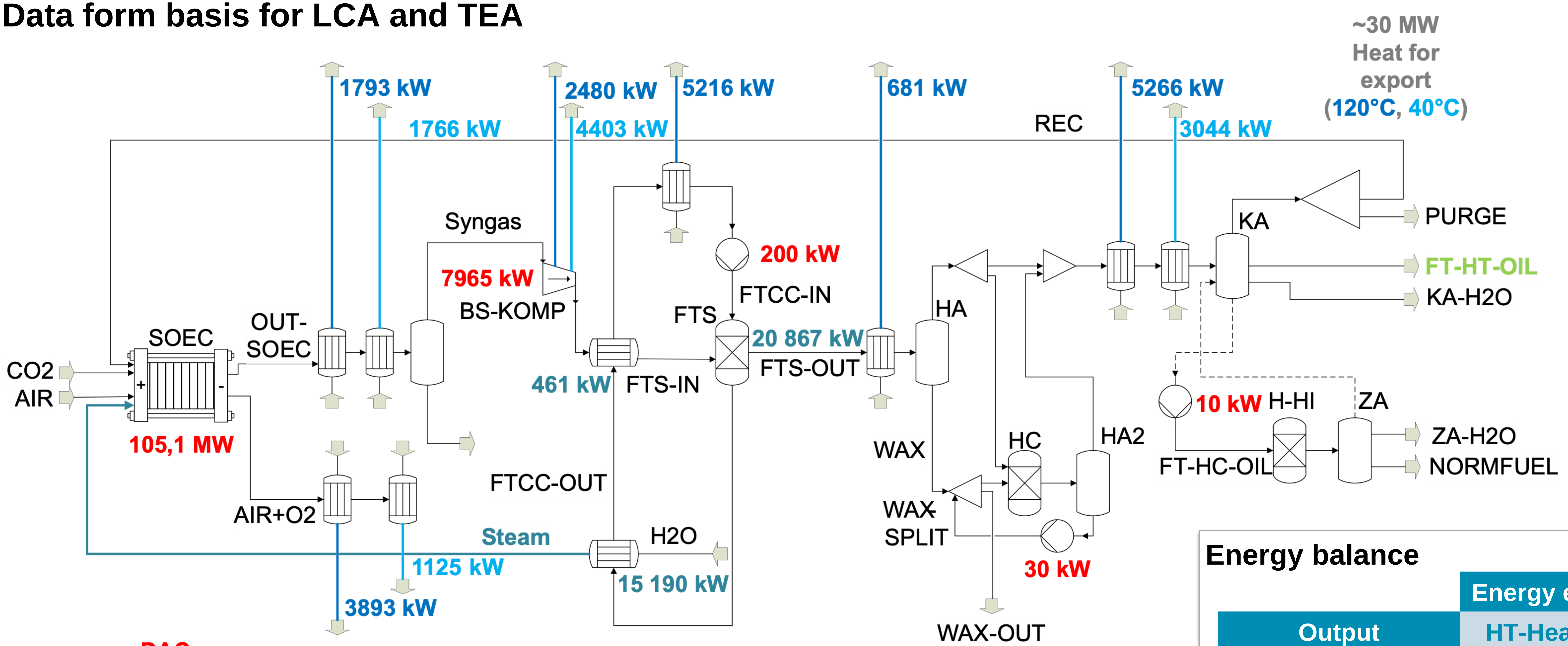
Copernicus project P2X - Activities in Phase II (2019-2023/2024)



Copernicus project P2X - Activities in Phase II (2019-2023/2024)

Process simulation of the coupled Co-SOEC/FTS/HC-HT section (100 MW Co-SOEC)

