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Overview to Power-to-Gas and methanation as an example

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791. WE-Heraeus-Seminar “The Physical, Chemical and Technological Aspects of the Fundamental Transition in Energy Supply from Fossil to Renewable Sources – Key Aspect: Energy Storage”

Physikzentrum Bad Honnef, June 18-22, 2023

Institute for Micro Process Engineering

Babylonian confusion (First book of Moses, 11,1 - 11,9)

- Power-to-Gas, P2G, PtG
- Power-to-Chemistry, P2C, PtC
- Power-to-Fuel, P2F, PtF
- Power-to-Liquid, P2L, PtL
- Power-to-X, P2X, PtX
- Power-to-Methane, P2M, PtM
- Power-to-Ammonia, P2A, PtA
- Power-to-Methanol, P2M, PtM
- Power-to-Molecules, P2M, PtM
- …
- Green hydrogen
- …

In this talk, Power-to-Gas means e-CH_4

Pieter Bruegel the Elder - The Tower of Babel (Rotterdam)
https://commons.wikimedia.org/wiki/File:Pieter_Bruegel_the_Elder_-_The_Tower_of_Babel_(Rotterdam)_-_Google_Art_Project_-_edited.jpg?uselang=de#filelinks

Some facts about natural gas in Germany (1/2)

- **Natural gas H**
  - LHV: 9,4 - 11,8 kWh/m³
  - HHV: 10,4 - 13,1 kWh/m³
- **Natural gas L**
  - LHV: 7,6 - 10,1 kWh/m³
  - HHV: 8,4 - 11,2 kWh/m³

- **Pure methane**
  - LHV: 9.97 kWh/m³
  - HHV: 11.1 kWh/m³

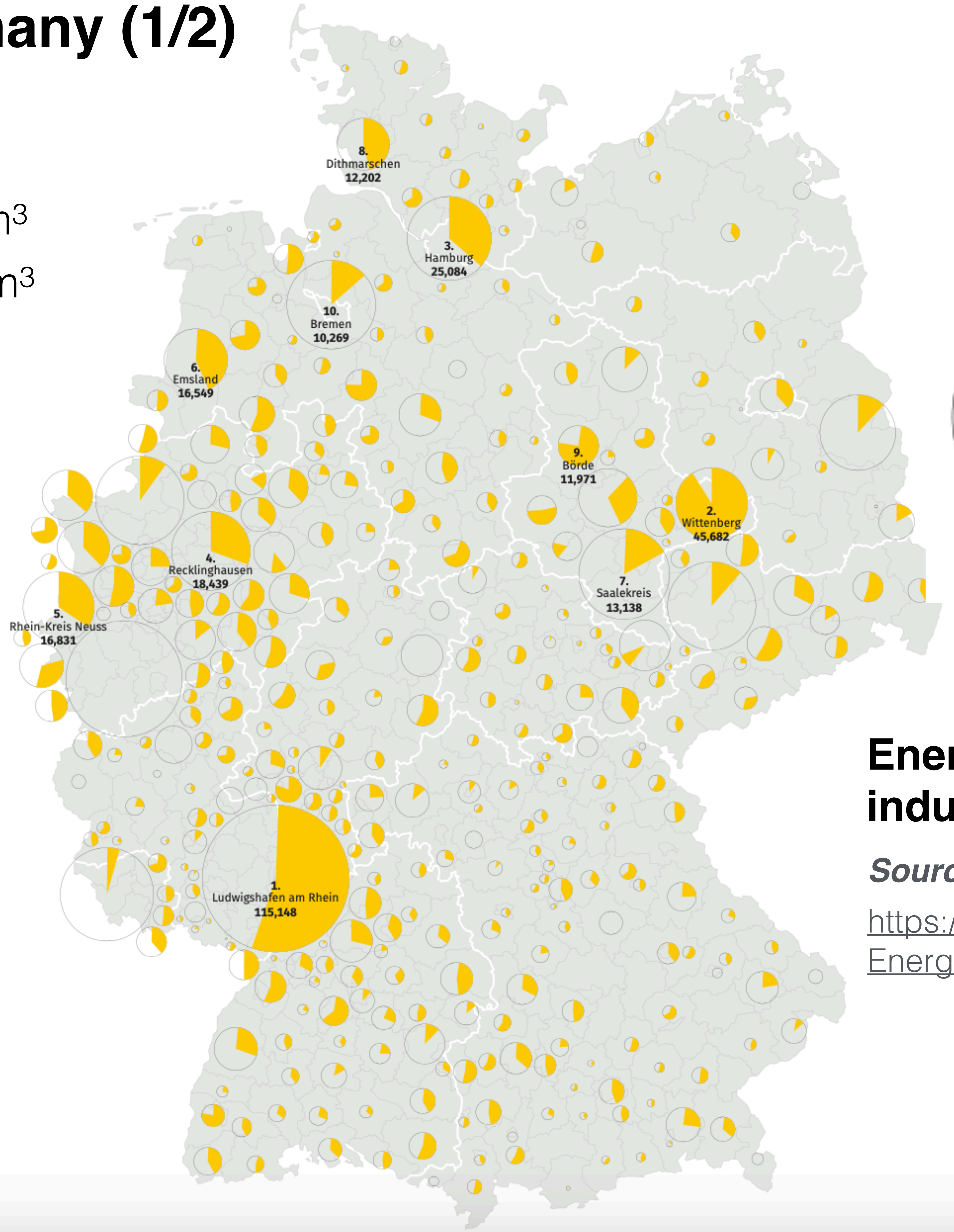
m³ at 1013 mbar, 0°C

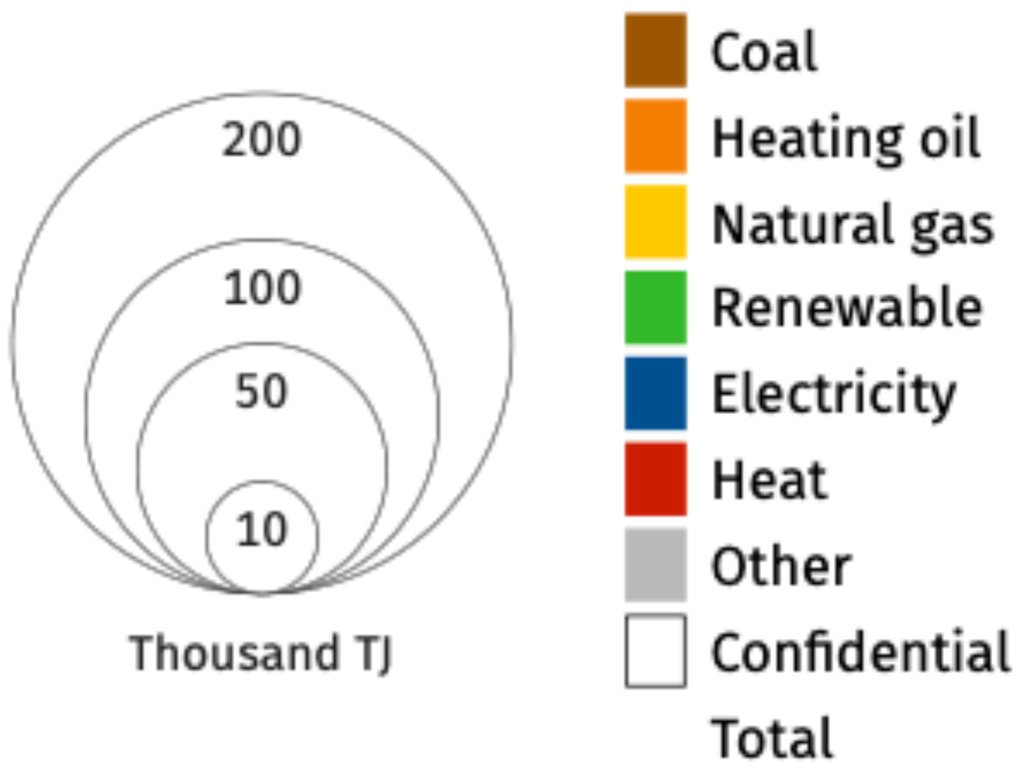
Source: https://www.geothermie.de/bibliothek/lexikon-der-geothermie/b/brennwert.html

- **Total consumption** in 2021 was **91 billion m³** (bcm, thereof 1 bcm biomethane)
- Equals ca. **800 - 900 TWh**

- FNR sees **biomethane potential** of **35 bcm** by 2030 (residues and energy crops)

Source: https://biogas.fnr.de/biogas-nutzung/biomethan





Energy consumption of industry by district (2020)

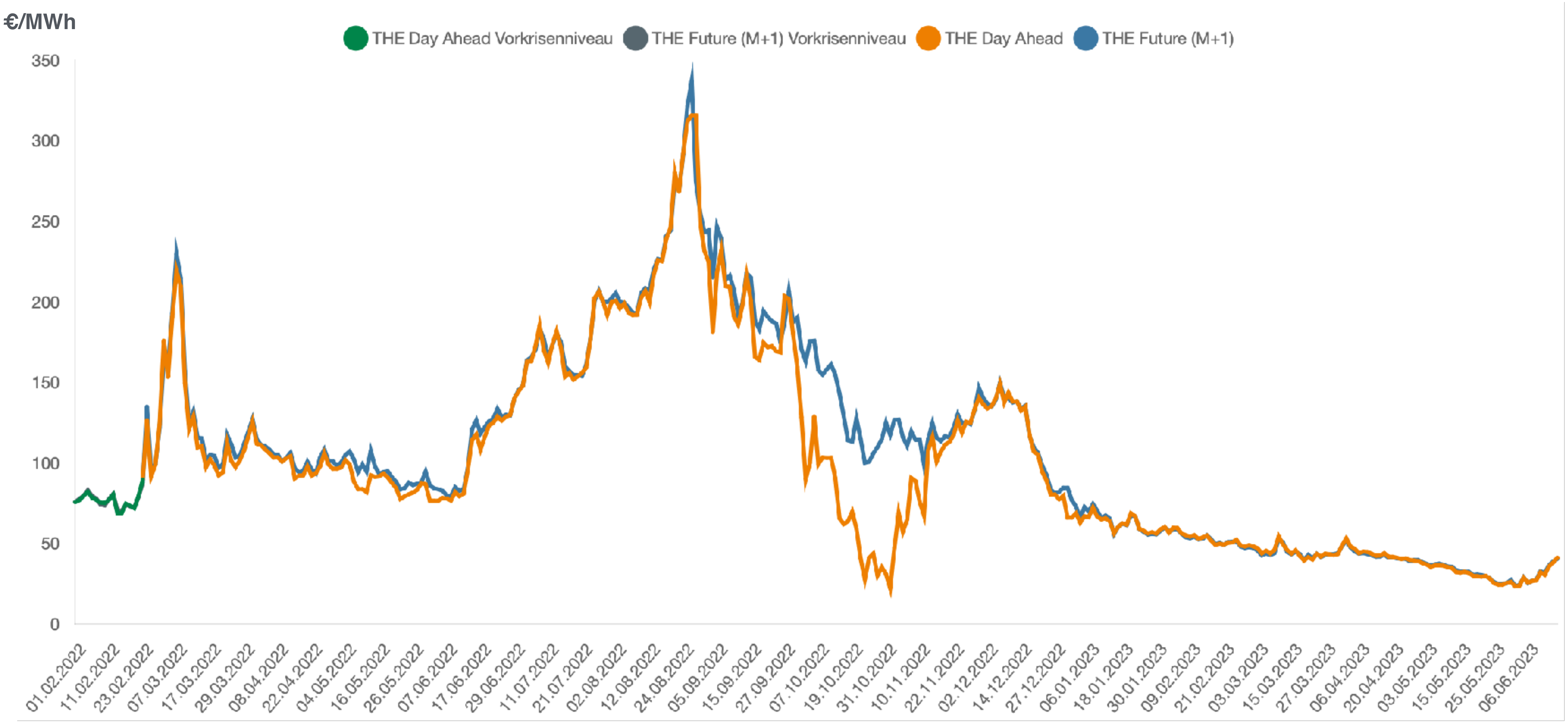
Source: https://service.destatis.de/DE/karten/EnergieverbrauchIndustrie2020.html#!en

Some facts about natural gas in Germany (2/2)

- **Storage capacity** for natural gas in Germany is **22.7 bcm** (21 porous rock storages, 29 cavern storages, pipelines not considered). This would store ca. **250 TWh** SRG (HHV, about 30% of the current consumption per year).
- Making 250 TWh SRG via **PtG needs a lot of green electricity**
  - 500 TWh at 50% overall efficiency
  - **312,5 TWh** at 80% overall efficiency
- **Current gross consumption** of electrical energy in Germany is **549 TWh** (**Wind: 125**, PV: 60.8, Hydro: 17.5, Biomass: 50.2)
- Current **curtailed electrical energy** per year in Germany (mostly from wind energy) is ca. **6 TWh**
- Current stock market **price of natural gas** in Germany is **40 - 50 €/MWh**
- Current stock market **price of electrical energy** in Germany is **80 - 90 €/MWh**
- Current **price of CO_2 certificates** in Germany is about **90 €/t**
- 1 MWh methane converts into 0.2 t of **CO_2**, which then gives currently a **penalty of 18 €/MWh** for fossil methane

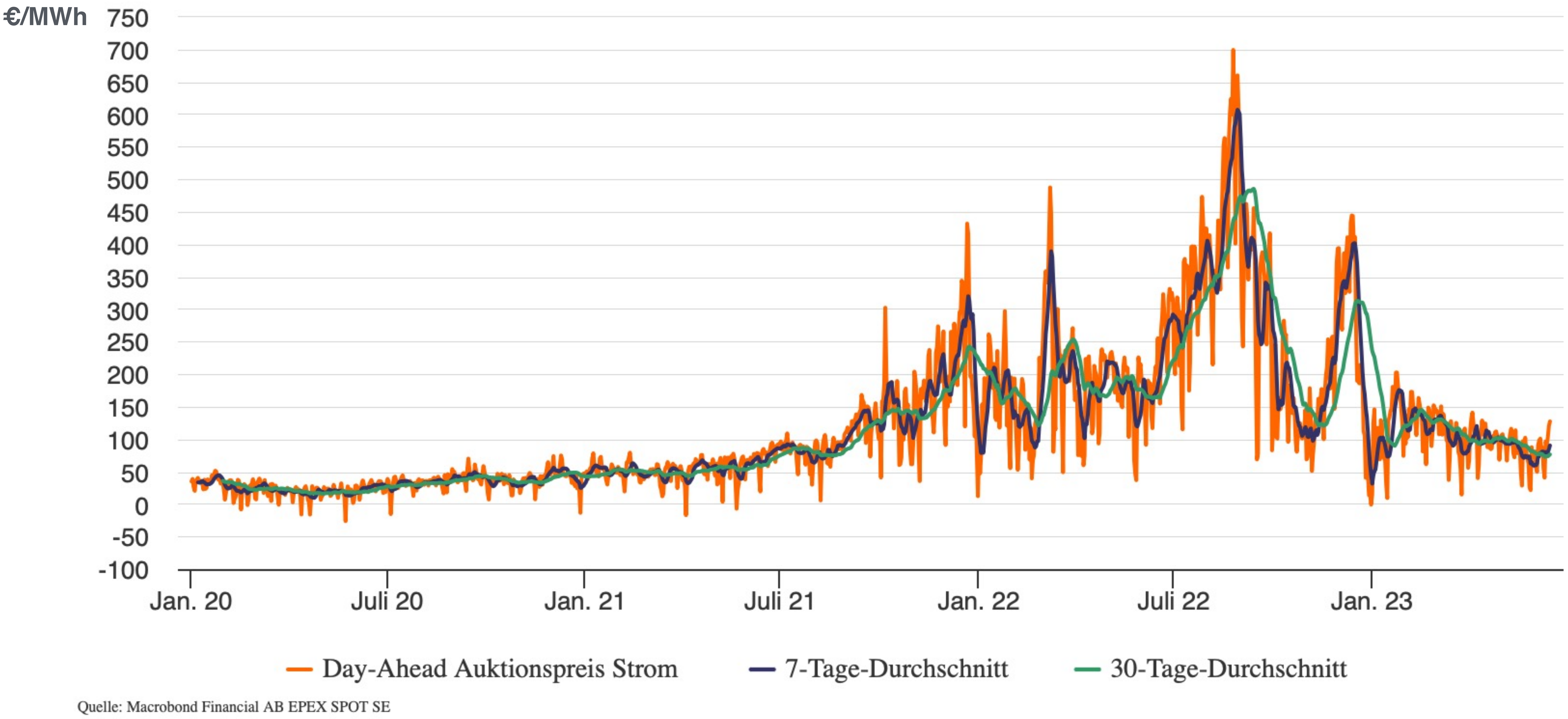
→ To make PtG economically viable, we need a much higher CO_2 certificate price or natural gas price, or a much lower electricity price; Imports from sweet spots and load-flexible plants

Stock market gas price in Germany



Source: https://www.bundesnetzagentur.de/DE/Gasversorgung/aktuelle_gasversorgung/_svg/Gaspreise/Gaspreise.html

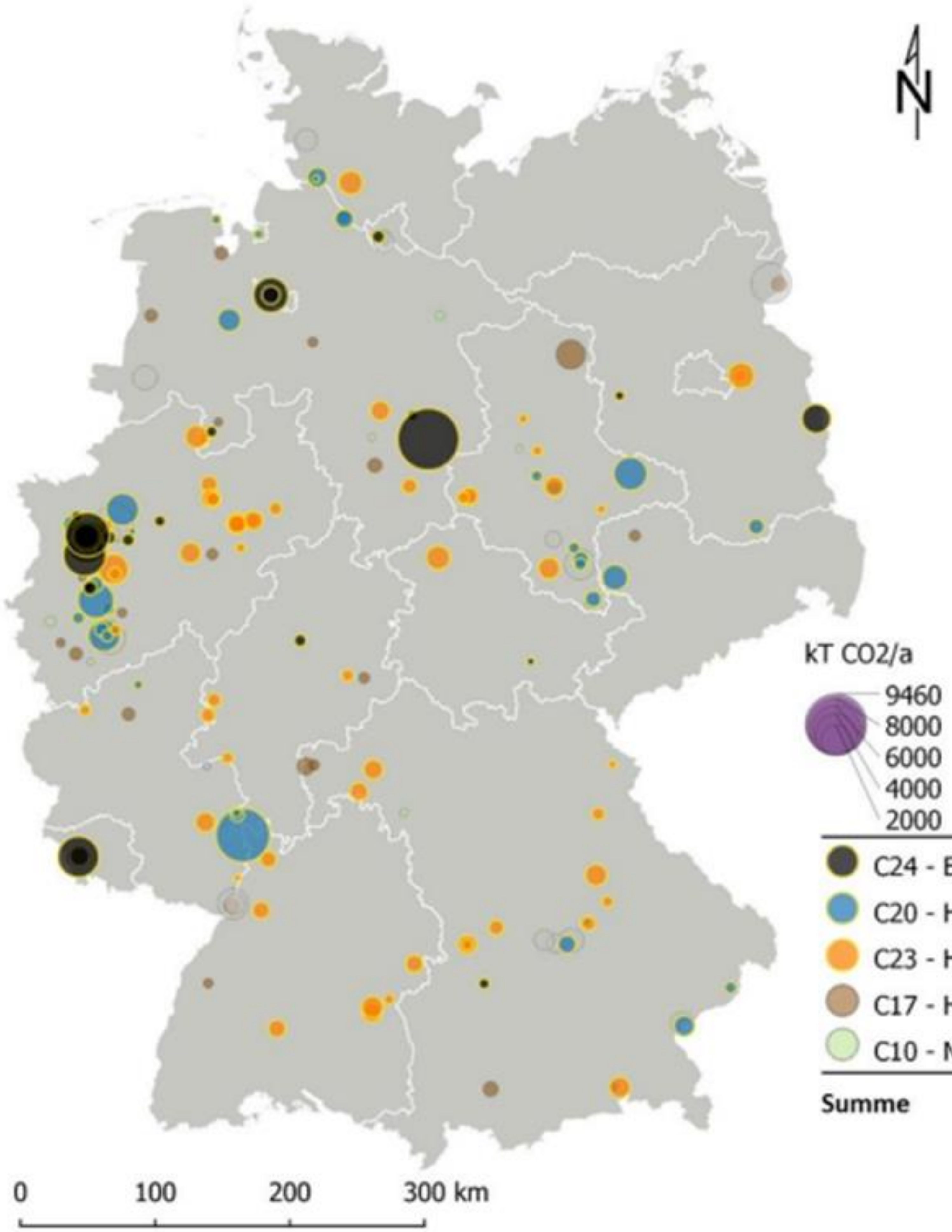
Stock market electricity price in Germany



Source: https://www.dashboard-deutschland.de/indicator/data_preise_strom

Where could the CO_2 come from?