Data form basis for LCA and TEA



DAC
7,7 MW_{el}
30,7 MW_{therm}

Balance of plant: 2%

Material balance

- In: 400 t/d CO_2
- Out: ~136 t/d hydrotreated FT-Oil

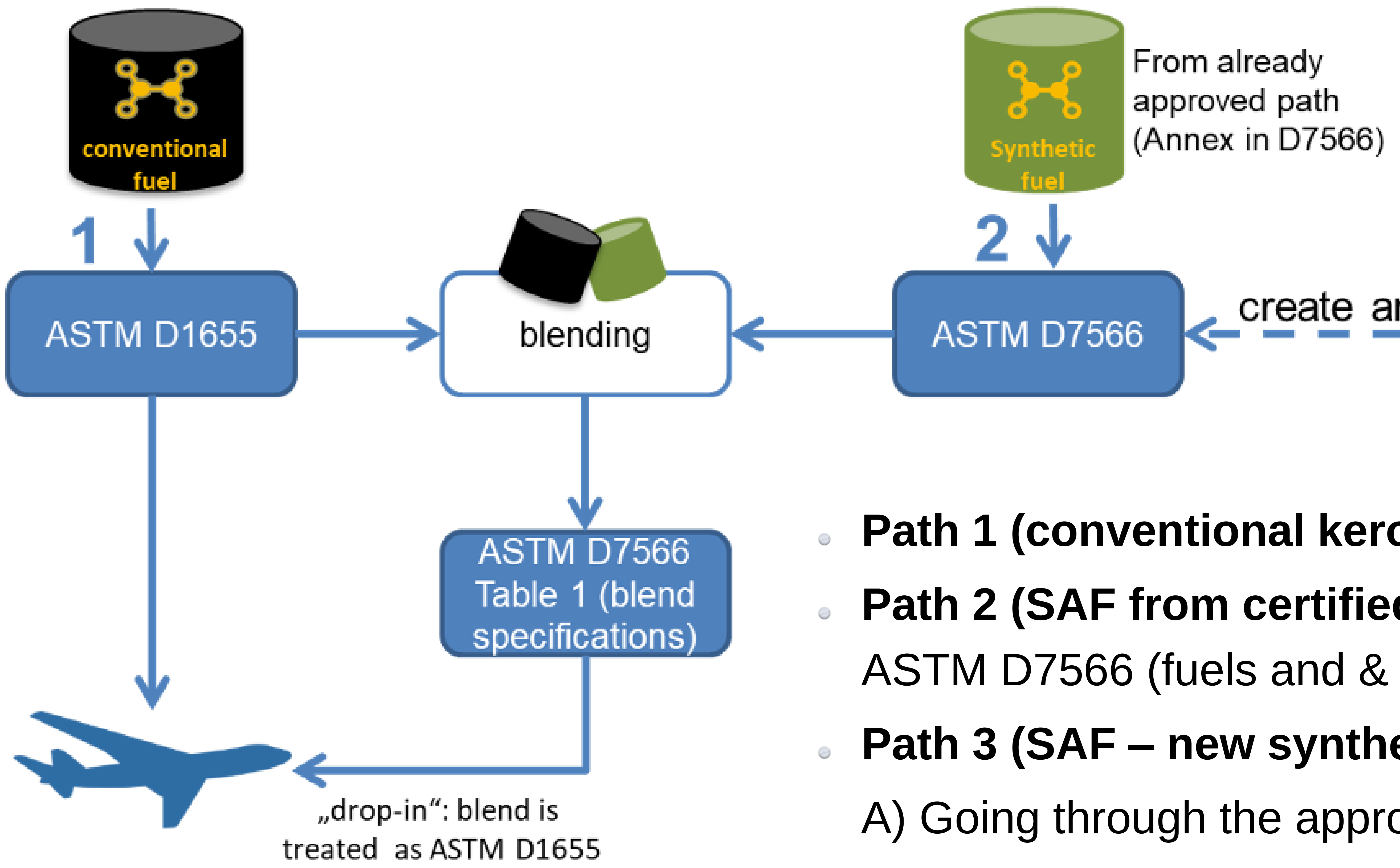
Energy balance

	Energy efficiency (including DAC)	
Output	**HT-Heat**	**HT- and LT-Heat**
65 MW (LHV)	48,2 %	52,3 %
70 MW (HHV)	52,0 %	56,4 %

D. Dhamo et al., SOEC-based production of e-Fuels via the Fischer-Tropsch route, in: W. Sitte and R. Merkle (eds), High Temperature Electrolysis - From Fundamentals to Application, IOP Publishing, Bristol, UK, 2023, doi: 10.1088/978-0-7503-3951-3

Approval and standard compliance of fuels

Jet Fuel



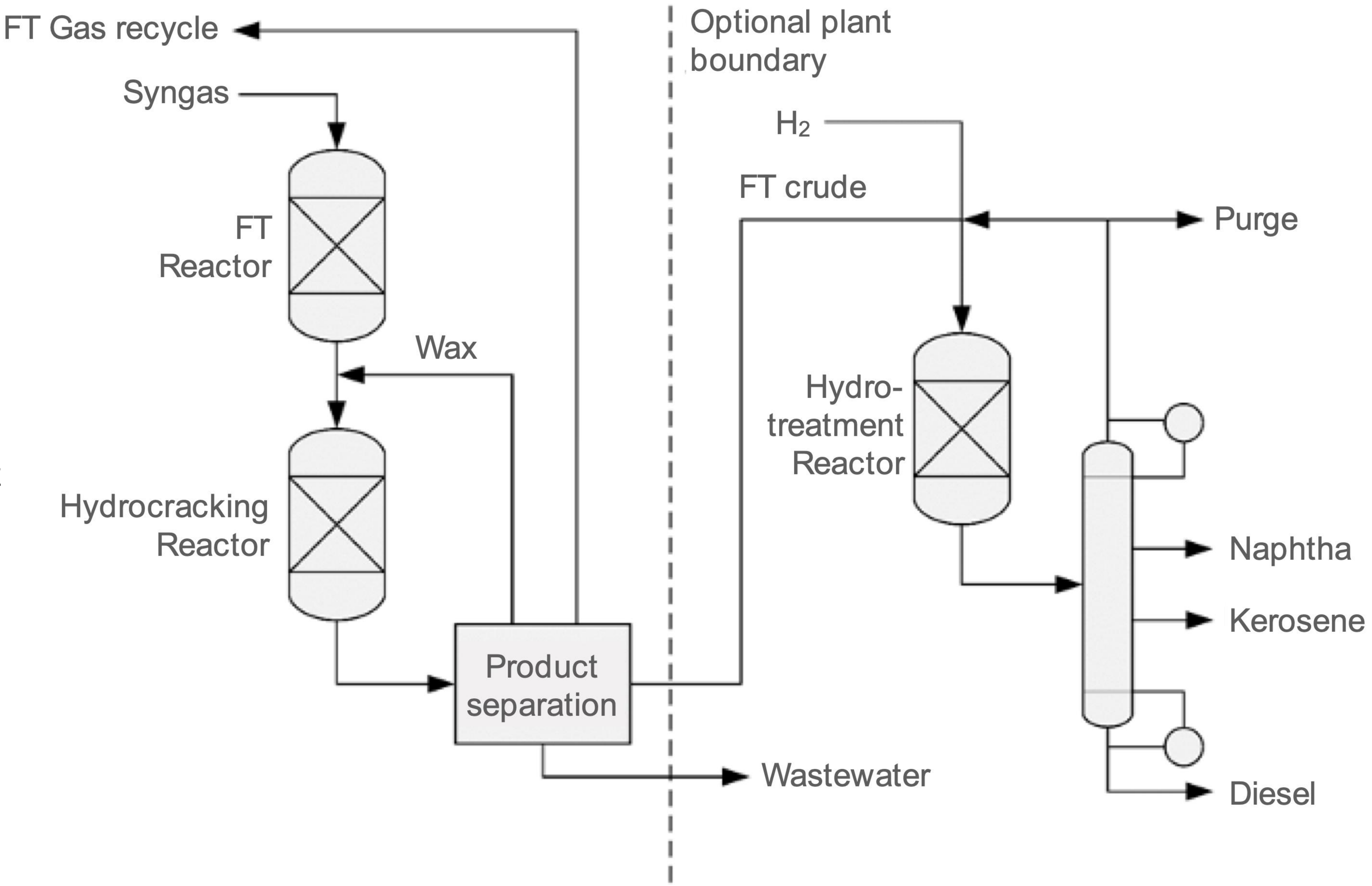
- **Path 1 (conventional kerosene):** must comply with specifications of ASTM D1655
- **Path 2 (SAF from certified synthesis route):** must comply with specifications of ASTM D7566 (fuels and & synthesis route)
- **Path 3 (SAF – new synthesis route)**
  A) Going through the approval process according to ASTM D4054
  B) Going through the fast track approval process according to ASTM D4054
- **Path 4 (SAF– Co-Processing)**
  Co-processing of SAF and fossil kerosene in conventional refinery (ASTM D1655)