And there is air, be it ambient or indoor…

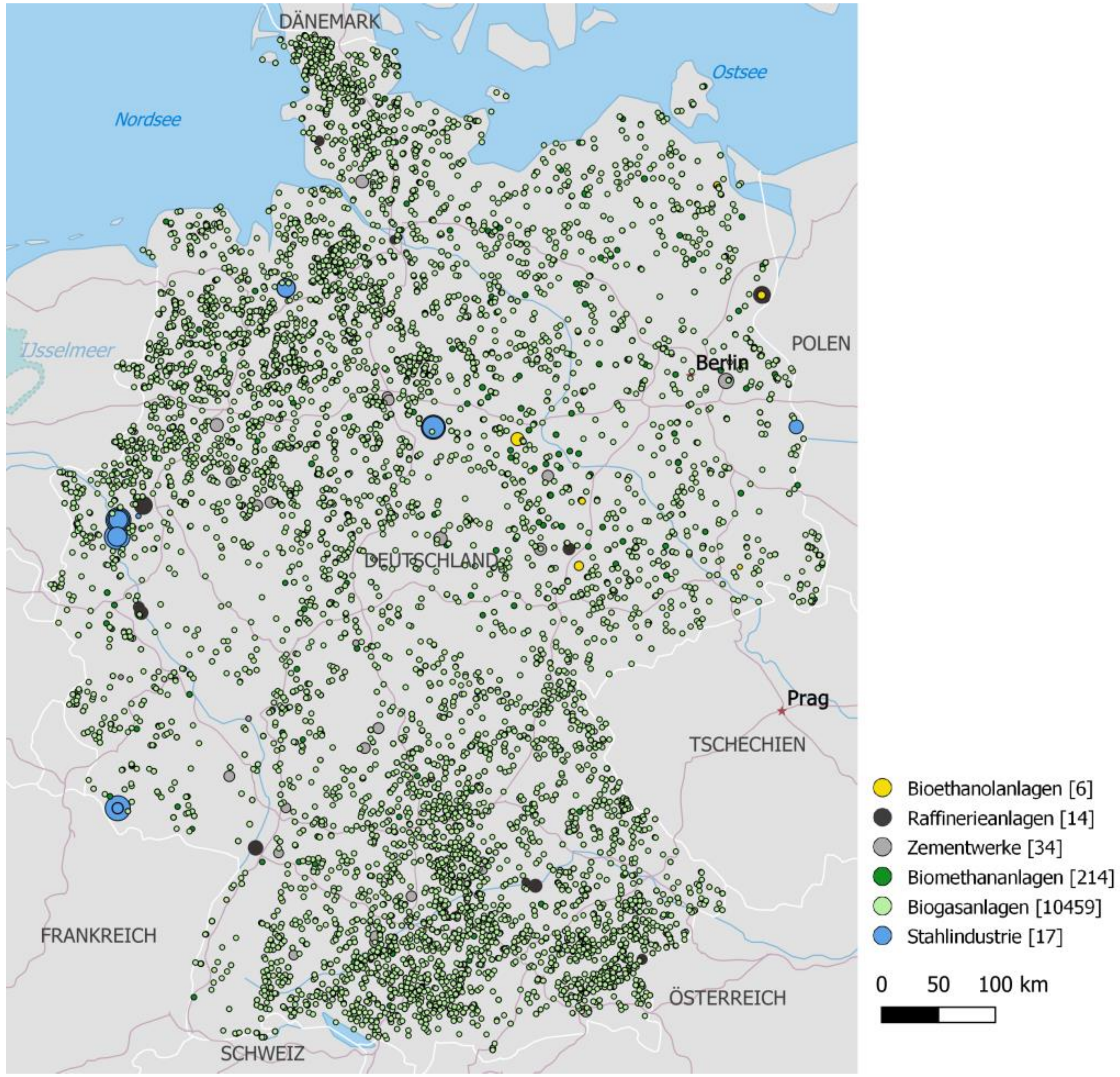


	CO_2 [kt/a]	Anzahl
C24 - Eisen- und Stahlerzeugung, Metalle	40.694	28
C20 - Herstellung chemischer Produkte	29.603	40
C23 - Herstellung von Zement, Glas, Keramik	27.546	57
C17 - Herstellung von Papier- und Pappe	6.779	21
C10 - Nahrungsmittelherstellung	1.326	9
Summe	**105.948**	**155**

Industrial point sources
106 Mio. t CO_2

Bioenergy plants
35 Mio. t CO_2

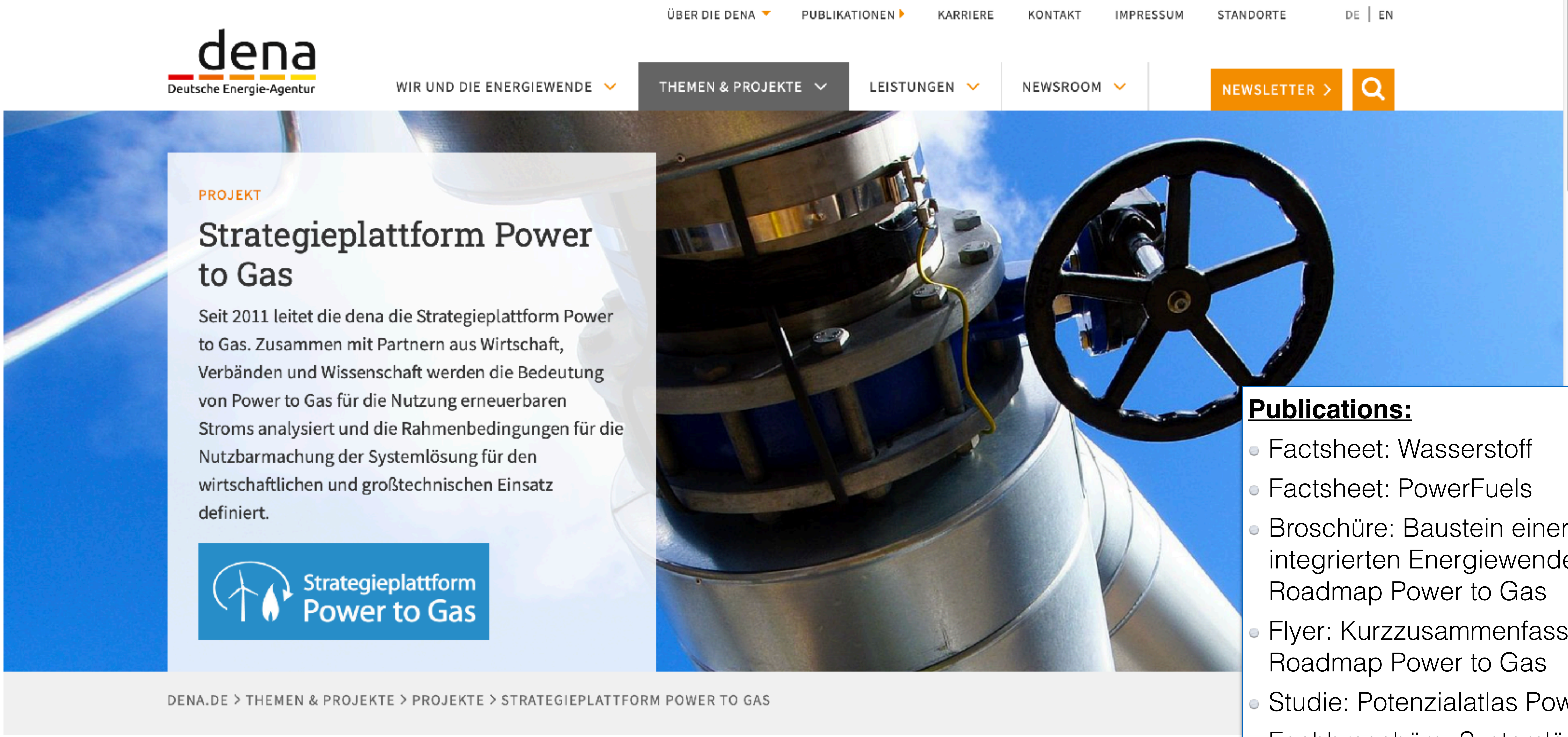
Fossil power plants
222 Mio. t CO_2



Source: Fröhlich et al. (2019), DEHST 2021: Emissionshandelspflichtige Anlagen in Deutschland 2020 (Stand 03.05.2021), eigene Darstellung IZES, MVA nicht vollständig, Umweltbundesamt 2021

Source: P. Heinzmann, S. Glöser-Chahoud, KIT-IIP, reFuels-Projekt am KIT, 2019

The PtX landscape in Germany - dena Strategieplattform Power to Gas (2011)

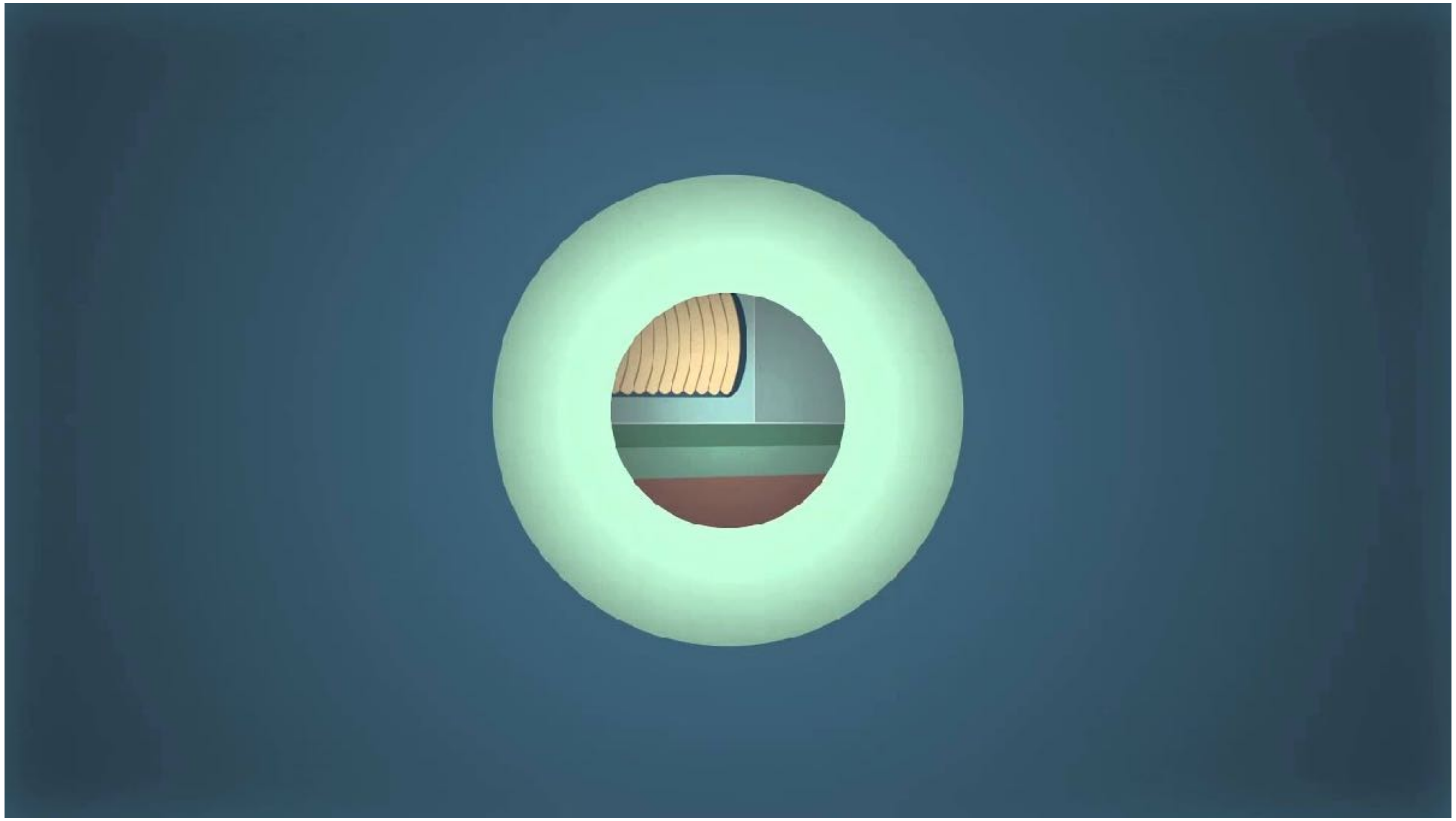


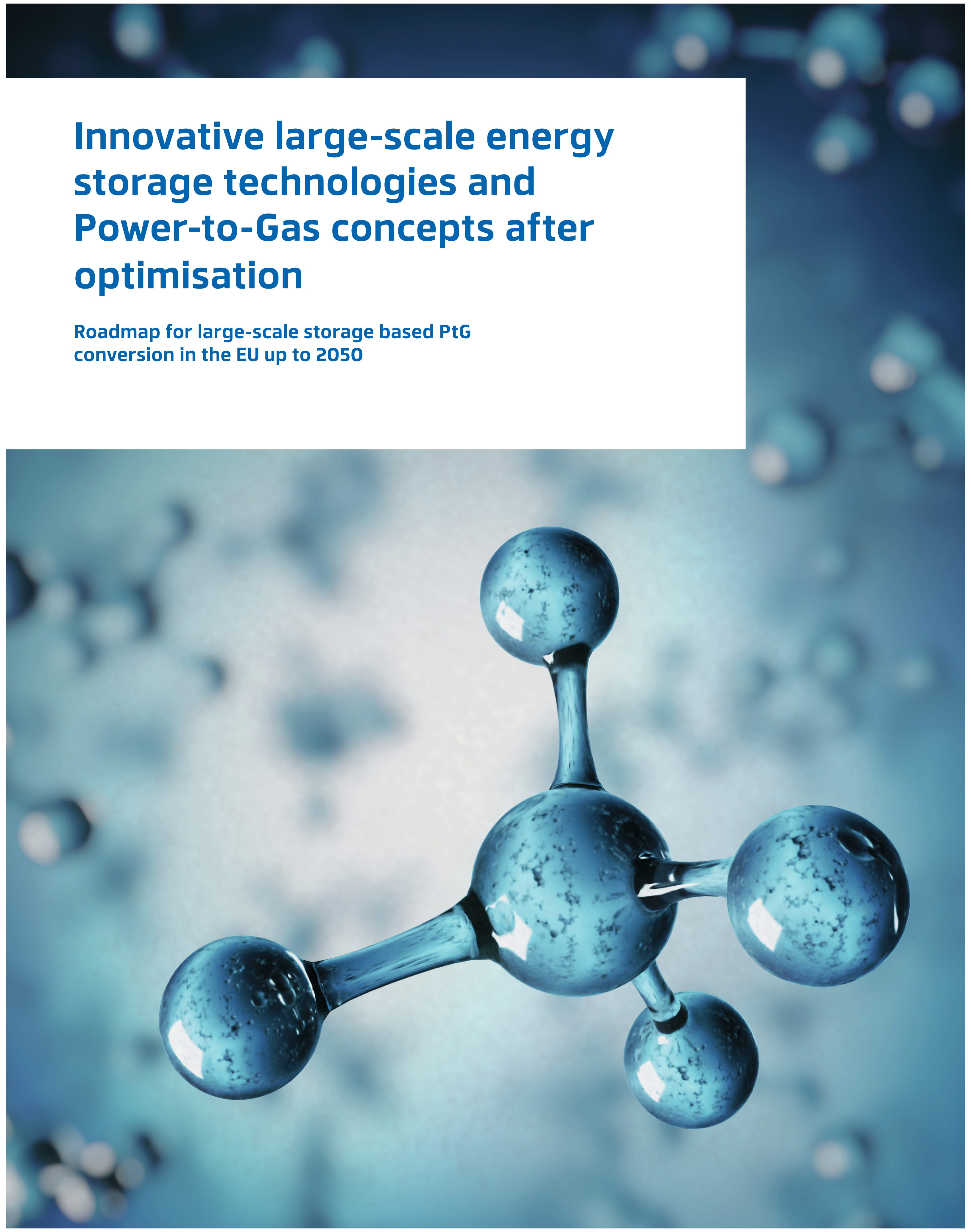
Publications:

- Factsheet: Wasserstoff
- Factsheet: PowerFuels
- Broschüre: Baustein einer integrierten Energiewende: Roadmap Power to Gas
- Flyer: Kurzzusammenfassung Roadmap Power to Gas
- Studie: Potenzialatlas Power to Gas
- Fachbroschüre: Systemlösung Power to Gas

Source: https://www.dena.de/themen-projekte/projekte/projektarchiv/strategieplattform-power-to-gas/

The PtX landscape in Germany - DVGW / H2020 Project Store&Go





Source: https://www.dvgw.de/themen/energiewende/power-to-gas

Methanation of carbon dioxide

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Main reaction

$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$	$\Delta H_R^0 = -165.1\ kJ/mol$	Sabatier reaction

Side reactions

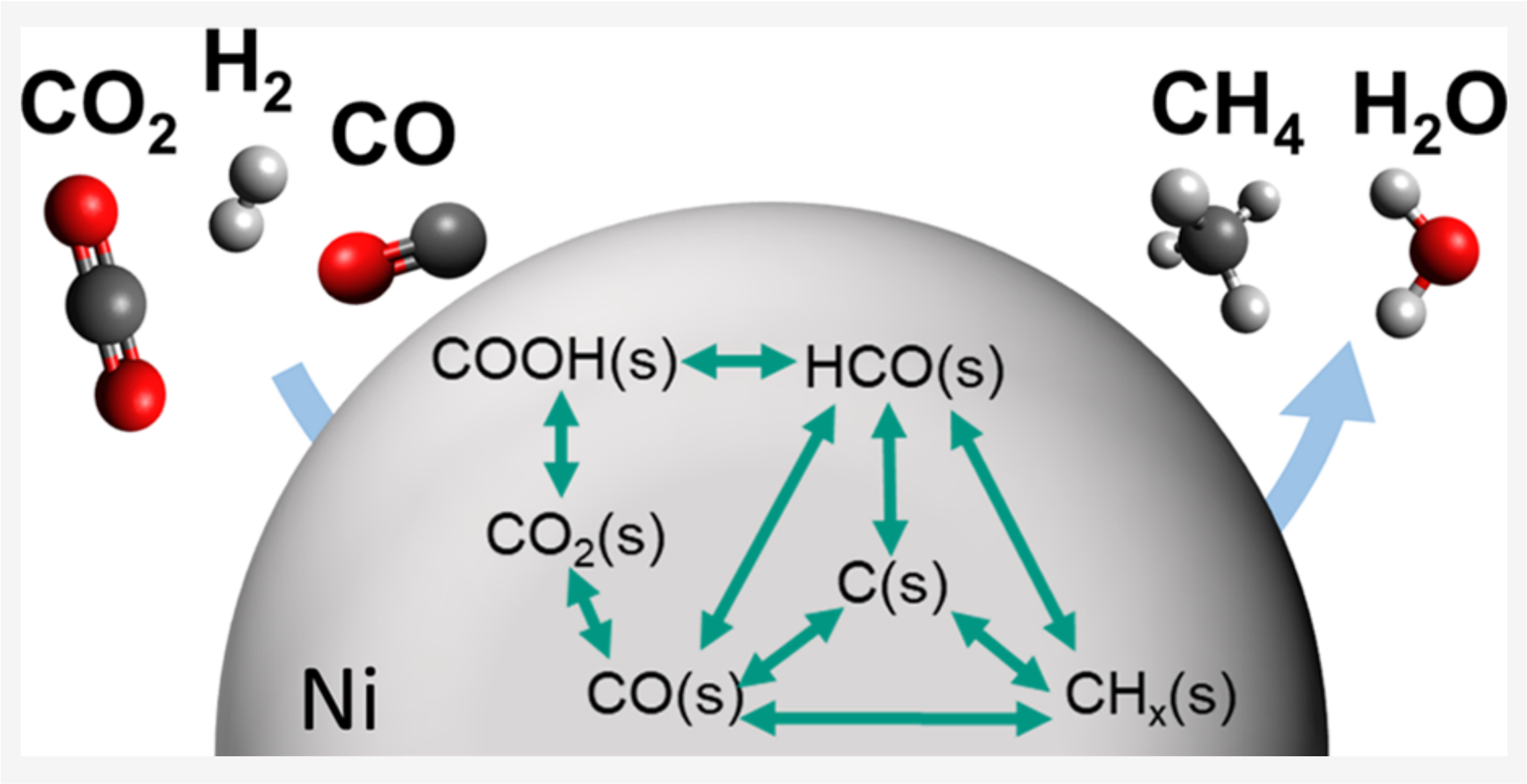
$CO_2 + H_2 \rightleftharpoons CO + H_2O$	$\Delta H_R^0 = 41.2\ kJ/mol$	Reverse water gas shift reaction (rWGS)
$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$	$\Delta H_R^0 = -206.3\ kJ/mol$	CO methanation
$2CO \rightleftharpoons CO_2 + C$	$\Delta H_R^0 = -172.5\ kJ/mol$	Boudouard reaction
$CH_4 \rightleftharpoons C + 2H_2$	$\Delta H_R^0 = 74.9\ kJ/mol$	Methane pyrolysis

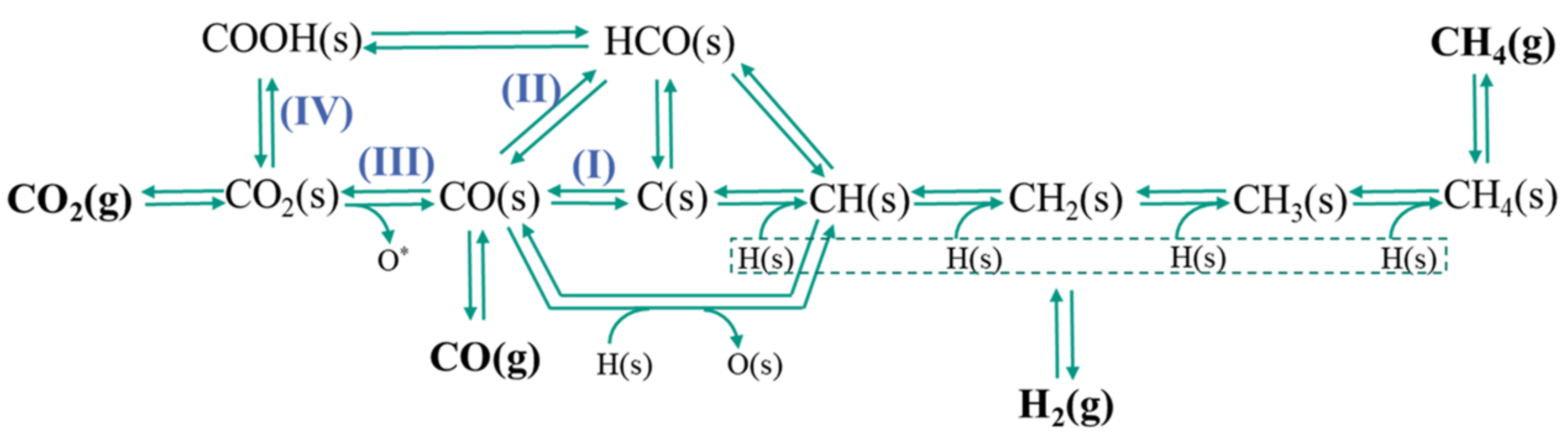
Catalysts

- Typically Ni supported on Al_2O_3, SiO_2, ZrO_2, TiO_2, $MgAl_2O_4$
- Typically 5-40 wt.-% Ni
- Issues: carbon formation, sintering, stability in transient operation

Detailed reaction mechanism

Actual surface reaction mechanism is much more complex;
42 elementary steps proposed