Status of FT crude refining to SPK

Bench-scale plant(s), ca. 5-6 kg/day

- Co/Al_2O_3 catalyst
- T = 205 – 220 °C
- p = 20 bar
- H_2/CO = 2,1

- Pt-Zeolite catalyst
- T = 250 – 270 °C
- p = 20 bar



- Pt-Zeolite catalyst
- T = 250 – 260 °C
- p = 30 bar
- LHSV = 3-6 h^{-1}
- H_2/Oil = 400 mL_N/mL

- T: 150 – 230 °C

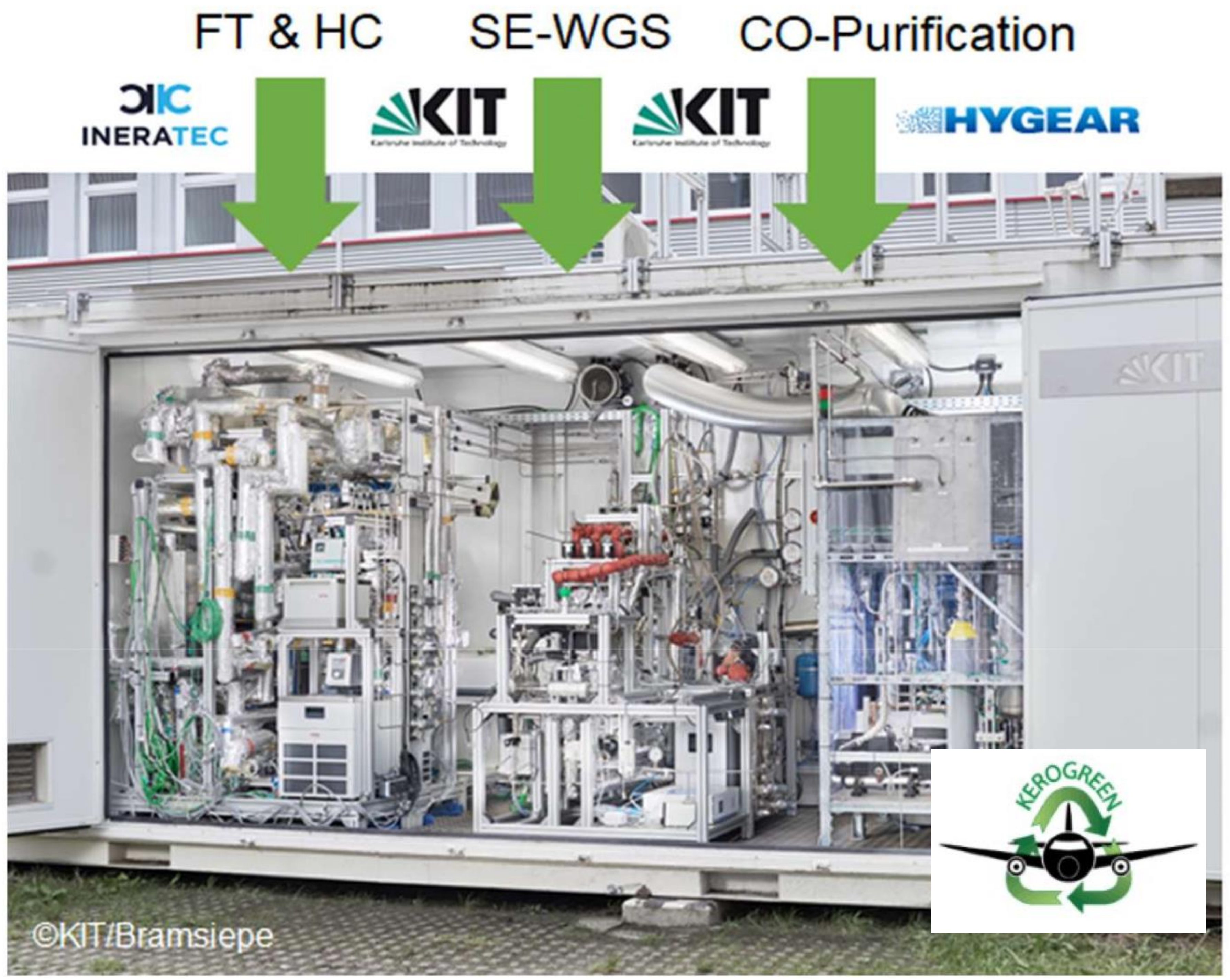
- By exploring promising catalysts and the effects of key process parameters (HC, HT, distillation) we got a kerosene cut fulfilling all parameters for SPK according to ASTM D7566
- SPK yield so far is about 35%