Source: D. Schmider et al., *Ind. Eng. Chem. Res.* **2021**, *60, 5792–5805*

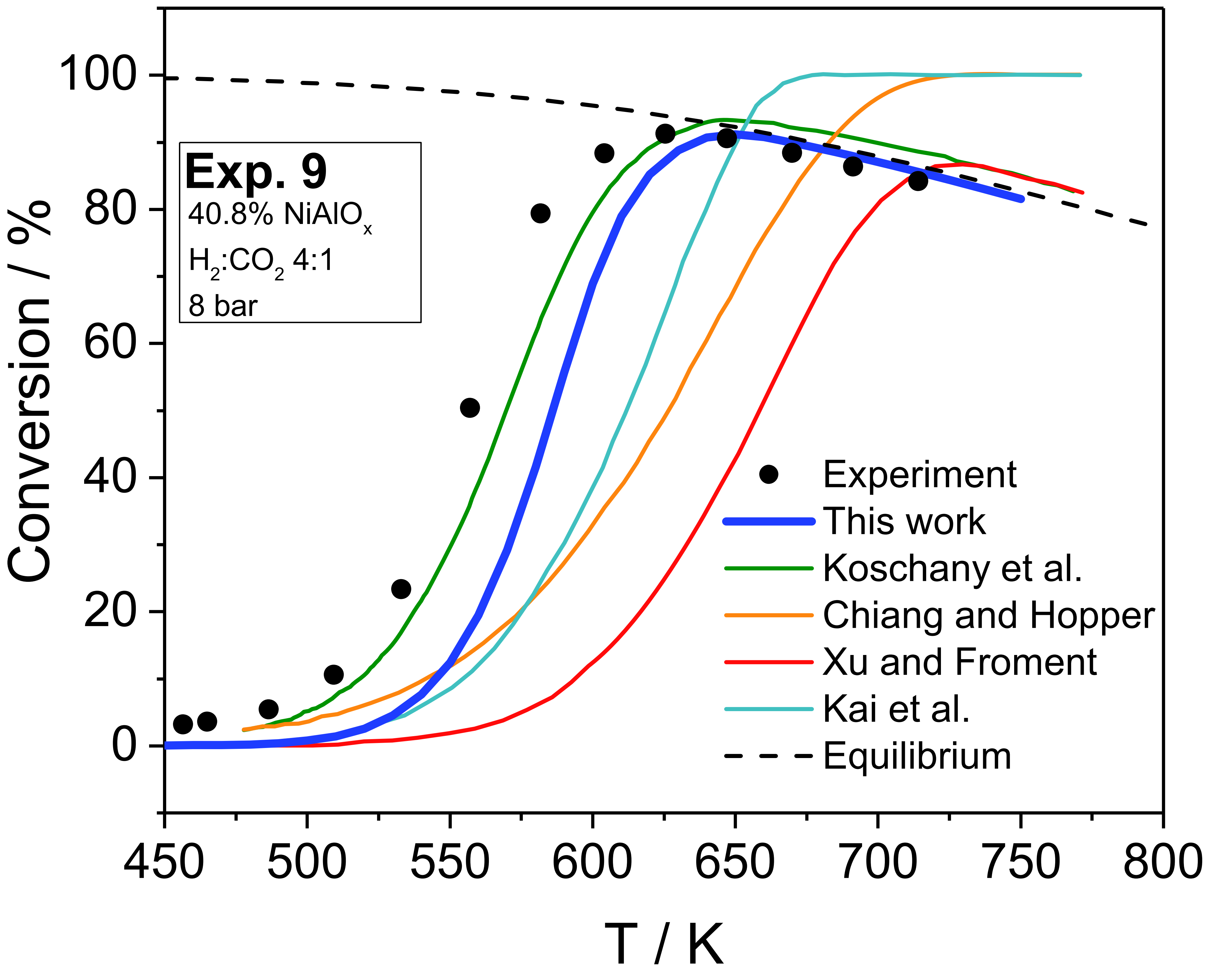
Table 2. Detailed, Thermodynamically Consistent Reaction Mechanism for the Methanation of CO and CO_2 over Ni[a]

reaction	A_j (cm, mol, s) or S_0 (*)	β_j	$E_{a,j}$ (kJ mol^{-1})	ε_{ij} (kJ mol^{-1})
$H_2 + 2(s) \rightarrow 2H(s)$ (R1)	1.46×10^{-2}*	0	0	
$2H(s) \rightarrow H_2 + 2(s)$ (R2)	4.54×10^{21}	−0.138	96.1	
$CH_4 + (s) \rightarrow CH_4(s)$ (R3)	1.06×10^{-2}*	0	0	
$CH_4(s) \rightarrow CH_4 + (s)$ (R4)	2.79×10^{15}	0.085	37.0	
$H_2O + (s) \rightarrow H_2O(s)$ (R5)	1.16×10^{-1}*	0	0	
$H_2O(s) \rightarrow H_2O + (s)$ (R6)	2.04×10^{12}	−0.031	61.0	
$CO_2 + (s) \rightarrow CO_2(s)$ (R7)	6.29×10^{-5}*	0	0	
$CO_2(s) \rightarrow CO_2 + (s)$ (R8)	4.99×10^{7}	0.018	25.8	
$CO + (s) \rightarrow CO(s)$ (R9)	3.74×10^{-1}*	0	0	
$CO(s) \rightarrow CO + (s)$ (R10)	1.14×10^{12}	−0.103	112.0	50.0†
$CO_2(s) + (s) \rightarrow CO(s) + O(s)$ (R11)	1.60×10^{23}	−1.001	89.3	
$CO(s) + O(s) \rightarrow CO_2(s) + (s)$ (R12)	5.81×10^{19}	0	123.6	50.0†
$CO(s) + (s) \rightarrow C(s) + O(s)$ (R13)	2.36×10^{14}	0	116.2	50.0†
$C(s) + O(s) \rightarrow CO(s) + (s)$ (R14)	2.54×10^{18}	0	148.1	105.0‡
$CO(s) + H(s) \rightarrow C(s) + OH(s)$ (R15)	3.05×10^{18}	−0.223	105.3	50.0†
$C(s) + OH(s) \rightarrow CO(s) + H(s)$ (R16)	2.18×10^{18}	0.128	62.8	105.0‡
$CO(s) + H(s) \rightarrow HCO(s) + (s)$ (R17)	6.82×10^{21}	−0.979	132.1	
$HCO(s) + (s) \rightarrow CO(s) + H(s)$ (R18)	2.18×10^{20}	−0.021	0.2	−50.0†
$HCO(s) + (s) \rightarrow CH(s) + O(s)$ (R19)	5.10×10^{15}	0.023	81.7	
$CH(s) + O(s) \rightarrow HCO(s) + (s)$ (R20)	3.42×10^{19}	−0.023	110.2	
$H(s) + C(s) \rightarrow CH(s) + (s)$ (R21)	1.33×10^{24}	−0.456	157.7	105.0‡
$CH(s) + (s) \rightarrow C(s) + H(s)$ (R22)	2.63×10^{22}	0.456	22.3	
$CH(s) + H(s) \rightarrow CH_2(s) + (s)$ (R23)	3.21×10^{25}	−0.084	81.1	
$CH_2(s) + (s) \rightarrow CH(s) + H(s)$ (R24)	6.16×10^{24}	0.084	95.2	
$CH_2(s) + H(s) \rightarrow CH_3(s) + (s)$ (R25)	7.78×10^{22}	−0.048	59.5	
$CH_3(s) + (s) \rightarrow CH_2(s) + H(s)$ (R26)	6.16×10^{24}	0.048	95.9	
$CH_3(s) + H(s) \rightarrow CH_4(s) + (s)$ (R27)	3.63×10^{21}	−0.048	65.7	
$CH_4(s) + (s) \rightarrow CH_3(s) + H(s)$ (R28)	6.16×10^{21}	0.048	53.6	
$H(s) + O(s) \rightarrow OH(s) + (s)$ (R29)	1.16×10^{24}	−0.176	104.2	
$OH(s) + (s) \rightarrow H(s) + O(s)$ (R30)	7.70×10^{19}	0.176	29.8	
$H(s) + OH(s) \rightarrow H_2O(s) + (s)$ (R31)	2.34×10^{20}	0.075	44.1	
$H_2O(s) + (s) \rightarrow OH(s) + H(s)$ (R32)	2.91×10^{21}	−0.075	90.4	
$2OH(s) \rightarrow H_2O(s) + O(s)$ (R33)	1.01×10^{20}	0.251	95.1	
$H_2O(s) + O(s) \rightarrow 2OH(s)$ (R34)	1.89×10^{25}	−0.251	215.8	
$H(s) + CO_2(s) \rightarrow COOH(s) + (s)$ (R35)	1.29×10^{25}	−0.46	117.2	
$COOH(s) + (s) \rightarrow CO_2(s) + H(s)$ (R36)	1.29×10^{20}	0.46	33.8	
$COOH(s) + (s) \rightarrow CO(s) + OH(s)$ (R37)	6.03×10^{23}	−0.216	54.4	
$CO(s) + OH(s) \rightarrow COOH(s) + (s)$ (R38)	1.45×10^{21}	0.216	97.6	50.0†
$COOH(s) + H(s) \rightarrow HCO(s) + OH(s)$ (R39)	4.22×10^{23}	−1.145	104.7	
$HCO(s) + OH(s) \rightarrow COOH(s) + H(s)$ (R40)	3.25×10^{19}	0.245	16.1	
$2CO(s) \rightarrow CO_2(s) + C(s)$ (R41)	6.31×10^{13}	0.5	241.7	100.0†
$C(s) + CO_2(s) \rightarrow 2CO(s)$ (R42)	1.88×10^{21}	−0.5	239.3	105.0‡

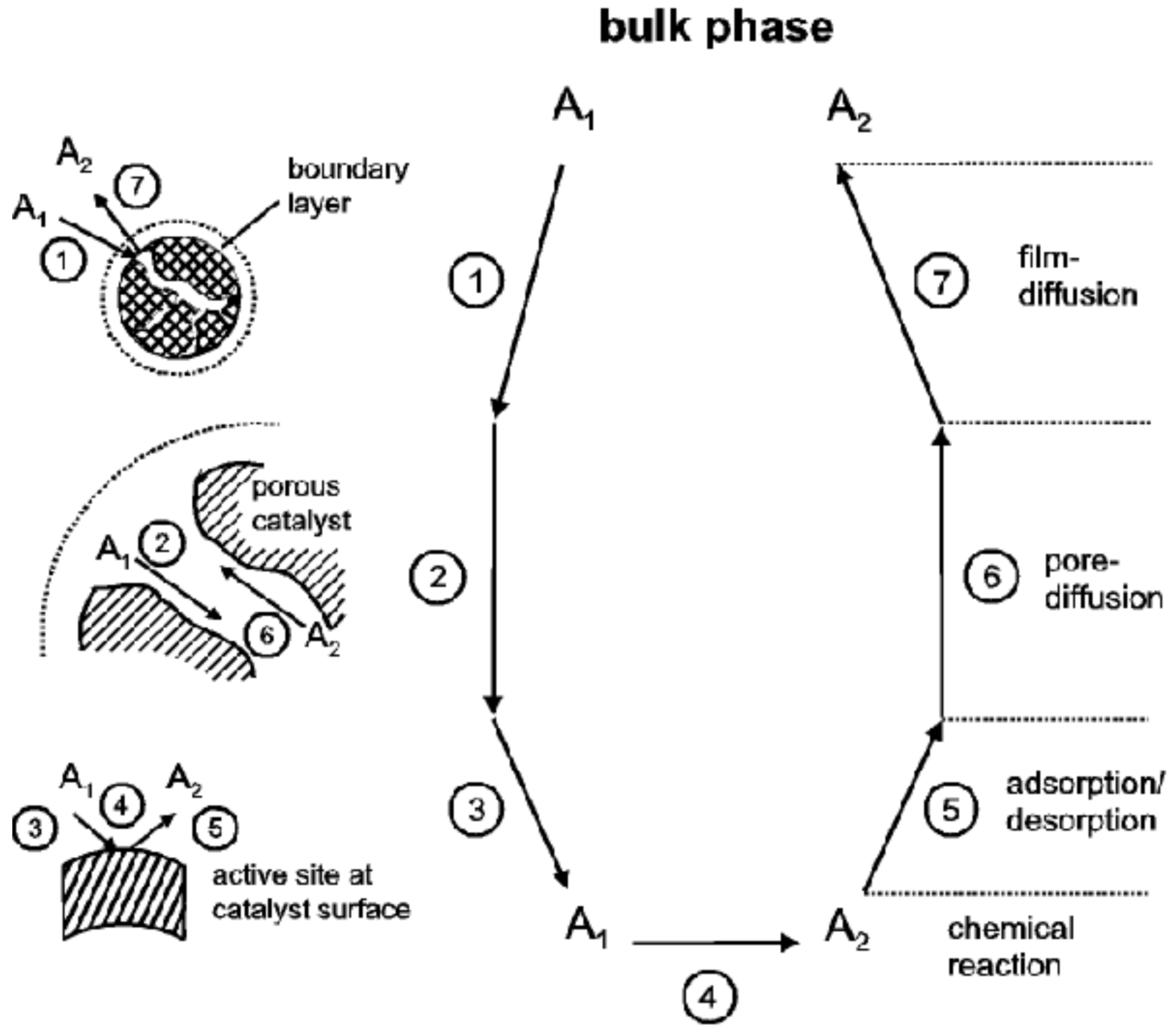
[a](s) represents an empty surface site. † denotes coverage dependency on CO(s), ‡ on C(s). The mechanism is available in electronic form at www.detchem.com.

Kinetics for a stoichiometric mixture of $H_2:CO_2$ = 4:1

Comparison of the predicted conversions for a CO_2 methanation experiment for the detailed kinetic model (blue) and a sample of global models.



- Note that the reaction is fast and highly exothermic, and isothermal conditions are difficult to achieve.
- In addition to heat removal from the reactor, heat and mass transport around and inside the catalyst particles may also affect the experimental results.



Source: D. Schmider et al., *Ind. Eng. Chem. Res.* **2021**, *60, 5792–5805*

Equilibrium position for a stoichiometric mixture of H_2:CO_2 = 4:1

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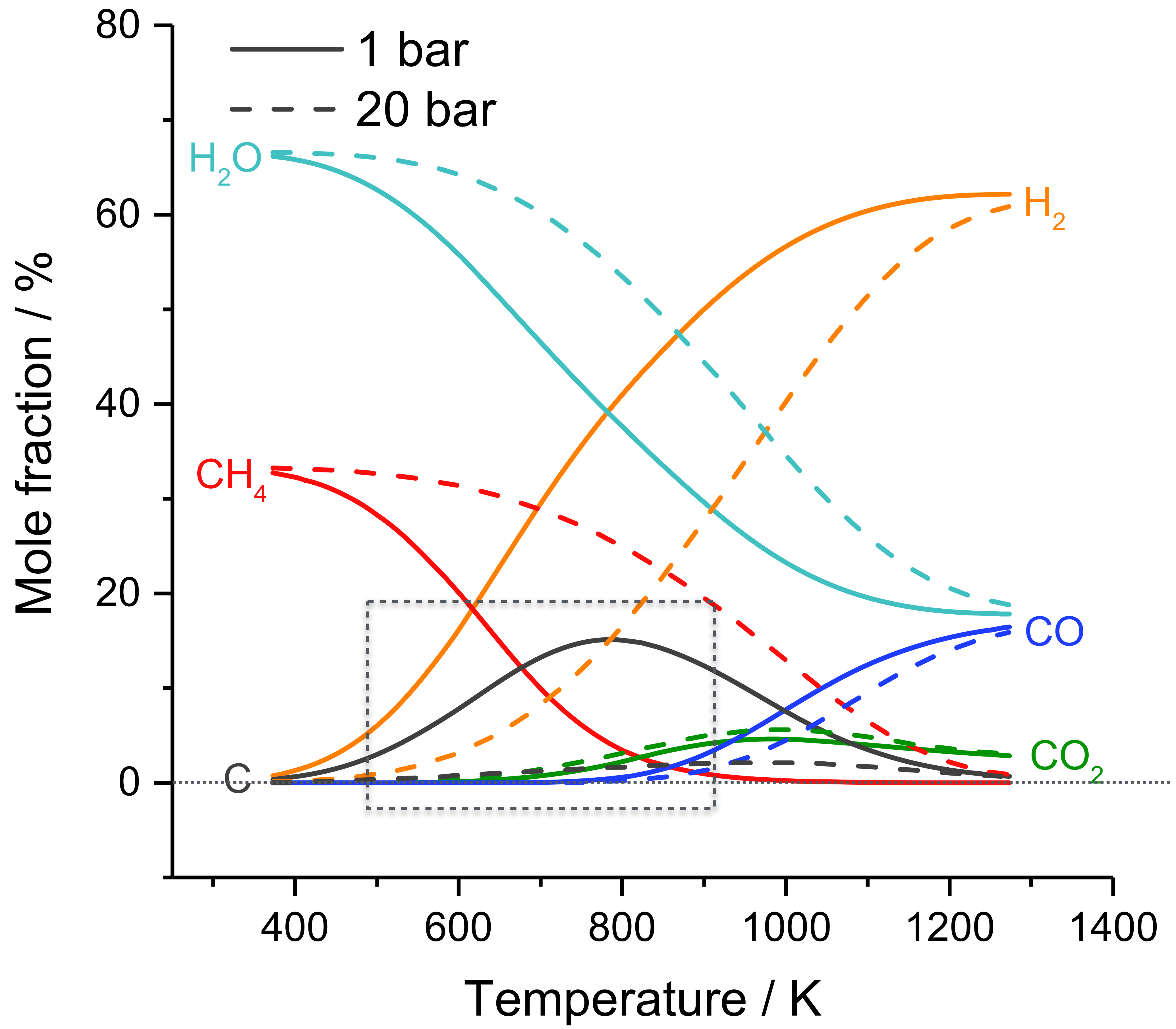
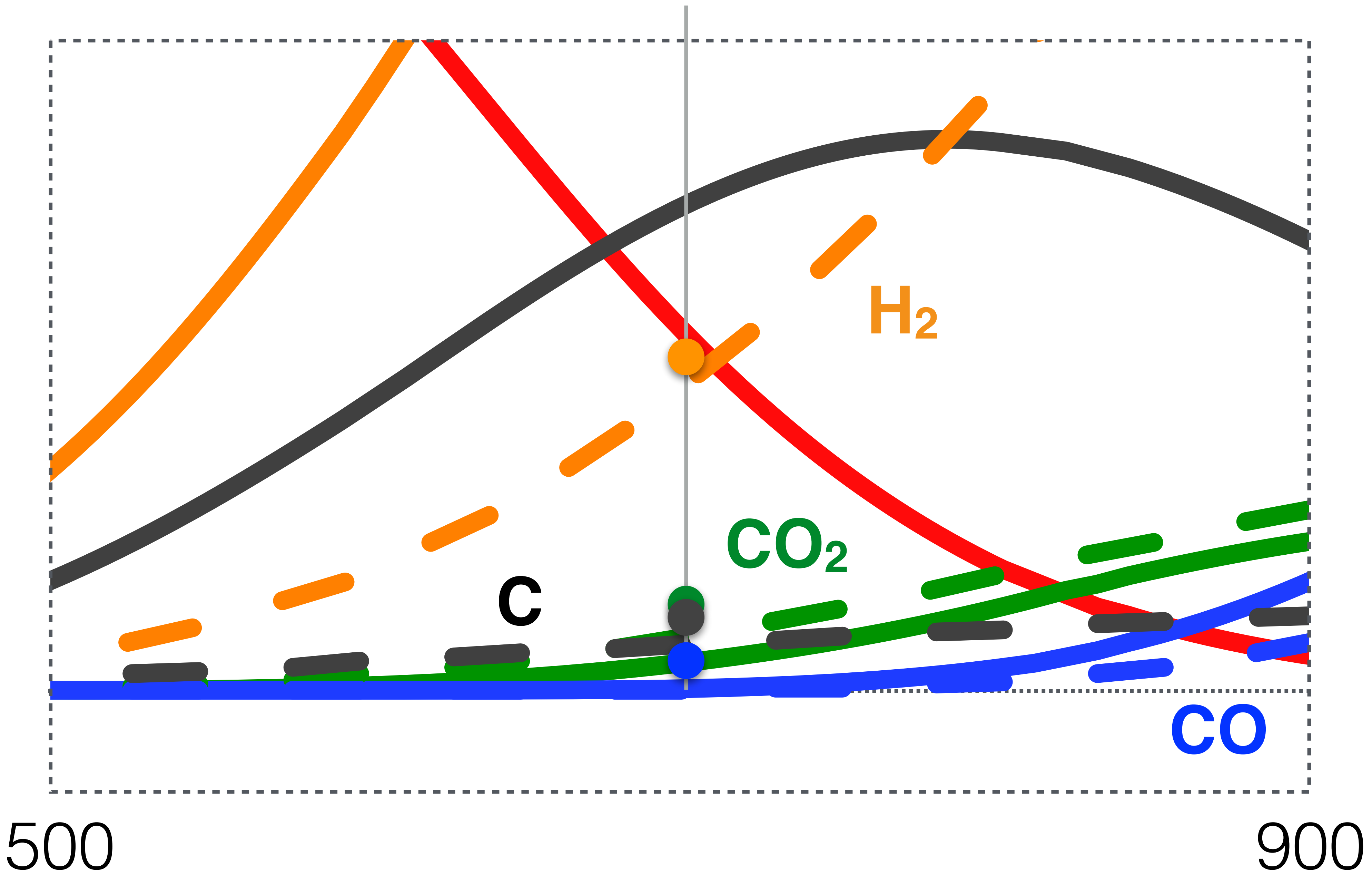
Thermodynamics set the boundary for what you may achieve in a practical system