D. Dhamo et al., SOEC-based production of e-Fuels via the Fischer-Tropsch route, in: W. Sitte and R. Merkle (eds), High Temperature Electrolysis - From Fundamentals to Application, IOP Publishing, Bristol, UK, 2023, doi: 10.1088/978-0-7503-3951-3

Status of FT crude refining to SPK

FT-Crude refining scheme recently validated

1. Generation of ca. 150 L of hydrocracked FT oil in a container plant at IMVT (EU project Kerogreen, capacity ca. 5-6 kg/day)

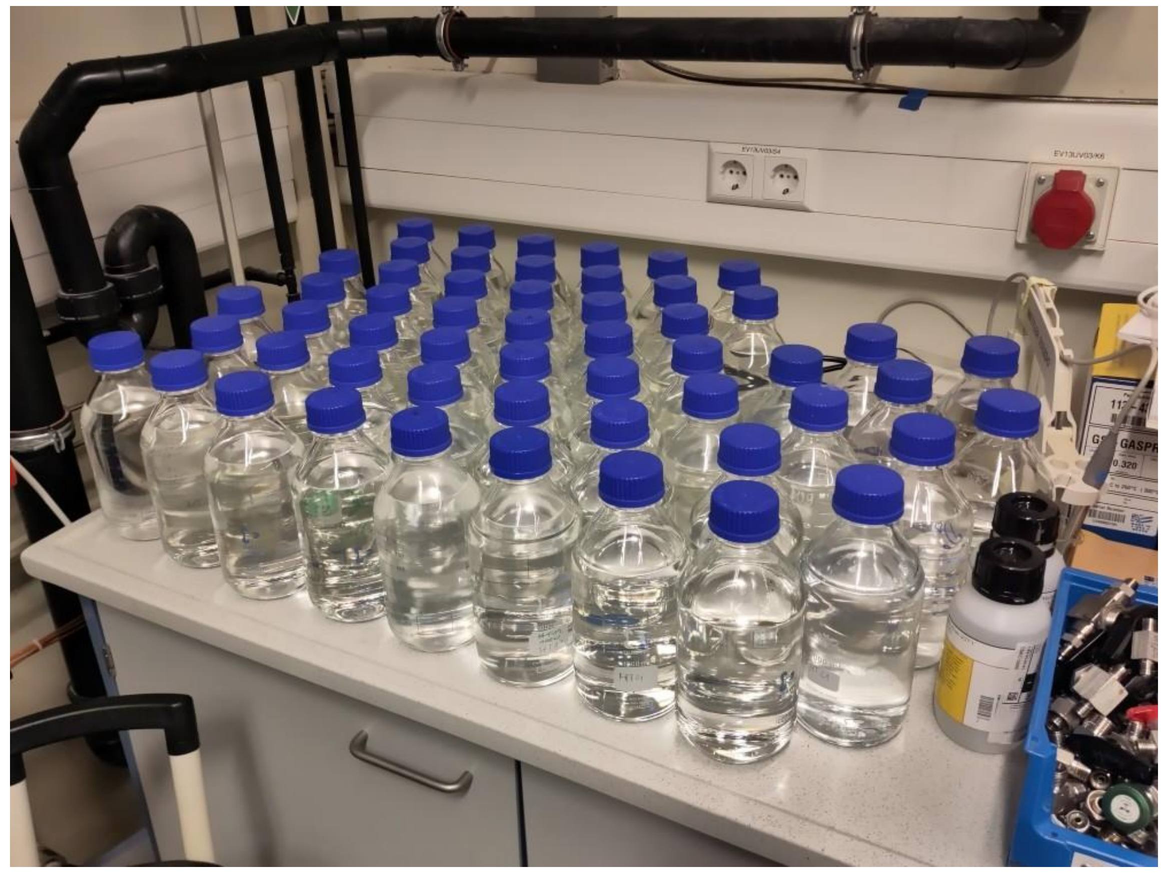


2. Hydrogenation/isomerisation of the hydro-cracked FT oil in lab plant (in batches, ca. 6 L/day)

- **Increasing isomer content (> 30%)**
- **Improving cold-flow properties**
- **Hydrogenation of olefins / oxygenates**

3. Distillation and analytics by ASG Analytik-Service, Neusäss, Germany

Lots of bottles in the lab…



Photos: R. Dittmeyer

P. Pfeifer, Production of carbon neutral fuels and upgrading to kerosene, 789. WE-Heraeus-Seminar „Sustainable Aviation Fuels - Design, Production and Climate Impact“, 24 May - 27 May 2023, Bad Honnef, Germany

Status of FT crude refining to SPK

SPK Characteristics

Distilled hydrocracked and hydrotreated FT oil

Main Parameters

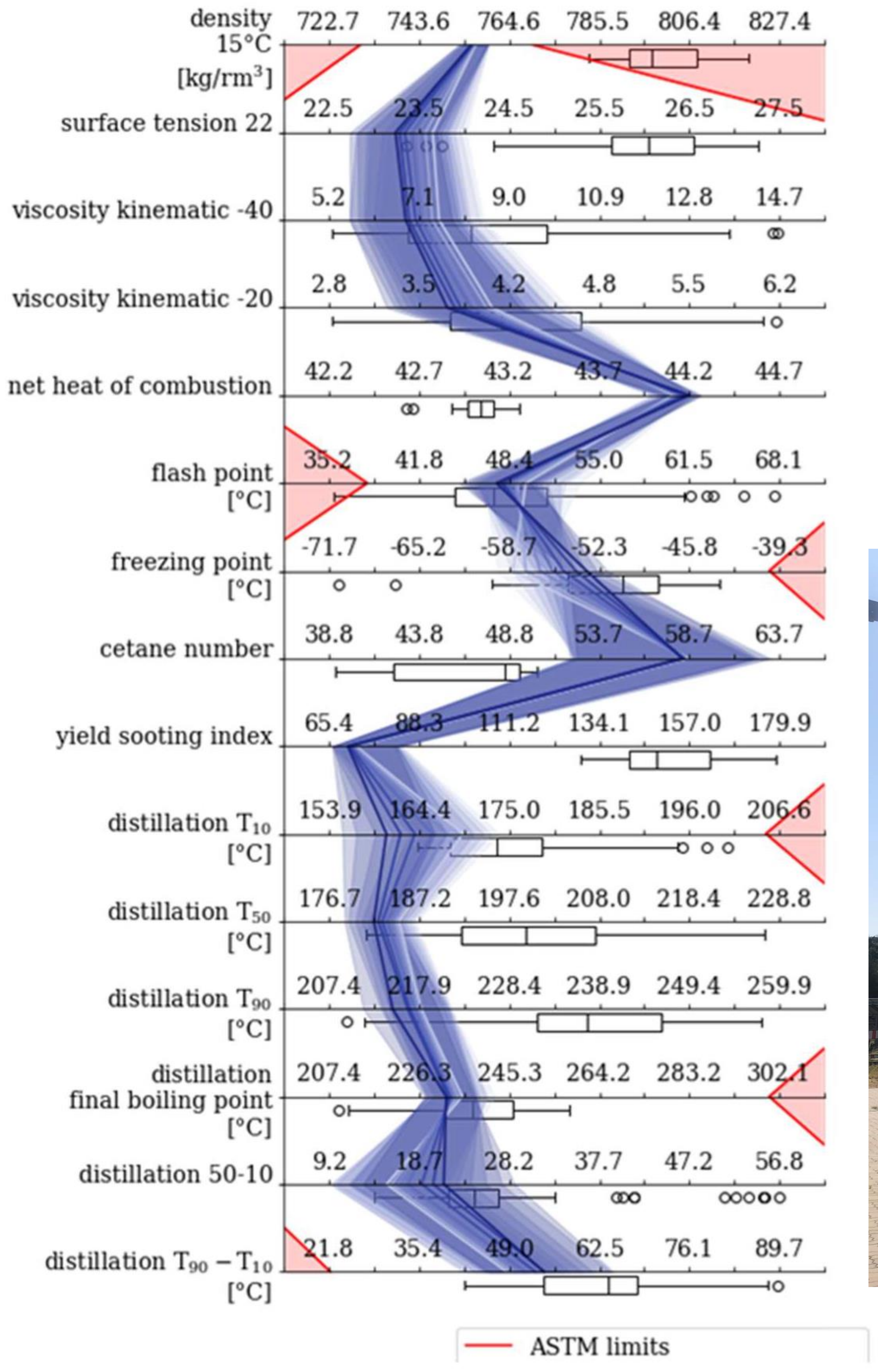
	ASTM 5766 Min	ASTM 5766 Max	Sample
Density g/cm³	0.73	0.76	0.745
Flash point °C	38		44
Freeze point °C		-40	-47