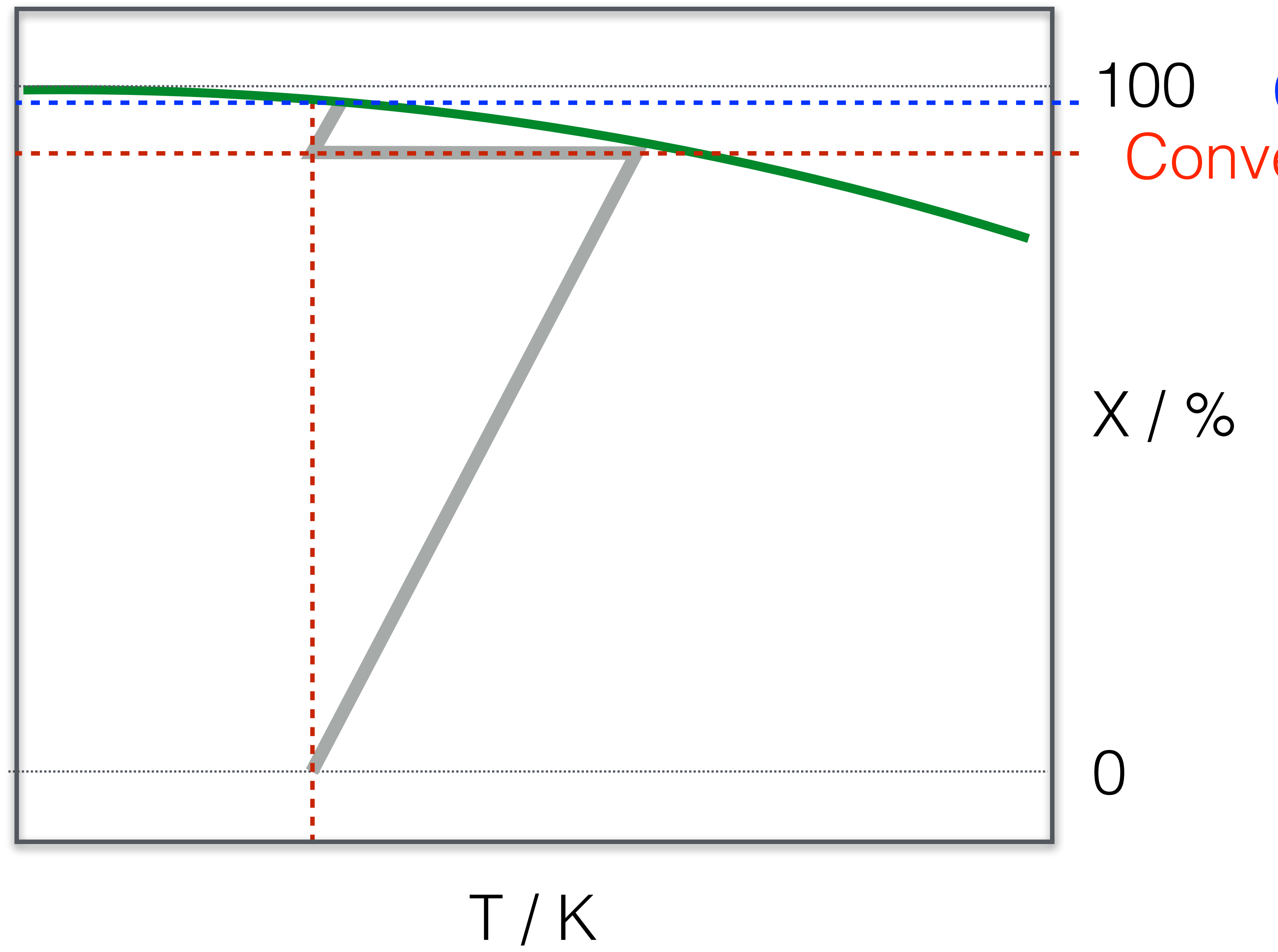


- High equilibrium conversion is favoured by low temperature and high pressure
- Carbon formation is expected over a wide temperature range, in particular at low pressure

Source: D. Schmider et al., *Ind. Eng. Chem. Res.* **2021**, *60, 5792–5805*

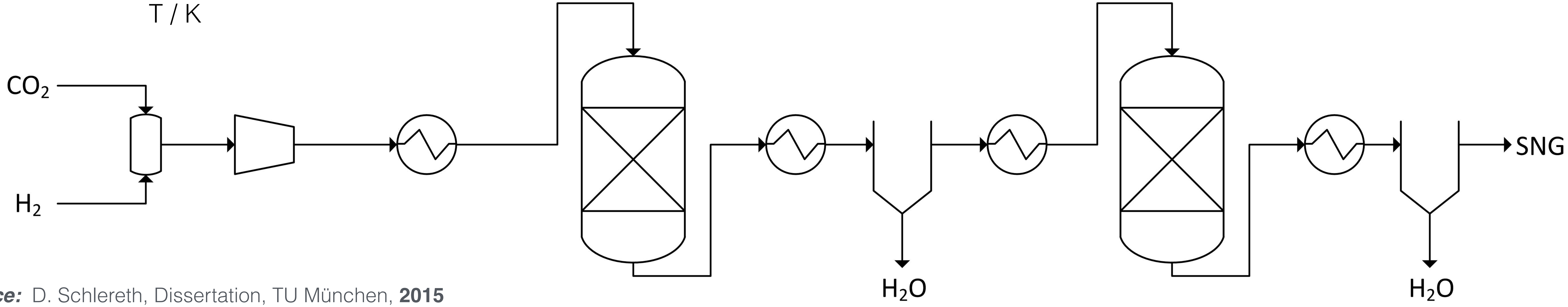
How to reach high conversion required for grid injection?

Standard approach in chemical engineering is to use consecutive adiabatic reactor stages with indirect or direct interstage cooling. In the case of methanation, two stages should be sufficient.



Simplified flow scheme of Solar Fuel's patented process.

Solar Fuel GmbH, The high efficiency process for the catalytic methanation of gas mixtures containing carbon dioxide and hydrogen **2011**, DE 10 2009 059 310 A1



Source: D. Schlereth, Dissertation, TU München, **2015**

Reactors for catalytic methanation

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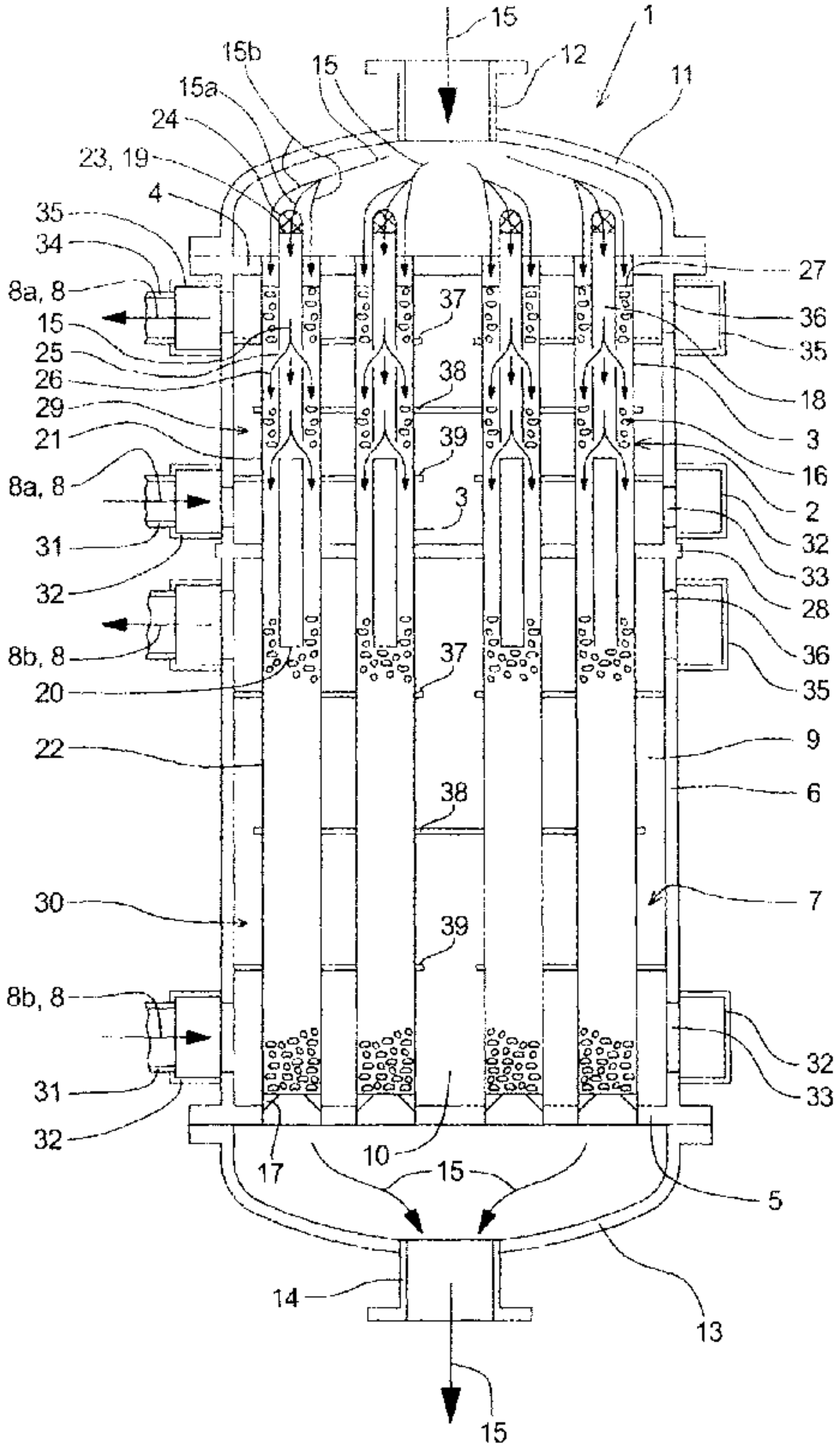
Packed bed tubular reactor with cooling by evaporation of water under pressure or by molten salt

Built by MAN Diesel & Turbo in 6.3 MW_{el} scale at EWE's biogas site in Werlte (2013).

- Methane content 92-95%
- Dynamic operation 70-100%
- Footprint 8 x 4 x 15.5 m

Source: https://bit.ly/3QoRQQi; https://bit.ly/3xqF1MK



Source: R. Bank, J. Dachs, F. Egner, V. Frick, M. Lehr, M. Specht, B. Stürmer, Shell- and-tube reactor for carrying out catalytic gas phase reactions **2012**, WO 2012 035 173 A1

Strongly exothermic reaction in cooled tubular packed-bed reactors

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Exponential dependency of the heat generation rate on temperature while cooling rate is linear creates hot spot

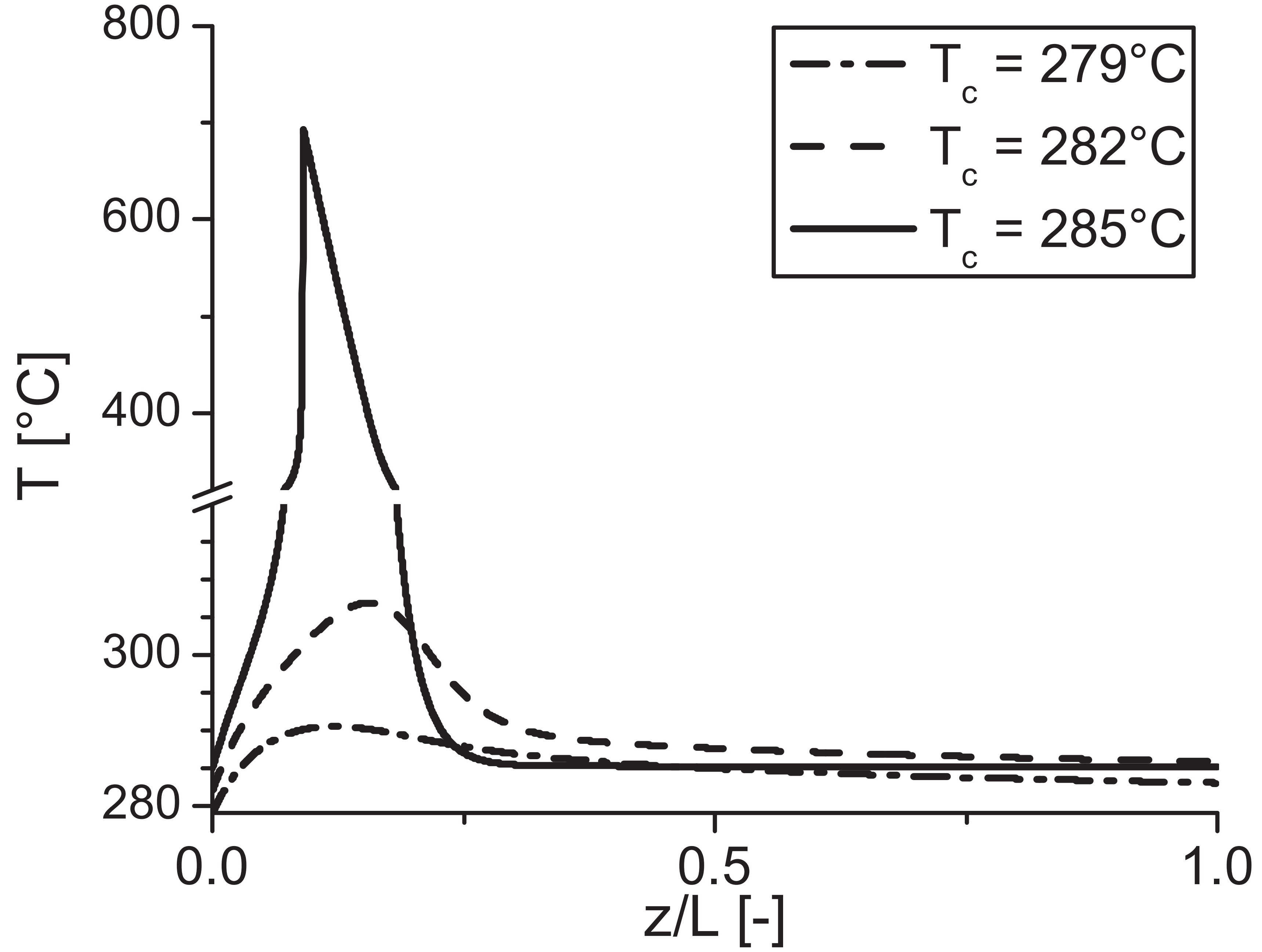
Material balance: $$\frac{\partial(uc_i)}{\partial z} = \rho_{bed} \sum \nu_{ij} r_j$$

Heat balance: $$\frac{\partial(u\rho c_p T)}{\partial z} = \rho_{bed} \sum r_j(-\Delta H_{R,j}) - \frac{4}{d}k(T - T_c)$$

Linear term

$$r_j = k_j^0 e^{-\frac{E}{RT}} \cdot f(\mathbf{c})$$

Exponential term



Challenges:

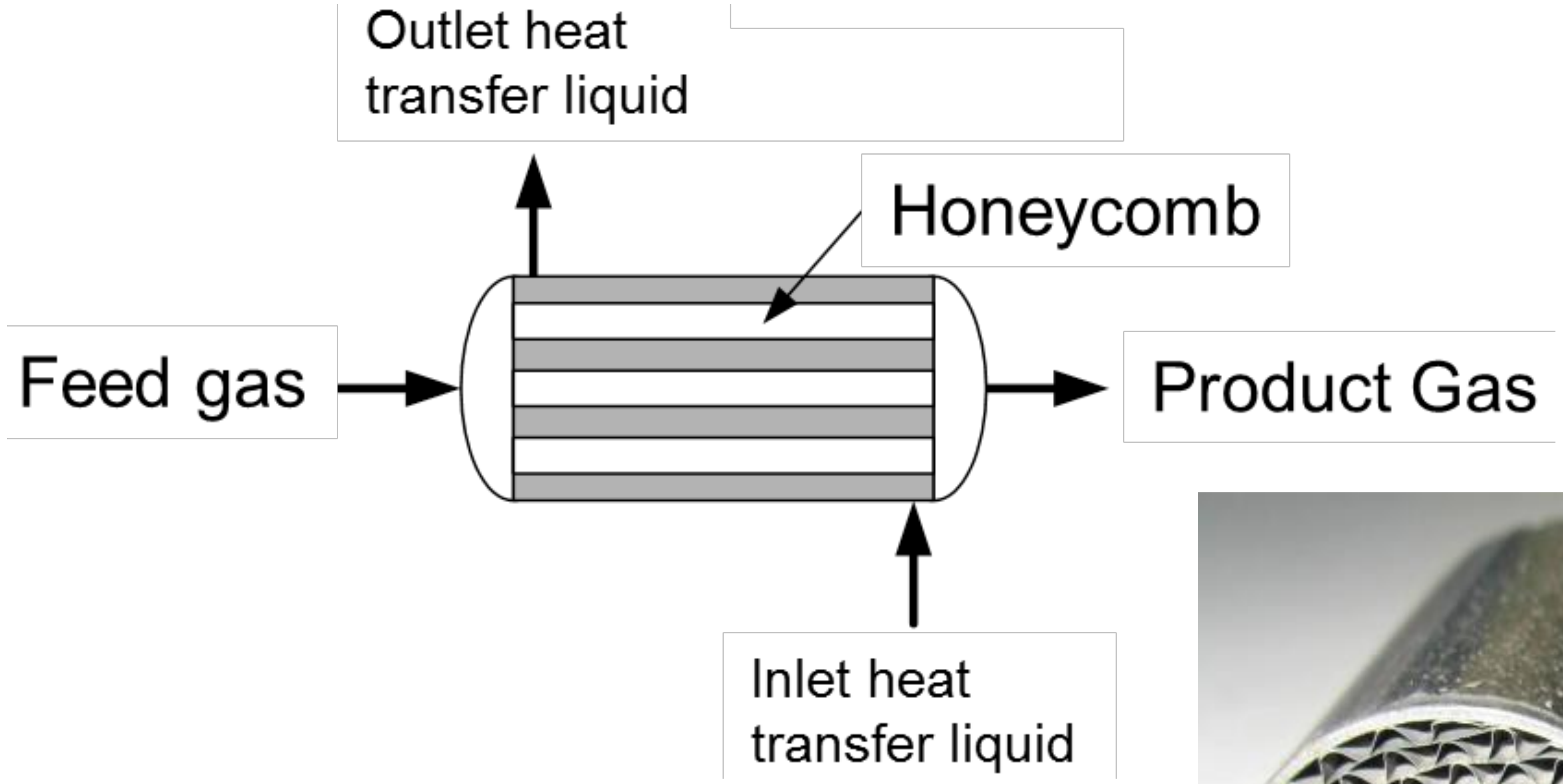
- Thermal runaway
- Catalyst deactivation by sintering
- Low conversion due to low average bed temperature caused by hot spot

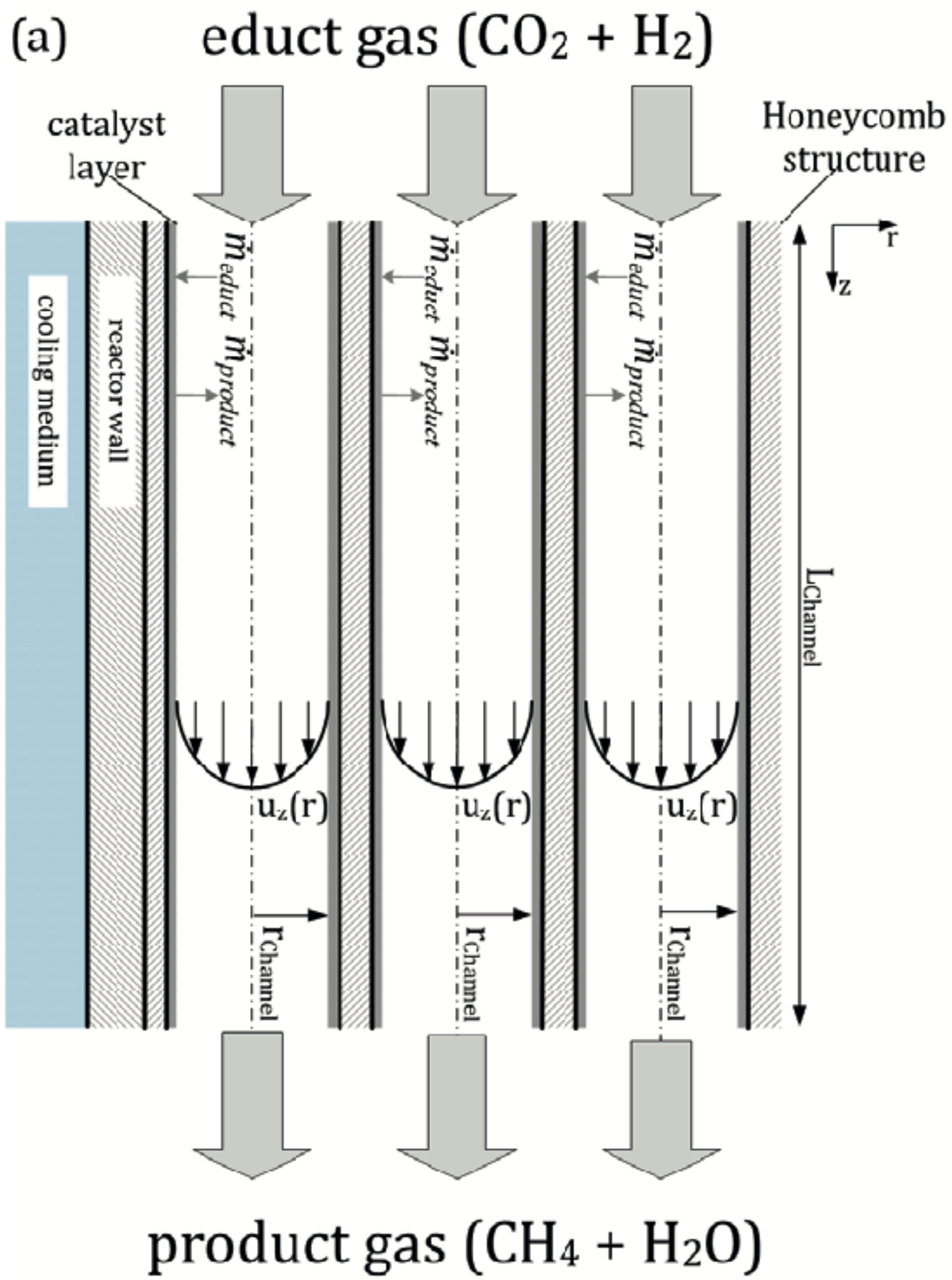
Source: D. Schlereth, O. Hinrichsen, *Chem. Eng. Res. Des.* **2014**, *92*, 702-712.

Reactors for catalytic methanation of CO_2

Advanced structured reactors

- Catalyst coated metallic honeycomb





Source: M. Götz et al., International Gas Union Research Conference, Copenhagen, **2014**, Paper-Code WP4.6, Abstract ID 210.

Source: M. Held et al., *Chem. Ing. Tech.* **2020**, *92*, 595-602.

Reactors for catalytic methanation of CO_2

Fluidised bed

- Bubbling fluidised bed with built in heat exchanger

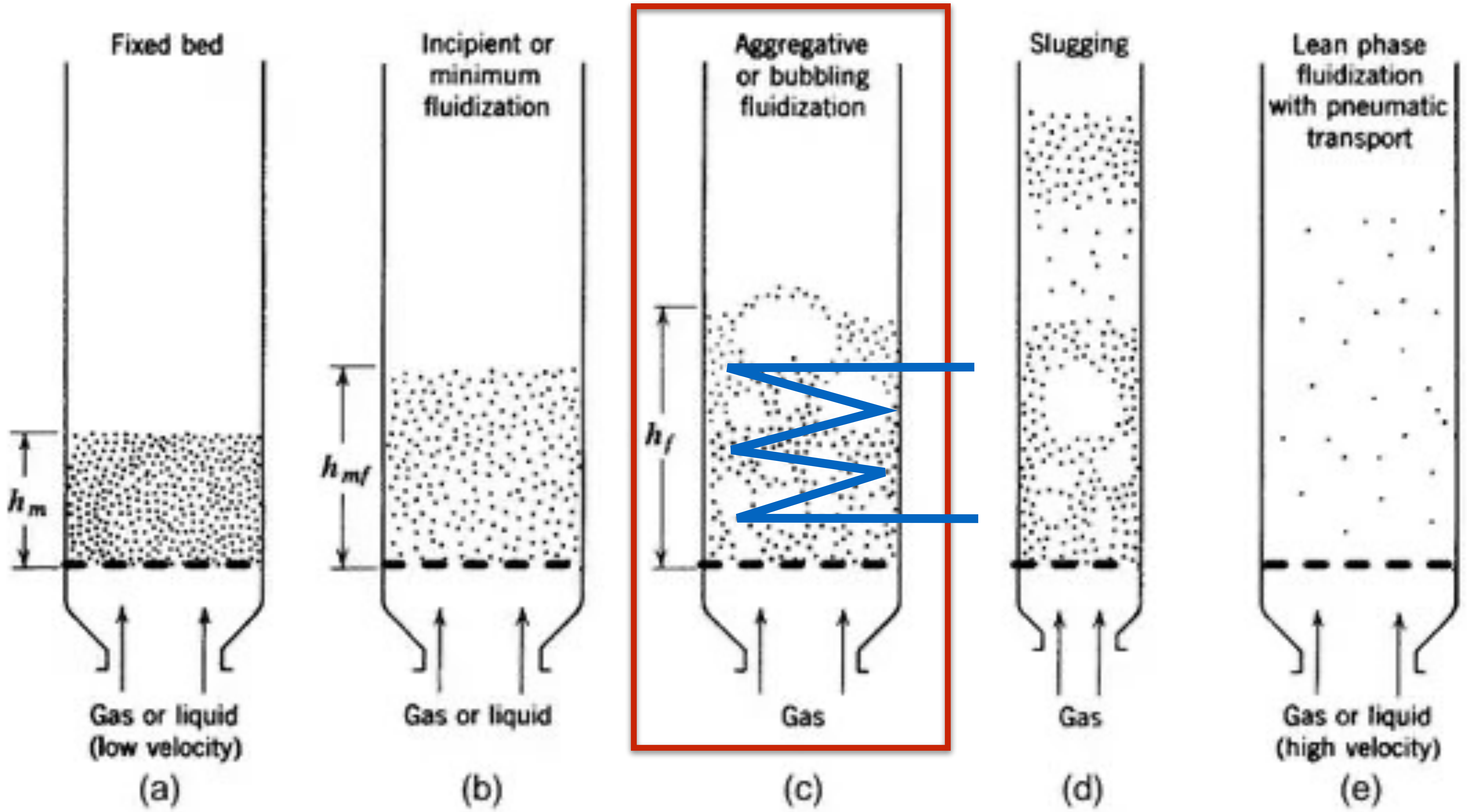


Figure R12.3-2 Various kinds of contacting of a batch of solids by fluid. Adapted from Kunii & Levenspiel, *Fluidized Engineering* (Huntington, NY: Robert E. Krieger Publishing Co., 1977).

Main advantage of fluidised bed over packed bed

- Improved heat transport due to solid's movement

Reactors for catalytic methanation of CO_2

Advanced fluidised bed reactors

- Three-phase slurry bubble column

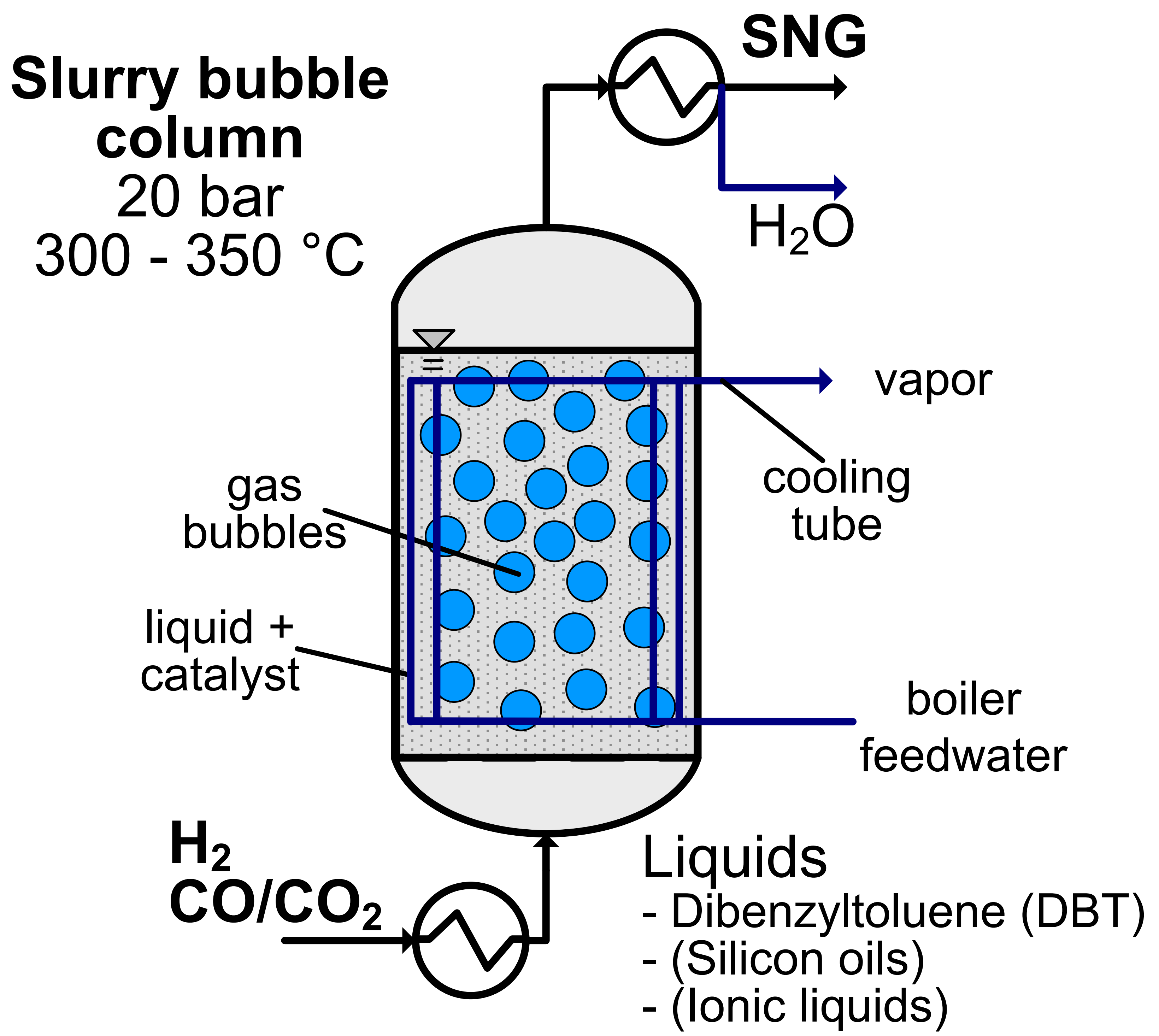
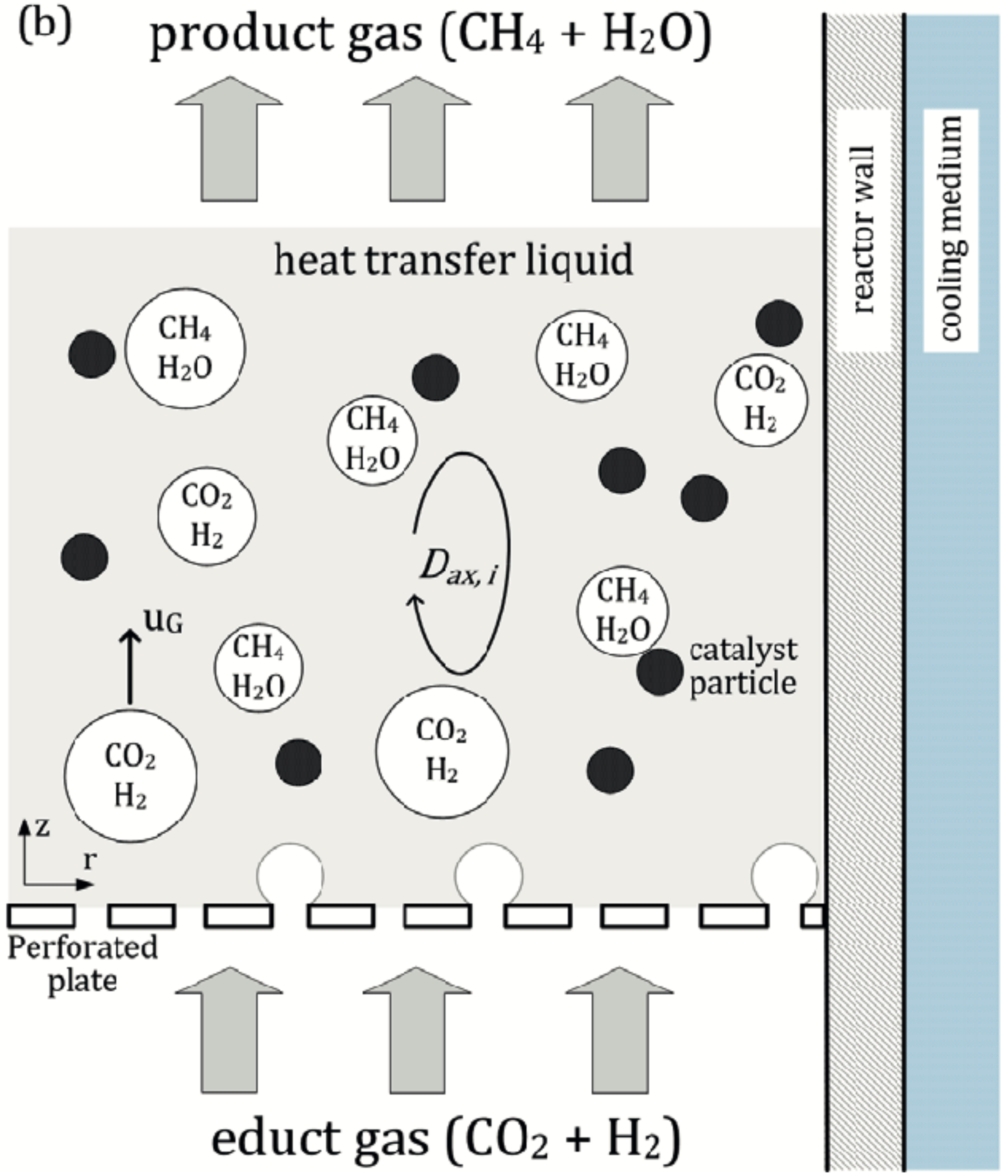


Figure 1: Schematic of a three-phase methanation reactor.

Source: M. Götz et al., International Gas Union Research Conference, Copenhagen, **2014**, Paper-Code WP4.6, Abstract ID 210.



Source: M. Held et al., *Chem. Ing. Tech.* **2020**, *92*, 595-602.

Reactors for catalytic methanation of CO_2

Honeycomb vs. slurry bubble column

- Mass transfer resistances

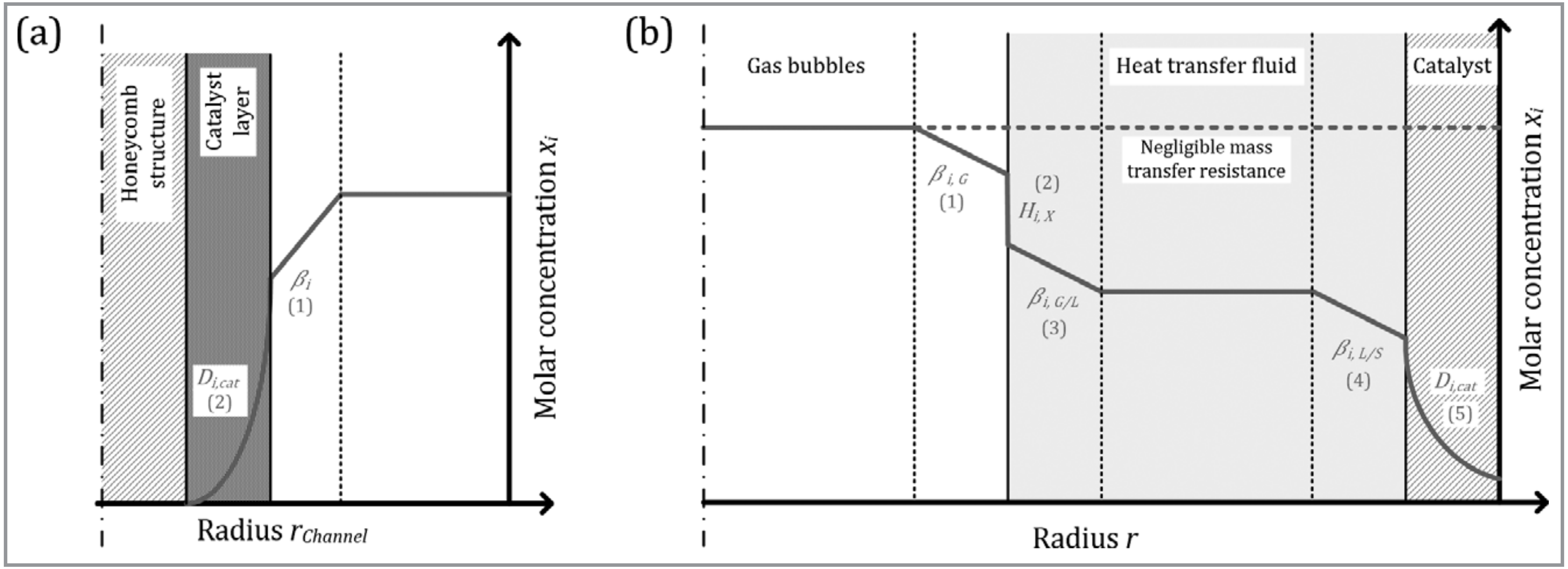


Figure 3. Mass transfer phenomena in the honeycomb reactor (a) and the three-phase reaction system (b) based on theoretical considerations.

Source: M. Held et al., *Chem. Ing. Tech.* **2020**, *92*, 595-602.

Reactors for catalytic methanation of CO_2

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Honeycomb vs. slurry bubble column

- Heat transfer resistances

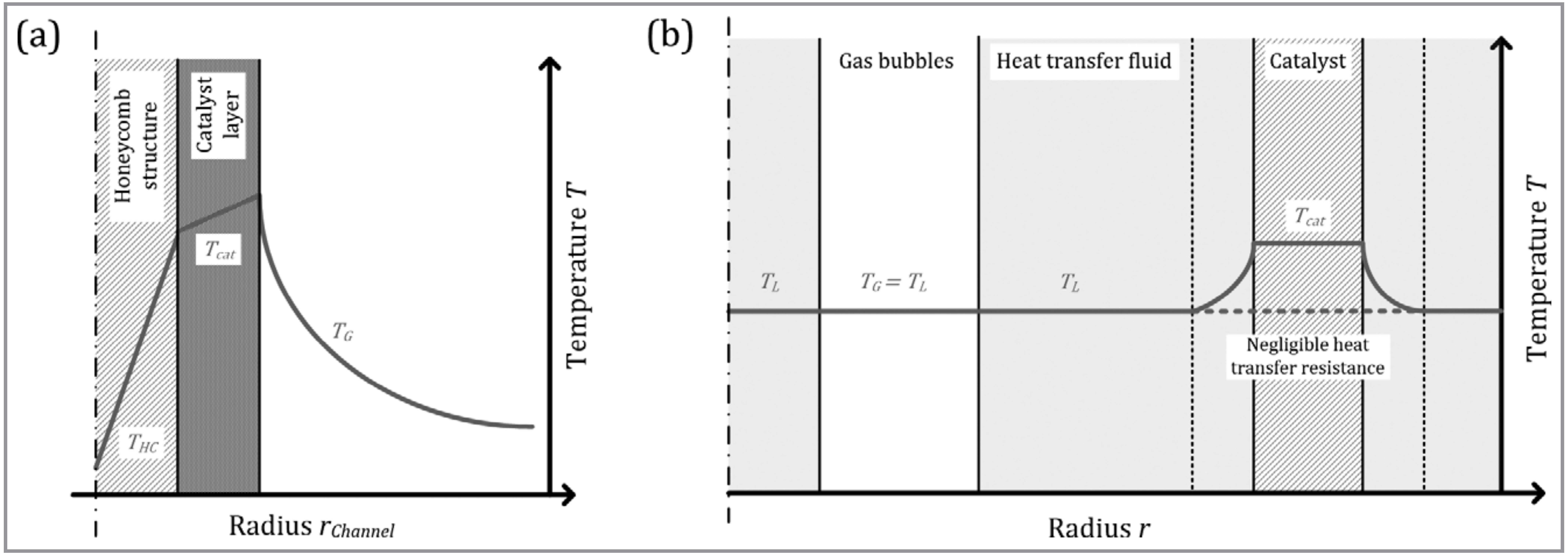


Figure 4. Heat transfer phenomena in the honeycomb reactor (a) and the three-phase reaction system (b) based on theoretical considerations.

Source: M. Held et al., *Chem. Ing. Tech.* **2020**, *92*, 595-602.

Reactors for catalytic methanation of CO_2

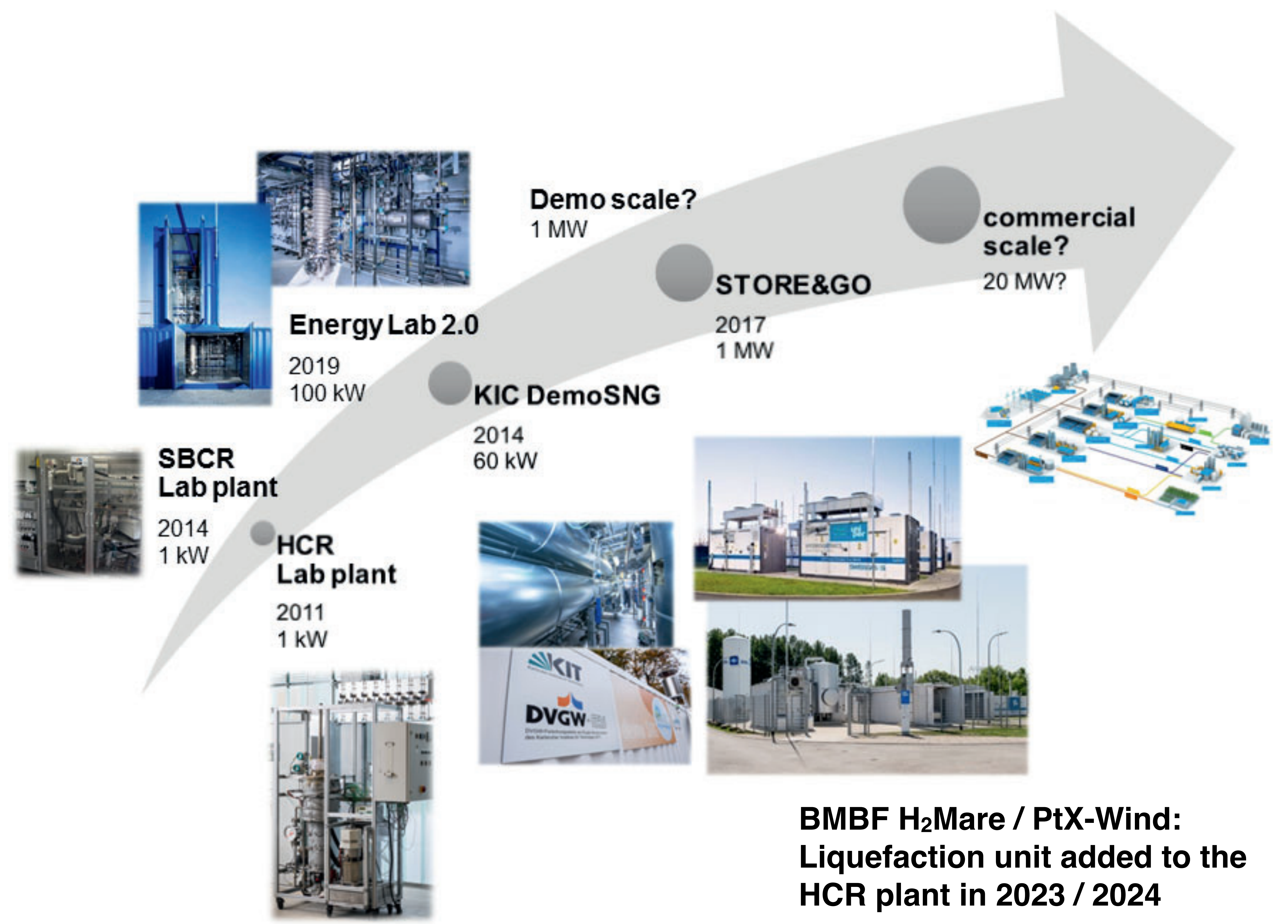
Honeycomb vs. slurry bubble column

- Scale-up

Slurry bubble column reactor plant

Honeycomb reactor plant

Source: Aerial photograph of the PtX facility at KIT's Energy Lab 2.0. March 2021. Source: MDR WISSEN – Bremst Corona den Verkehr aus? Wie uns ein Virus zum Umlenken zwingt. https://bit.ly/361kR1Y



BMBF H_2Mare / PtX-Wind: Liquefaction unit added to the HCR plant in 2023 / 2024

Figure 5. Scale-up strategy for methanation reactor concepts at the Engler-Bunte-Institut.