Simulation of other parameters by Dr. J. Melder and Dr. U. Bauder with SimFuel Platform

Product split:

	Yield, wt.-%
Naphtha, < 135°C	44,9
SPK, 135-230 °C	**39,9**
Diesel, > 230°C	15,2

P. Pfeifer, Production of carbon neutral fuels and upgrading to kerosene, 789. WE-Heraeus-Seminar „Sustainable Aviation Fuels - Design, Production and Climate Impact“, 24 - 27 May 2023, Bad Honnef, Germany



Outlook

- A slightly modified process for 2 bpd is being built in a 2nd PEC in the Energy Lab 2.0. More extensive validation and SPK yield optimization is targeted.
- Further scale-up to 8-10 bpd is planned in P2X Phase III.

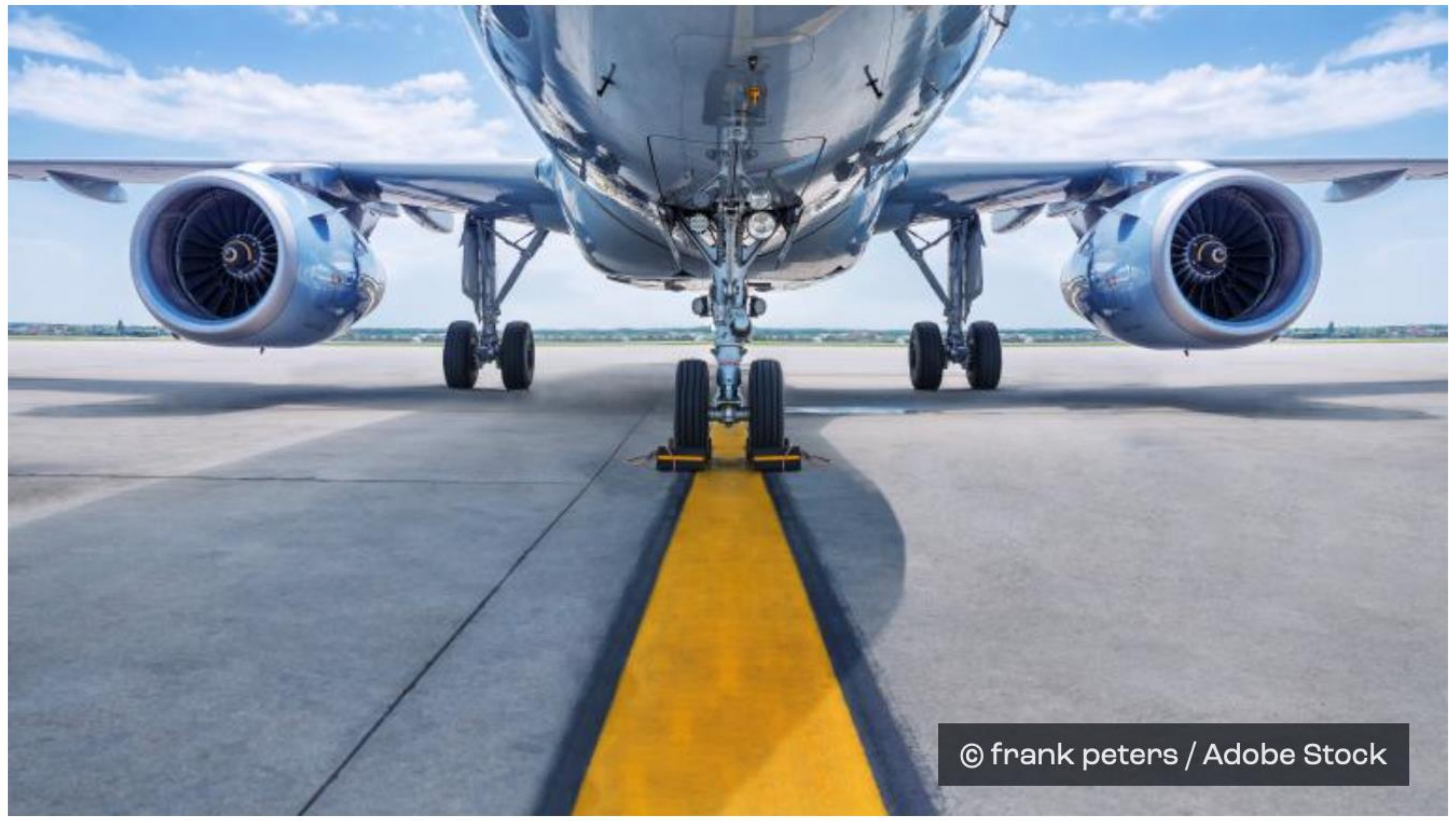
Status of FT reactor design optimization

1 MW (350 t/a) PtL Plants (atmosfair, Werlte; H&R, Hamburg)

10 times bigger modules

Inauguration at the EWE site in Werlte on October, 2021

10 MW Plant (3.500 t/a) in Frankfurt Höchst



28.04.2022 Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Wohnen

Pressemitteilung **Luftverkehr**

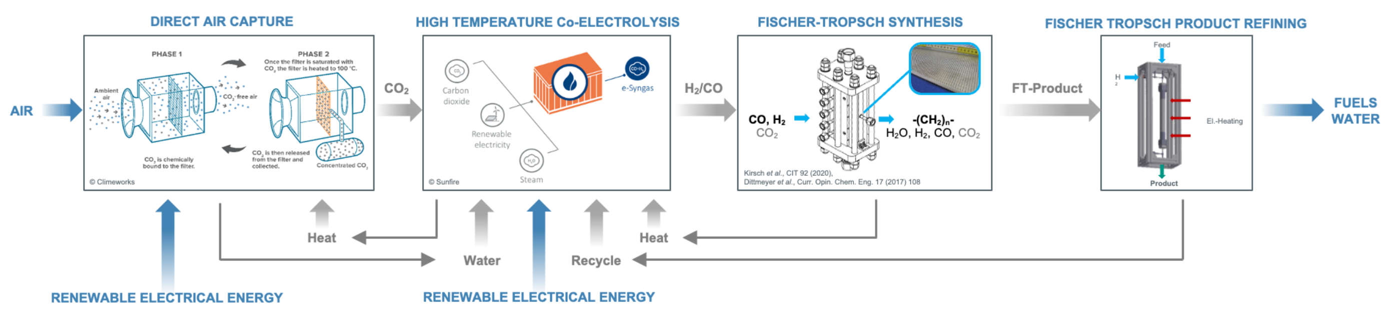
Pilotanlage für synthetisches Kerosin in Planung

Noch in diesem Jahr soll mit dem Bau der weltweit größten Pilotanlage für synthetisches Kerosin im Industriepark Frankfurt-Höchst begonnen werden. Dies teilte Wirtschafts- und Verkehrsminister Tarek Al-Wazir am Donnerstag in Wiesbaden mit.

Groundbreaking ceremony on April 19, 2023

Outlook

- Validate the process chain at the Energy Lab
  - Recycling streams
  - Updraging Container



- Improve the Kerosene yield
  - 39%

	Yield, wt.-%
Naphtha, < 135°C	44,9
SPK, 135-230 °C	**39,9**
Diesel, > 230°C	15,2

- Kopernikus phase 3
  - Scale up to 8-10 bpd (upgrading)

KOPERNIKUS P2X PROJEKTE
Die Zukunft unserer Energie

- Refineries for Futures

Final words

Portrait of Johann Wolfgang von Goethe (1749-1832) in the Roman campagna.
Johann Heinrich Wilhelm Tischbein, 1787, Städel Museum, Frankfurt am Main

***„Es ist nicht genug zu wissen;
man muss auch anwenden,
es ist nicht genug zu wollen,
man muss auch tun.“***

***„It is not enough to know,
one must also apply;
It is not enough to want,
one must also do.“***

Source: Goethe, Maximen und Reflexionen, Aphorismen und Aufzeichnungen. Nach den Handschriften des Goethe- und Schiller-Archivs. Hrsg. von Max Hederer, 1907. Aus Wilhelm Meisters Wanderjahre (1821), Aus Makariens Archiv.

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Thanks for your attention