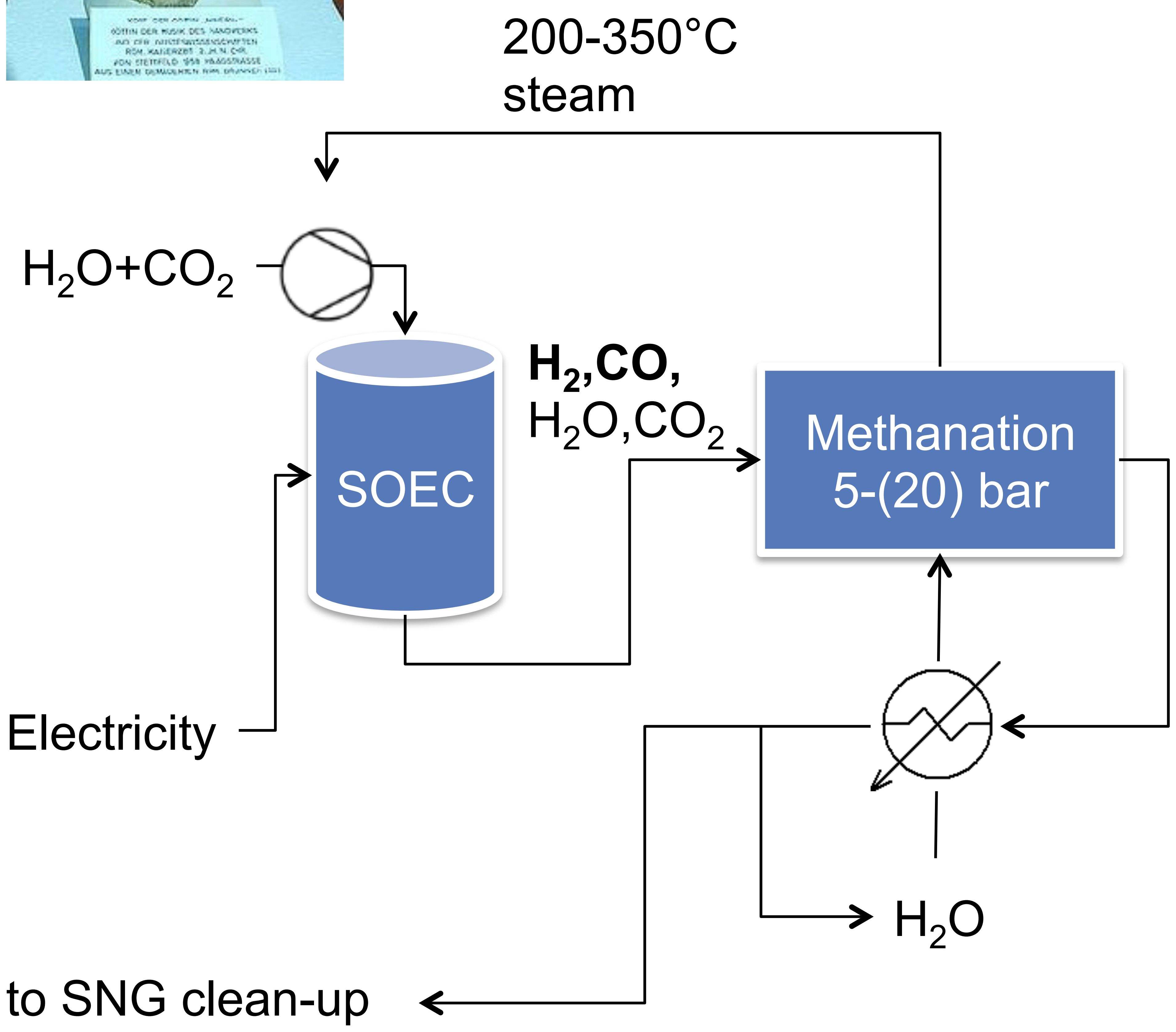
Source: M. Held et al., *Chem. Ing. Tech.* **2020**, *92*, 595-602.

Microreactor technology for CO/CO_2 methanation

Initiated in 2012 in the frame of KIC InnoEnergy project **MINERVE** („Management of Intermittent & Nuclear Electricity by highly efficiency lectrochemical Reactor for the Valorization of CO_2 in flexible Energies“)

Partners:

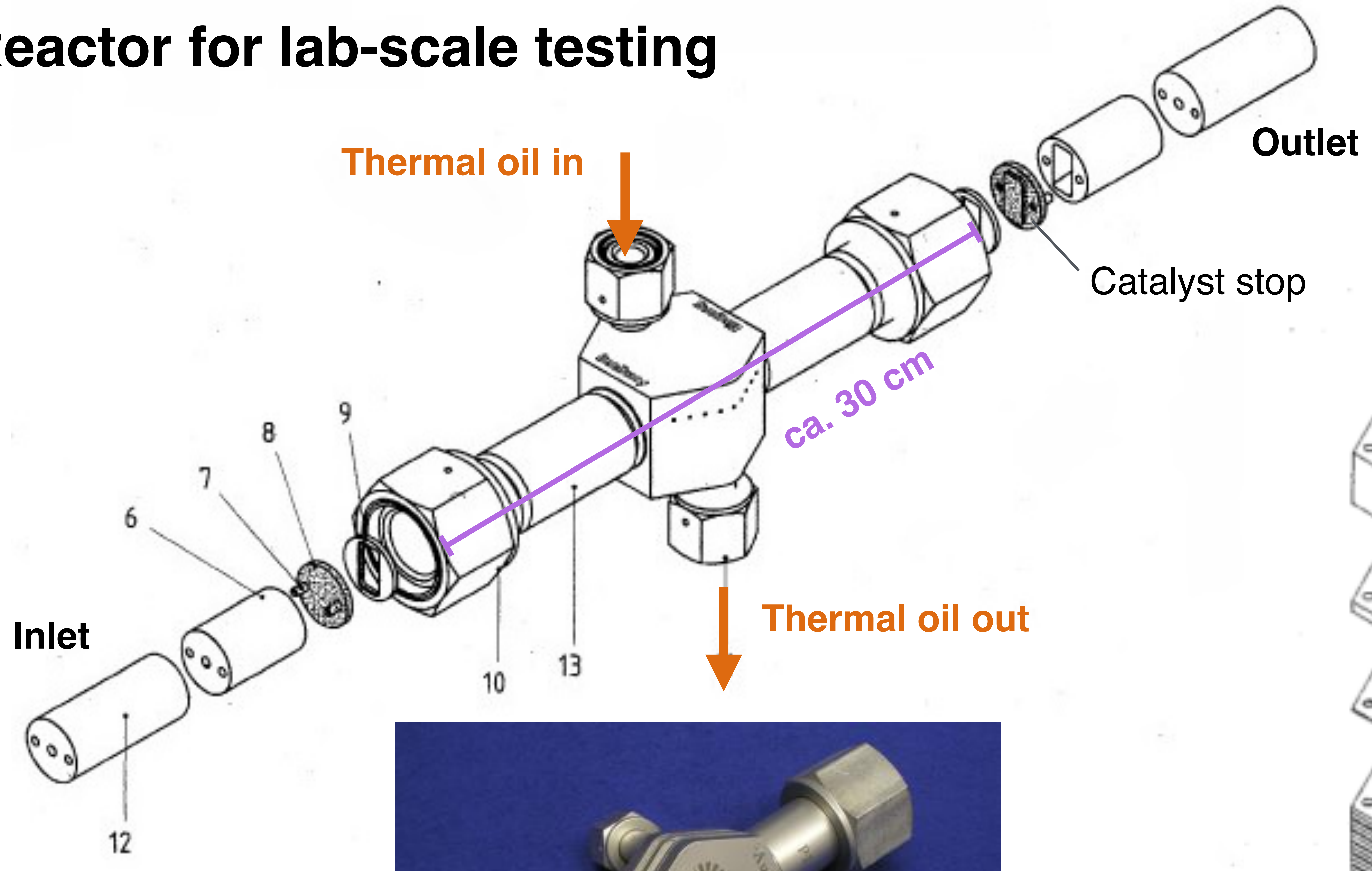
- GDF Suez, CRIGEN, Paris
- CEA, Grenoble
- KIT, Karlsruhe
- AGH, Cracow
- Solvay (Rhodia), Lyon



Rationale:

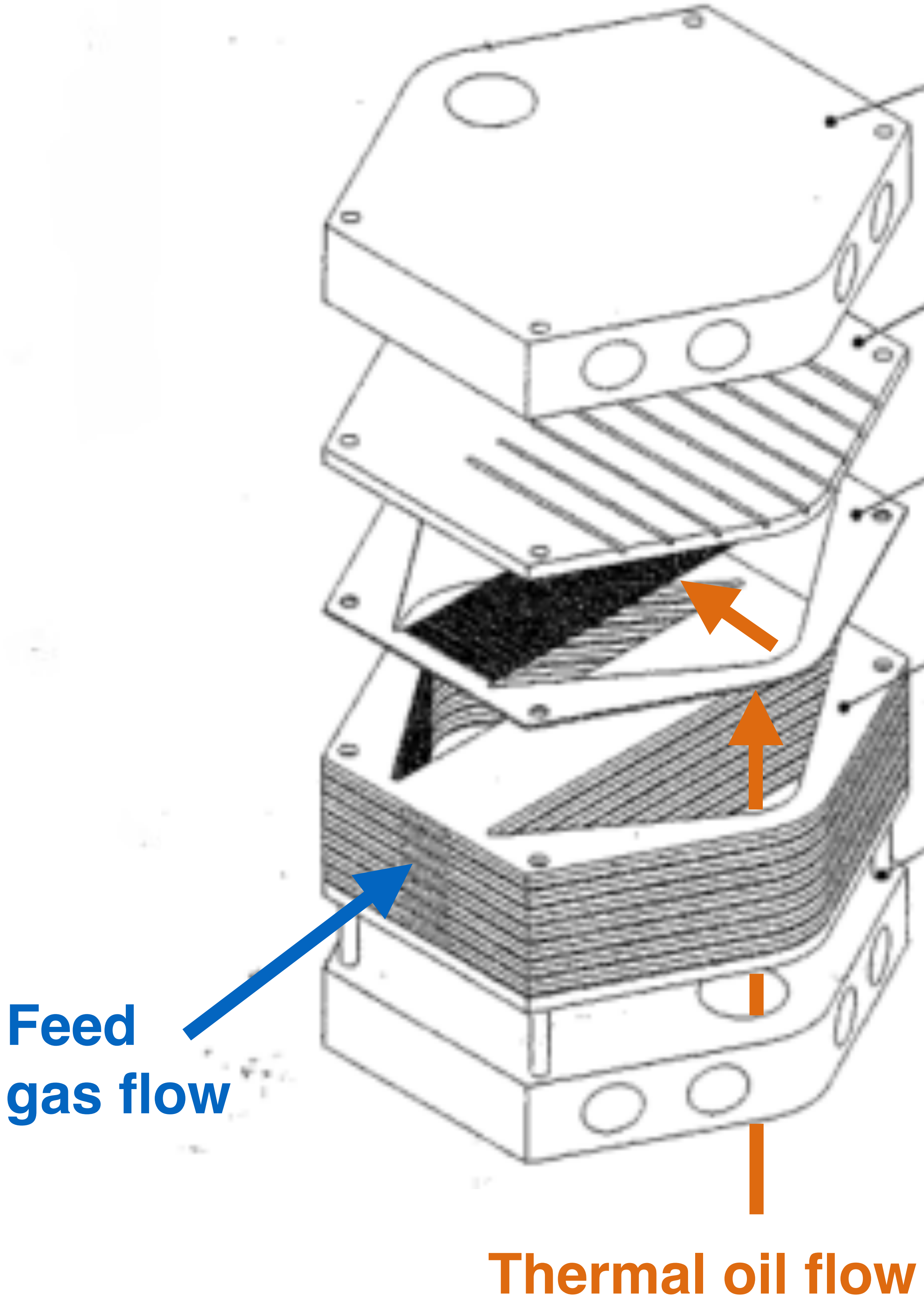
- Highly efficient solid oxide co-electrolyzer (> 80%)
- CAPEX reduction due to the double function of the co-electrolyzer (steam and CO_2 reduction to produce synthesis gas)
- Higher global efficiency due to utilization of the reaction heat of methanation by steam generation (feed for electrolysis)

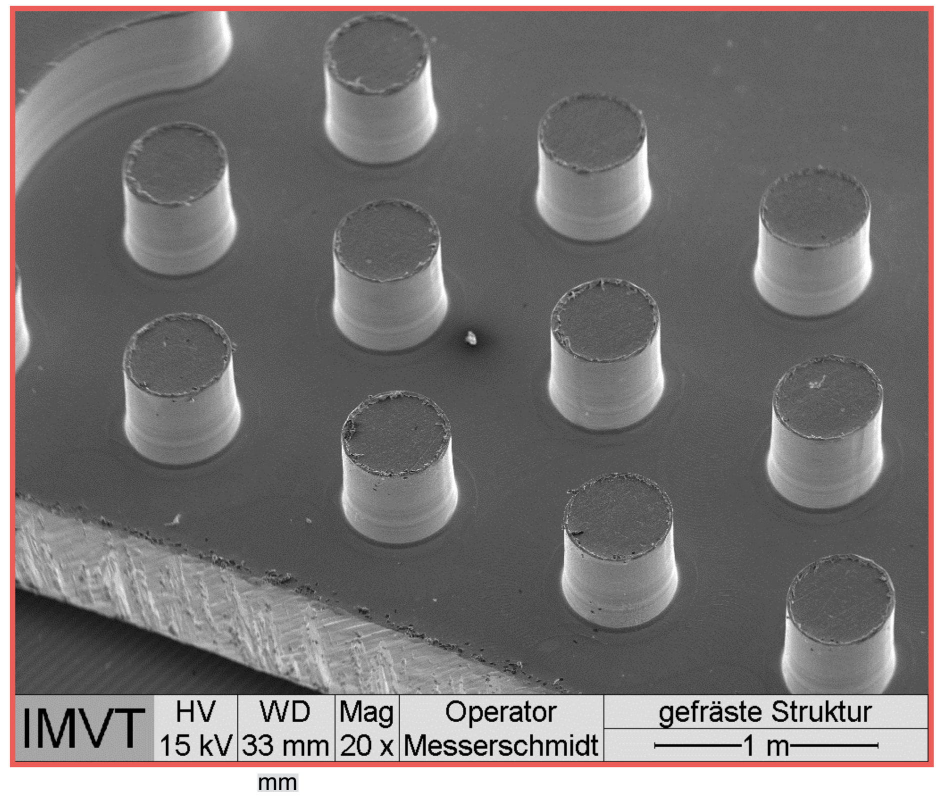
Reactor for lab-scale testing



Basic concept:

Isothermal conditions due to extraordinary cooling power





For details on the reactor, see: *Myrstad et al., Catal. Today 147 (2009) 301-304*

Microreactor technology for CO/CO_2 methanation

Key project outcomes

- Reduced heating requirement in co-electrolysis (slightly exothermic mode) through steam supply at high temperature, i.e. only 2 % of total energy input is required for heating

- “Raw” methane possesses good composition:
  - CH_4 95.389%
  - CO_2 0.019%
  - CO 0.000%
  - H_2O 0.461%
  - H_2 4.131%

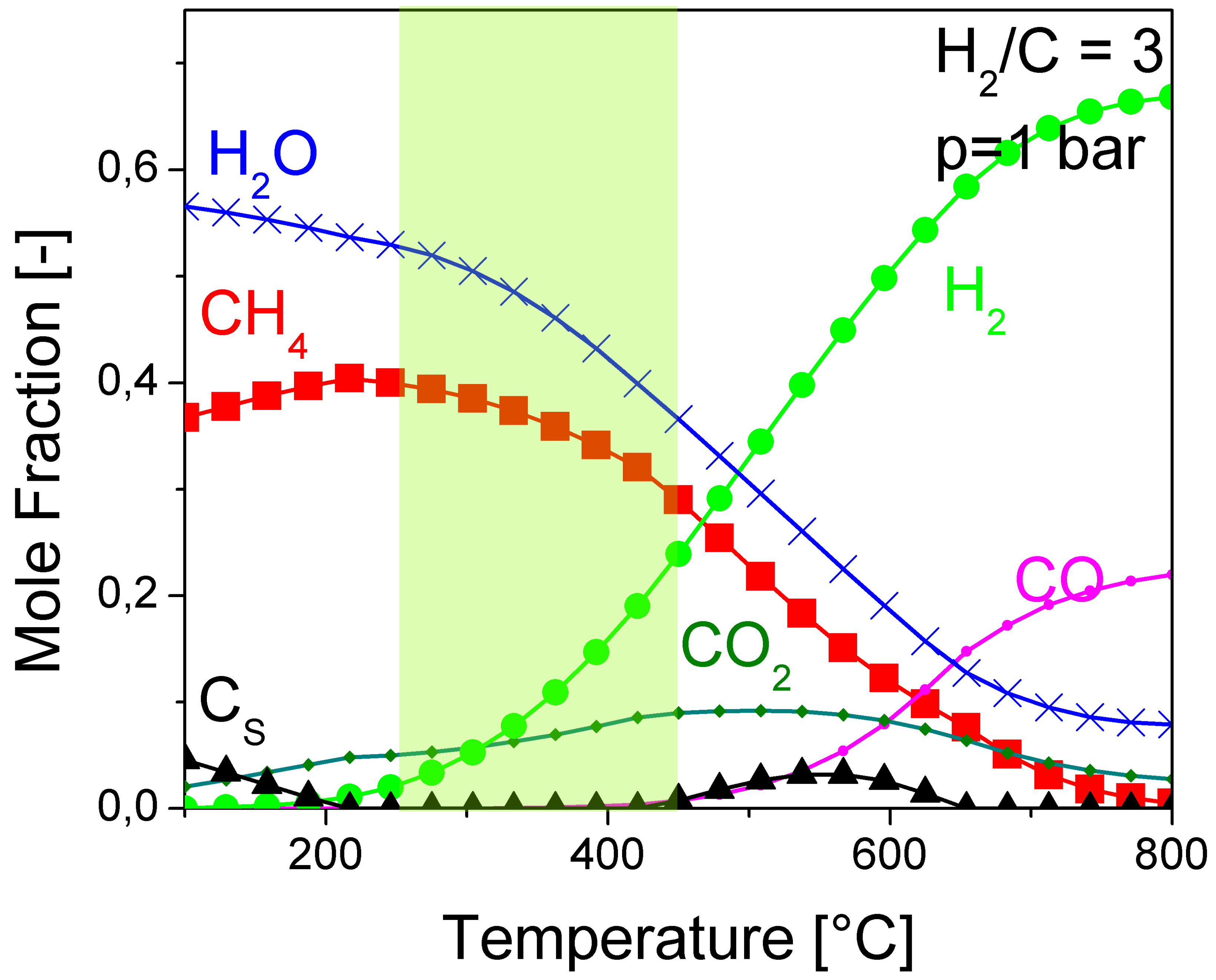
- Total efficiency: 83.5 %
  - AC/DC conversion of SOEC unit excluded
  - Efficiency is defined as: HHV (CH_4 + H_2) / [E(SOEC) + Q(aux)]

- CO_2 Utilization > 99.8 %

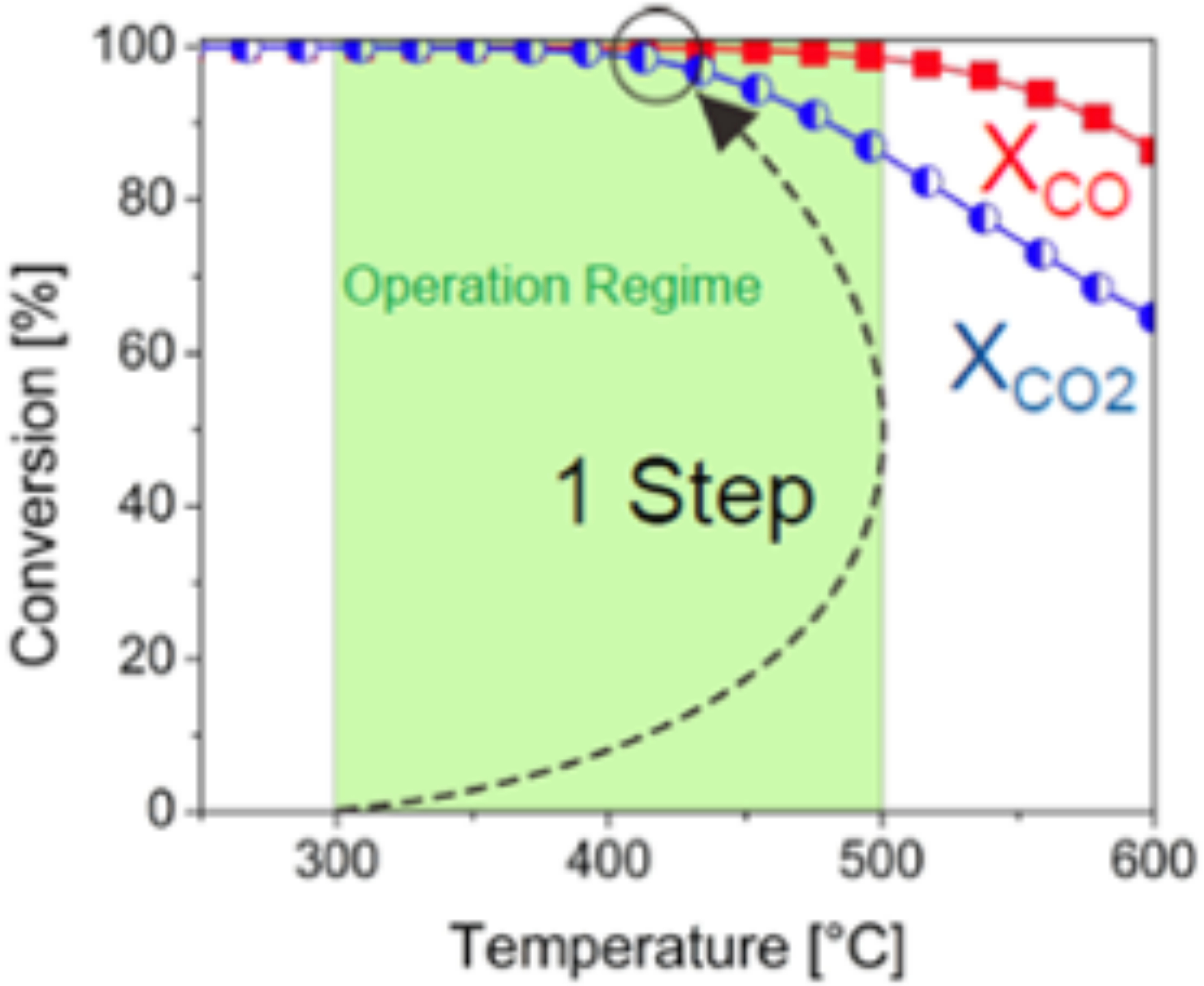
Microreactor technology for CO/CO_2 methanation

Concept: Polytropic reactor with hot spot / falling temperature profile

Thermodynamics



Desired temperature profile



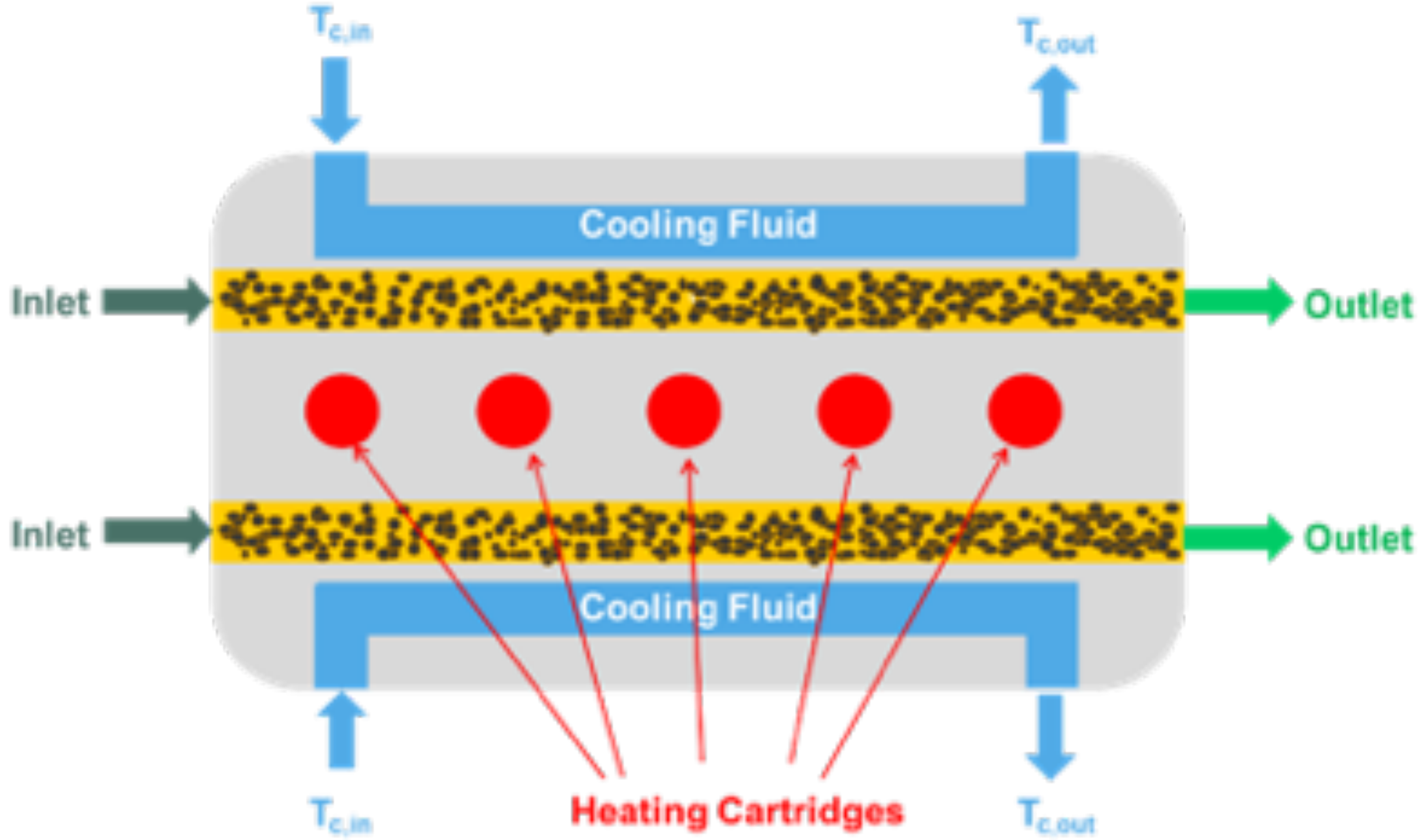
- Optimum operation regime : 250 < T < 450°C
- Preferential methanation of CO
- High temperature allowed at inlet, low temperature required at reactor exit

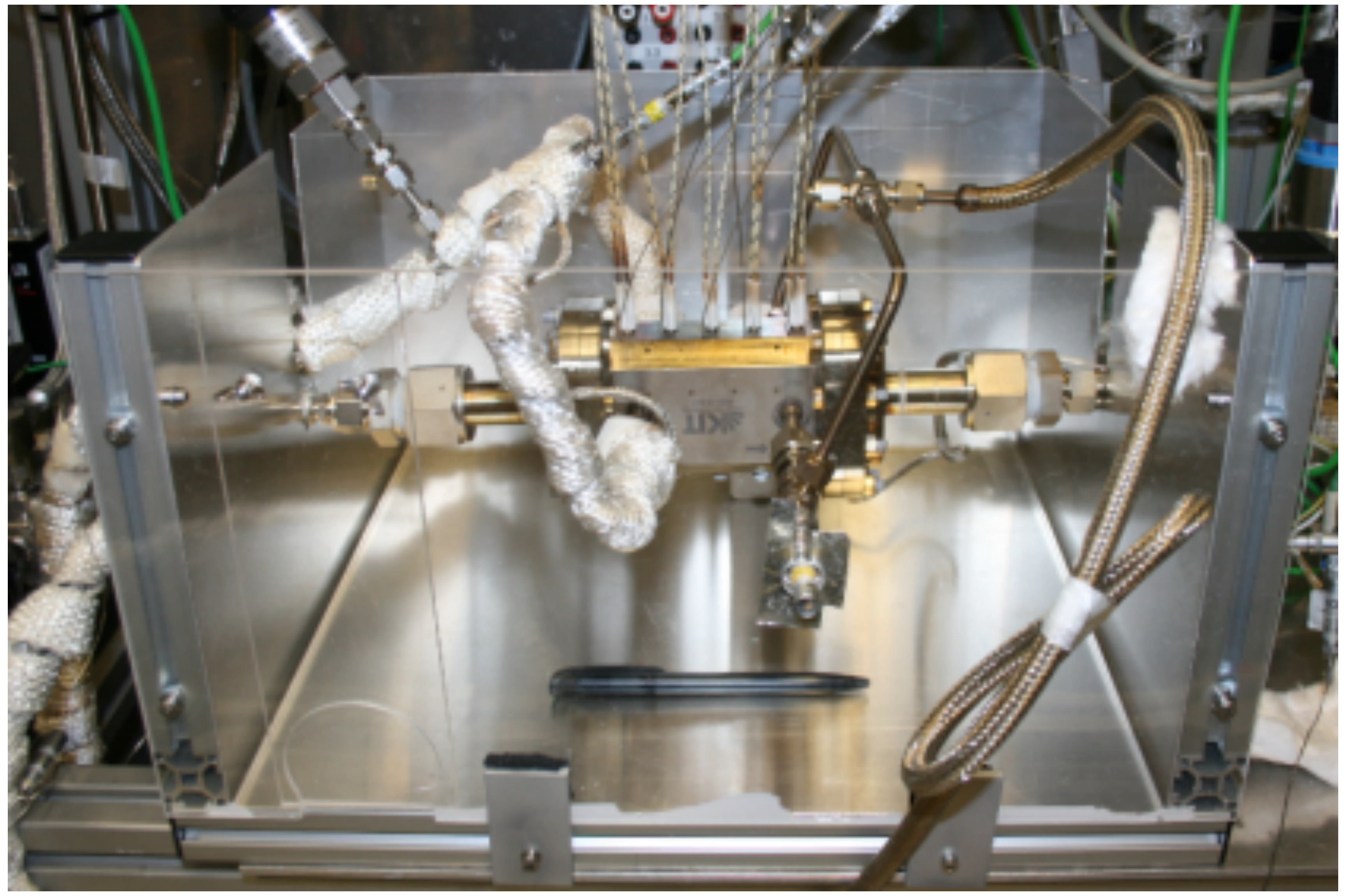
See also: M. Belimov et al., AIChE J. 2016 (DOI: 10.1002/aic.15461)

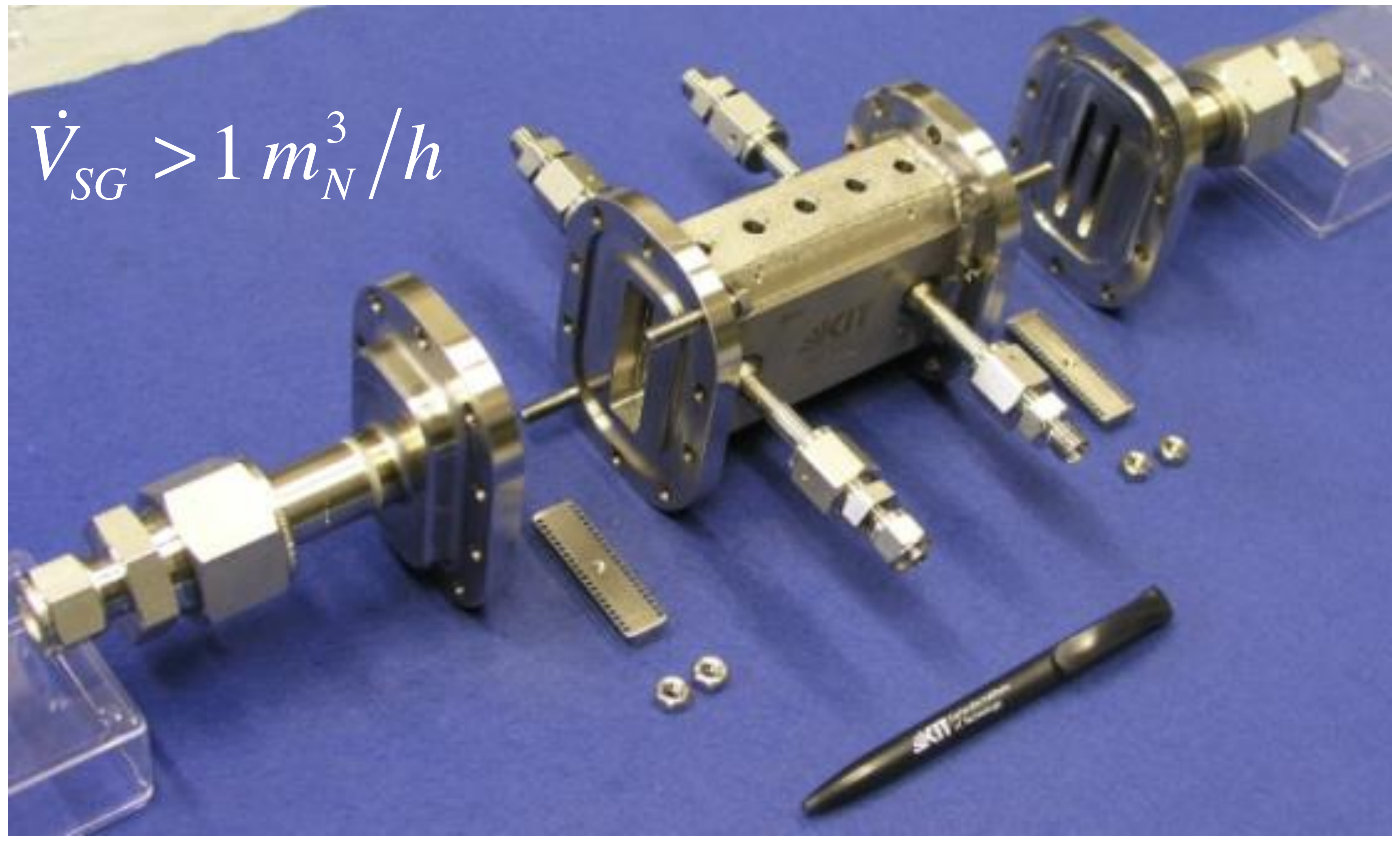
Scale-Up: Conceptual design of the first prototype

- **Geometry**
  - 2 Slits, width 5 cm, length 10 cm, hight 0.2 cm
- **Catalyst**
  - 5 g of a commercial Ni-catalyst; particle size 200 - 600 μm, diluted with SiC
  - m_{Cat} 10 times over design
- **Cooling / Heating**
  - Co-current, air / steam / pressurized water, 70 channels 500 μm x 500 μm cross section
  - 5 Heating cartridges for pre-heating (330°C ignition temperature)

Basic design principle:

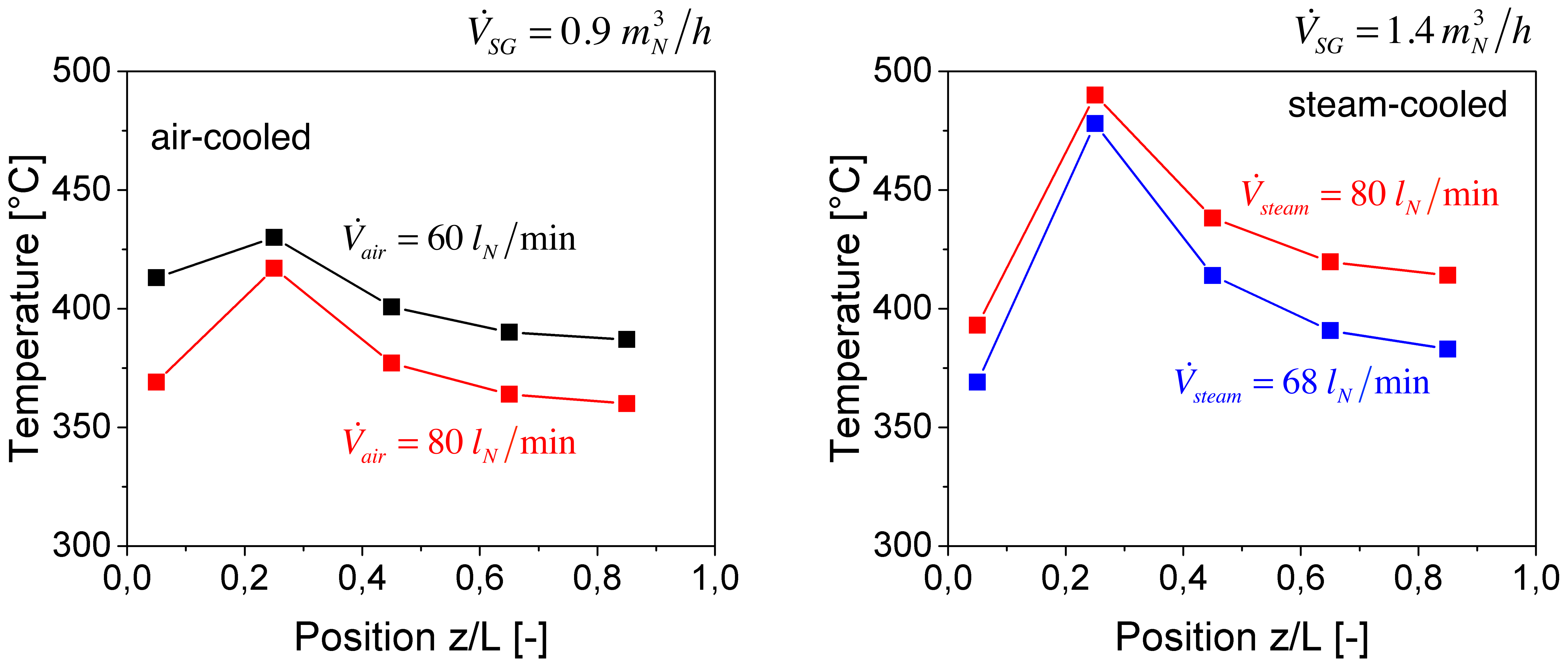






Key experimental results

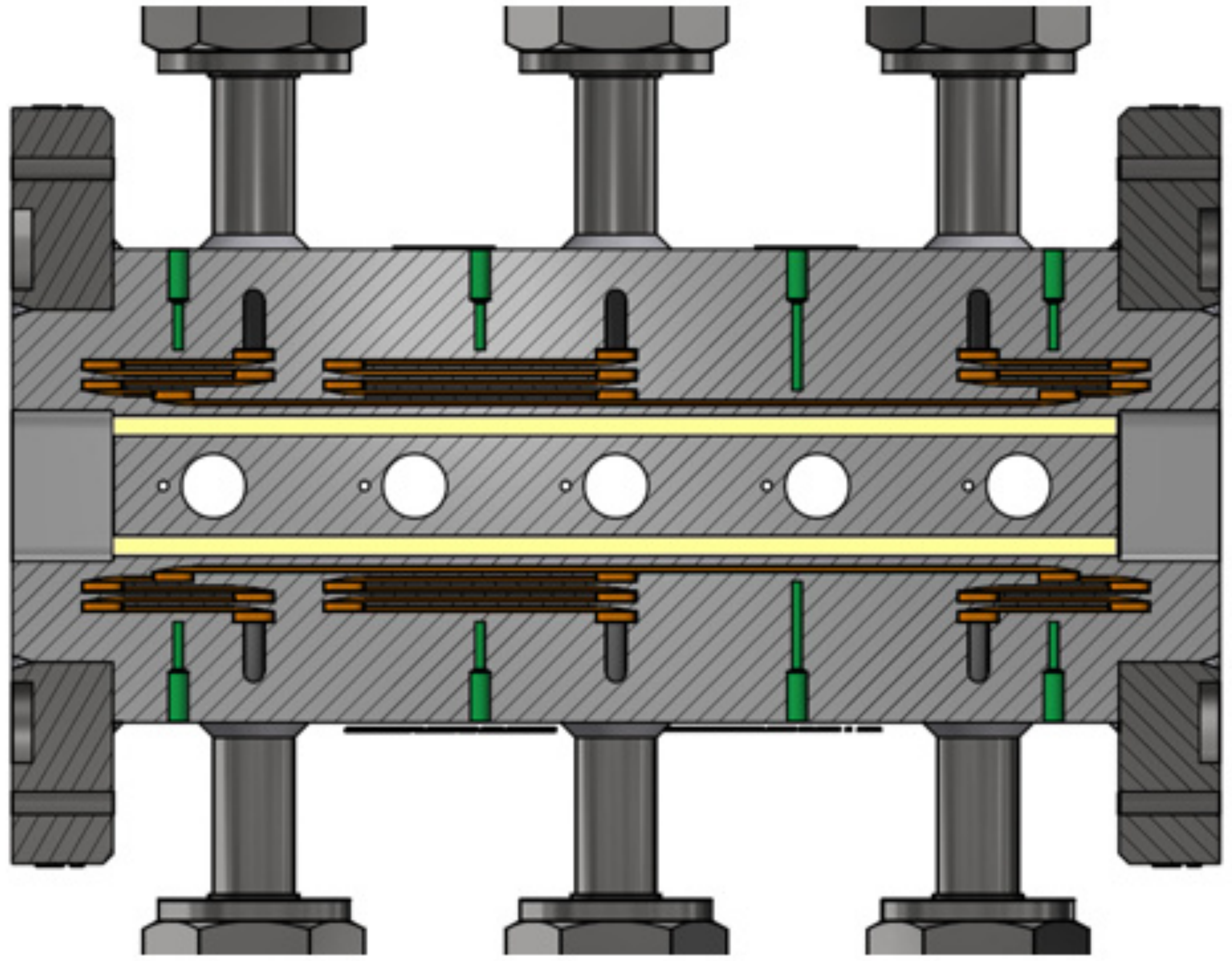
Operation with air and steam cooling

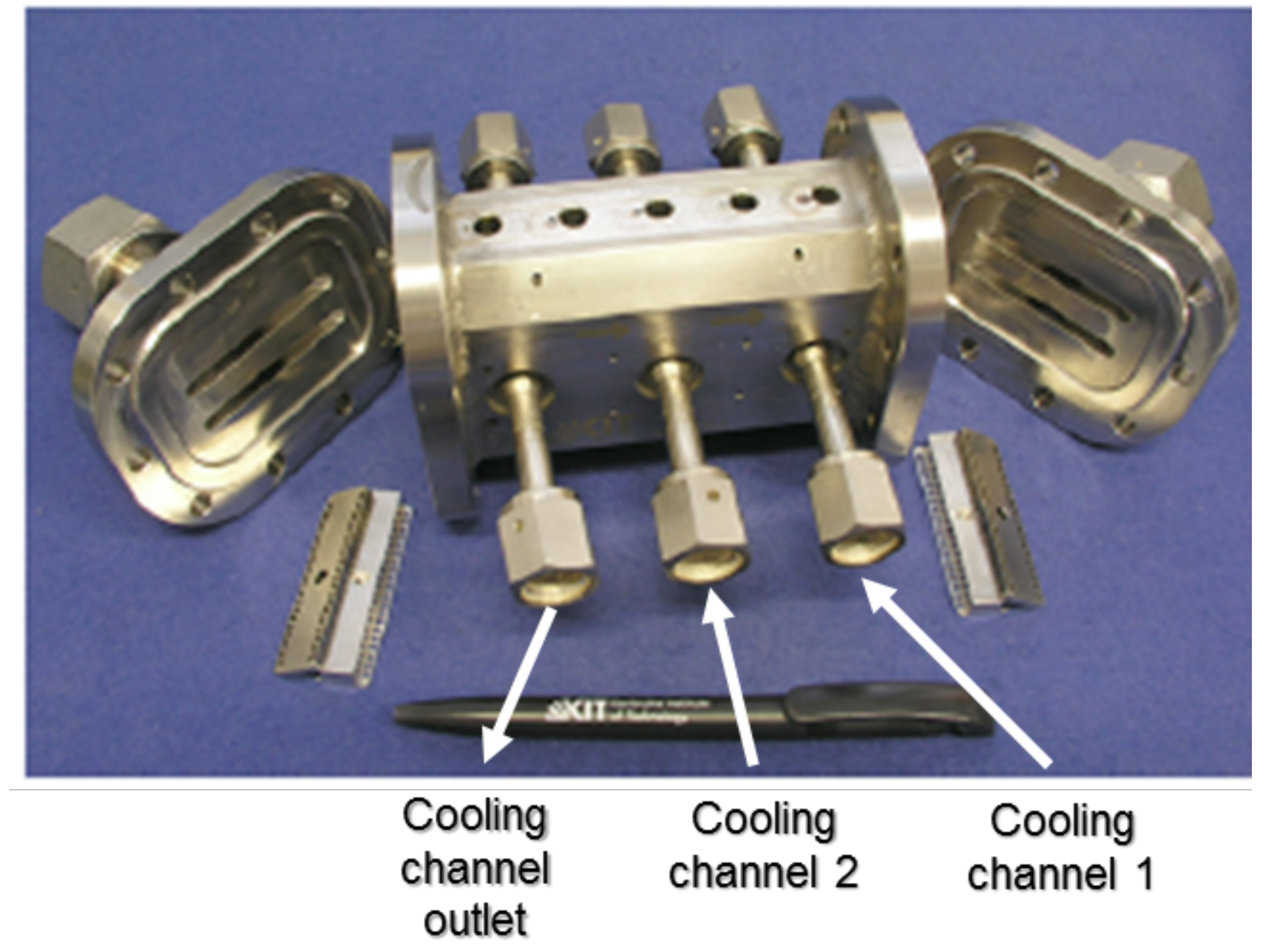


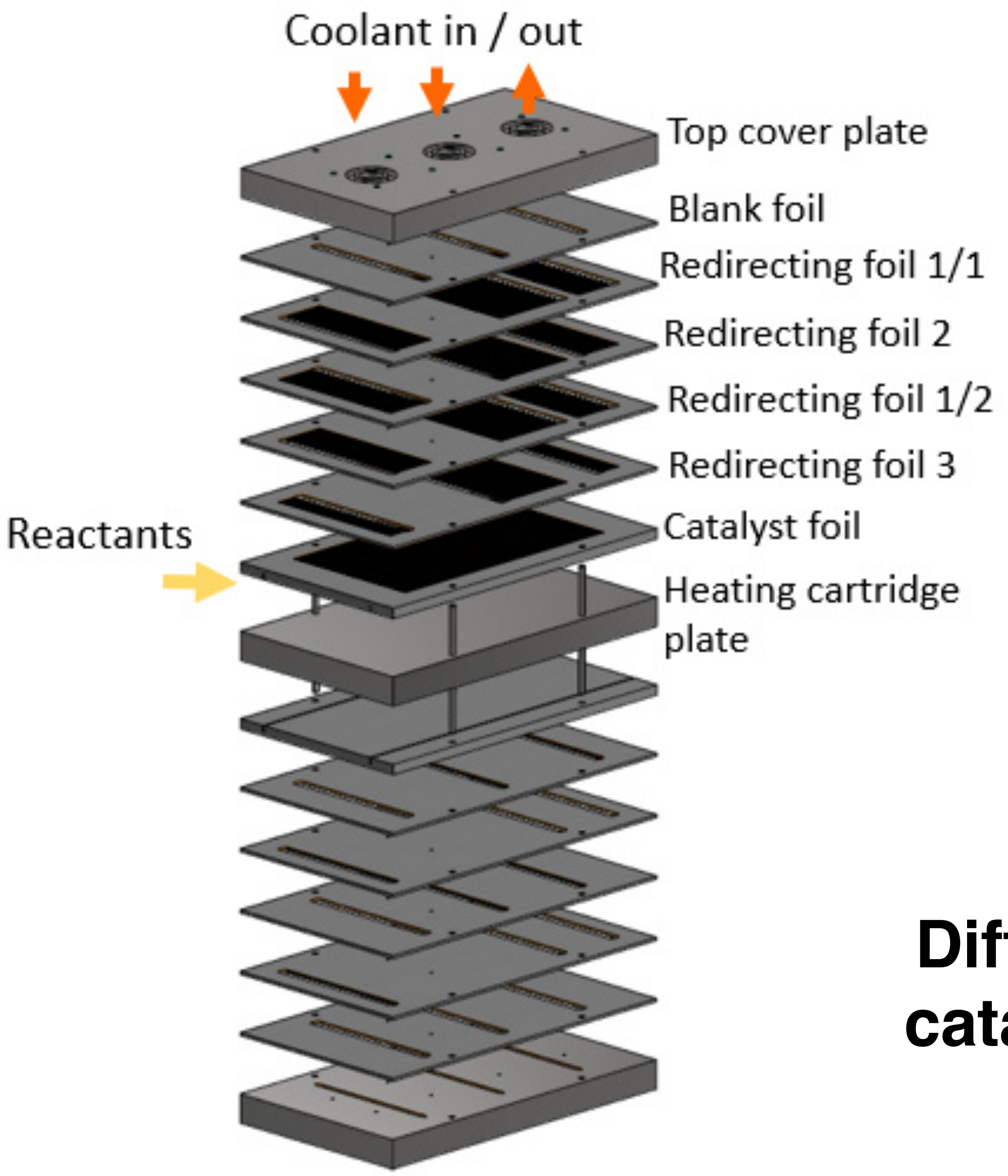
- Feed composition: 10% CO, 7% CO_2, 72% H_2 and N_2 (internal standard)
- Feed temperature: 300°C; coolant inlet temperature: 150°C
- Reduced in-situ in N_2/H_2 = 1:1 (4h at 450°C)

- Reproducible and stable T-profiles up to 1.4 m^3/h syngas feed (H/C = 4); exit temperature > 350°C
- 330 to 530 W of the generated heat transferred to air (ca. 40-50 W heat loss)
- Peak temperature < 500°C in catalyst bed even when applying heat transfer to air
- However, challenges with establishing the desired temperature profile without heating when applying evaporation cooling

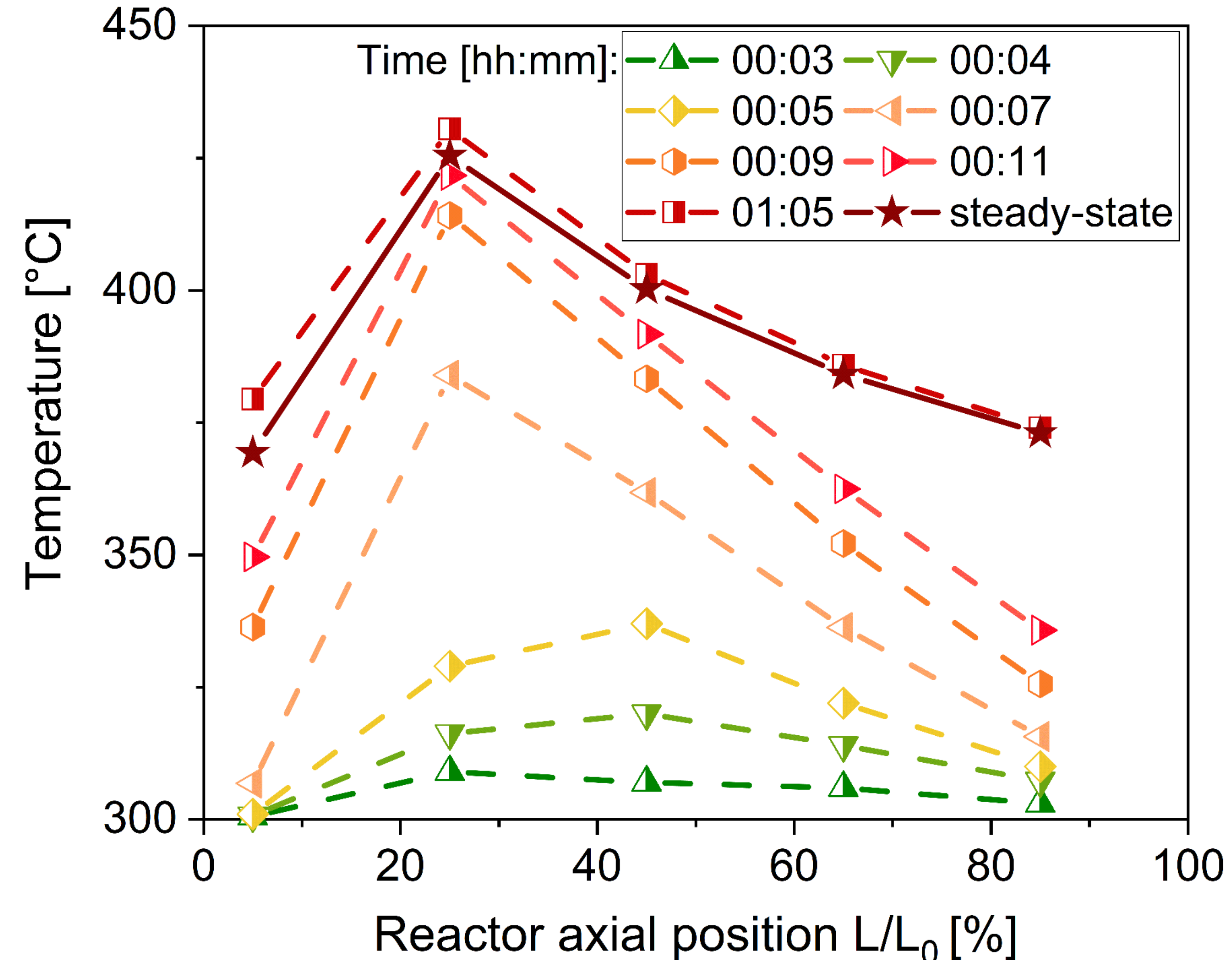
Revised prototype for evaporation cooling



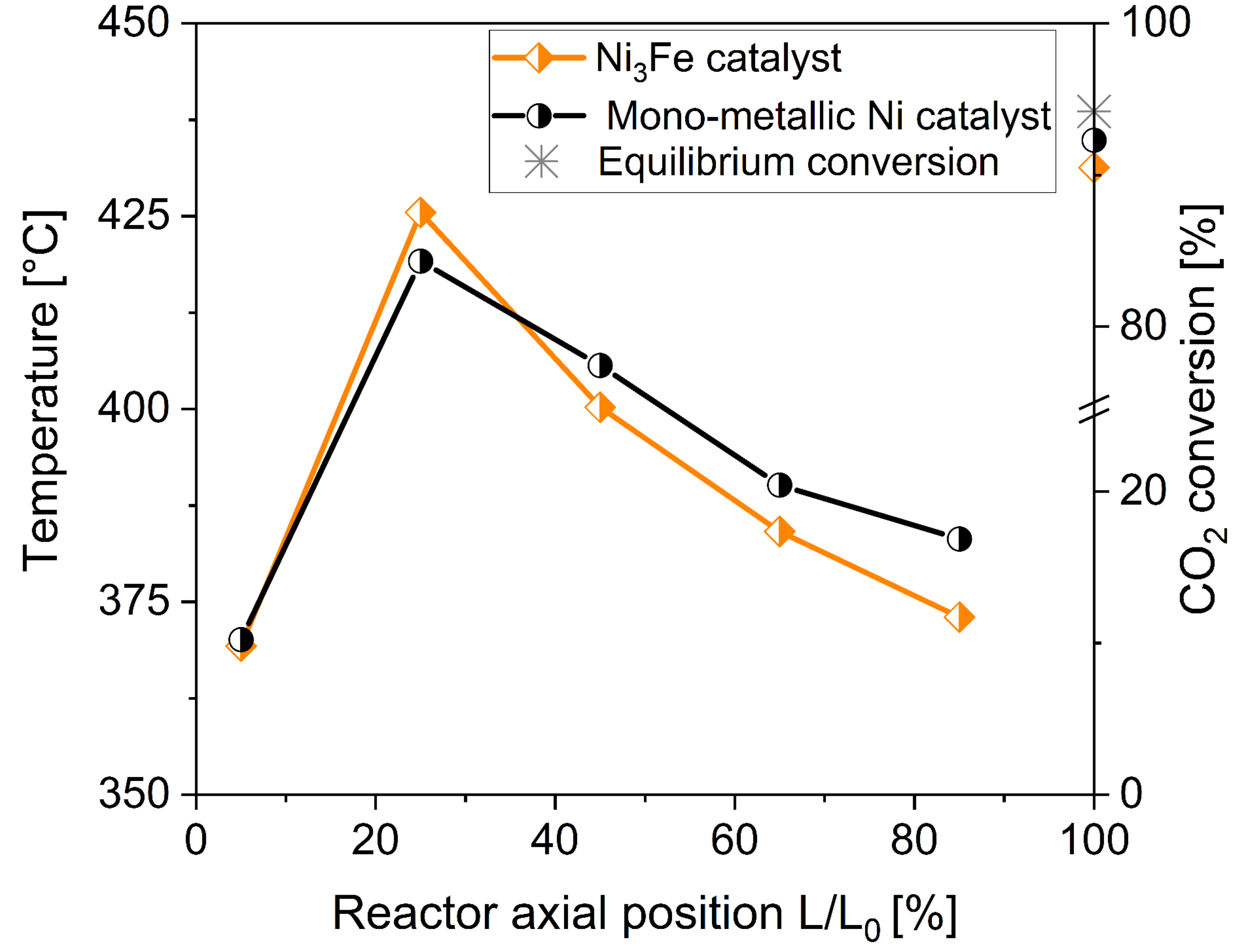




Start up behaviour



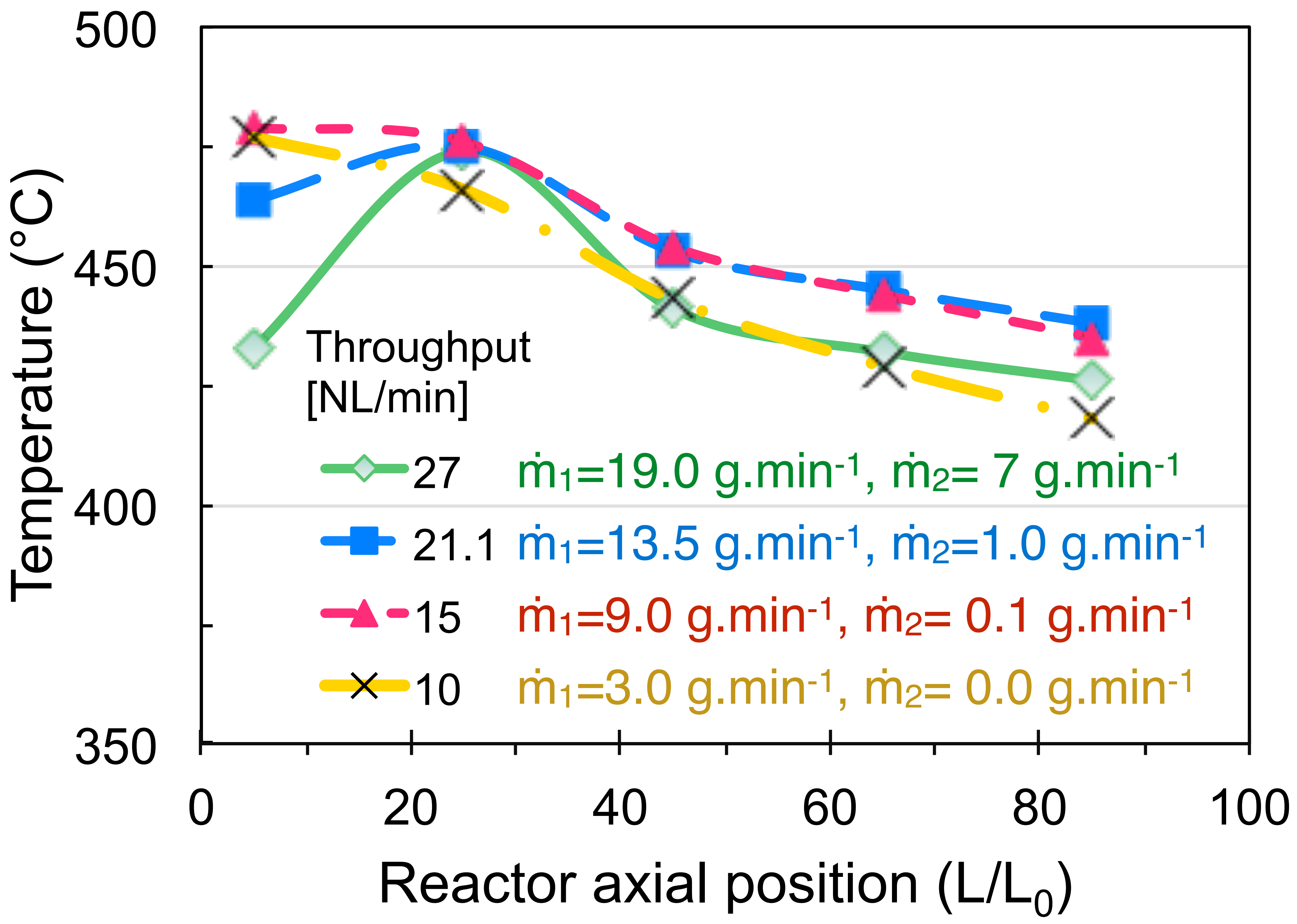
Different catalysts



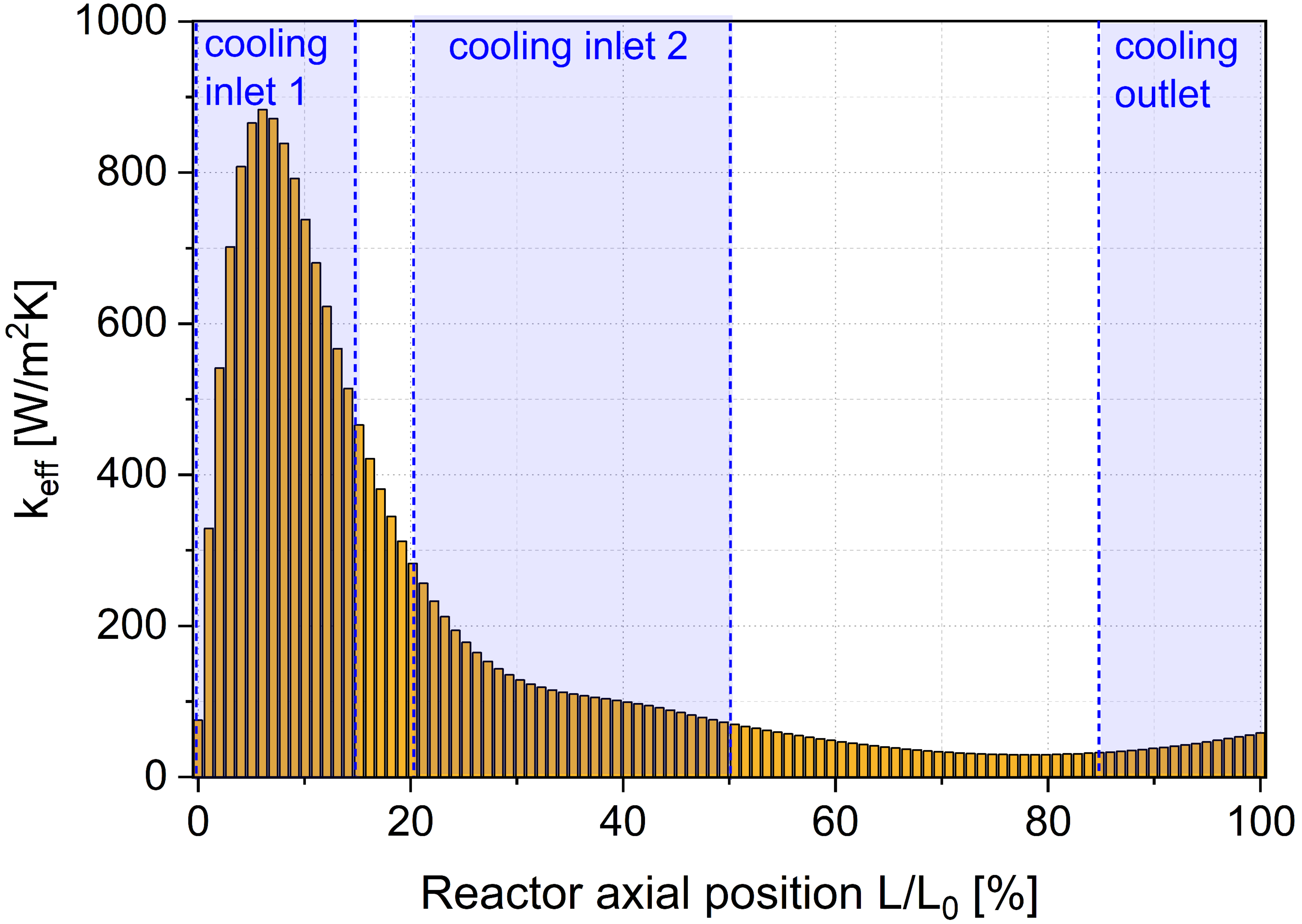
see also: Sarvenaz Farsi, PhD-Thesis, KIT, 2021

A more detailed view into the results

Varying the cooling water split in evaporation cooling



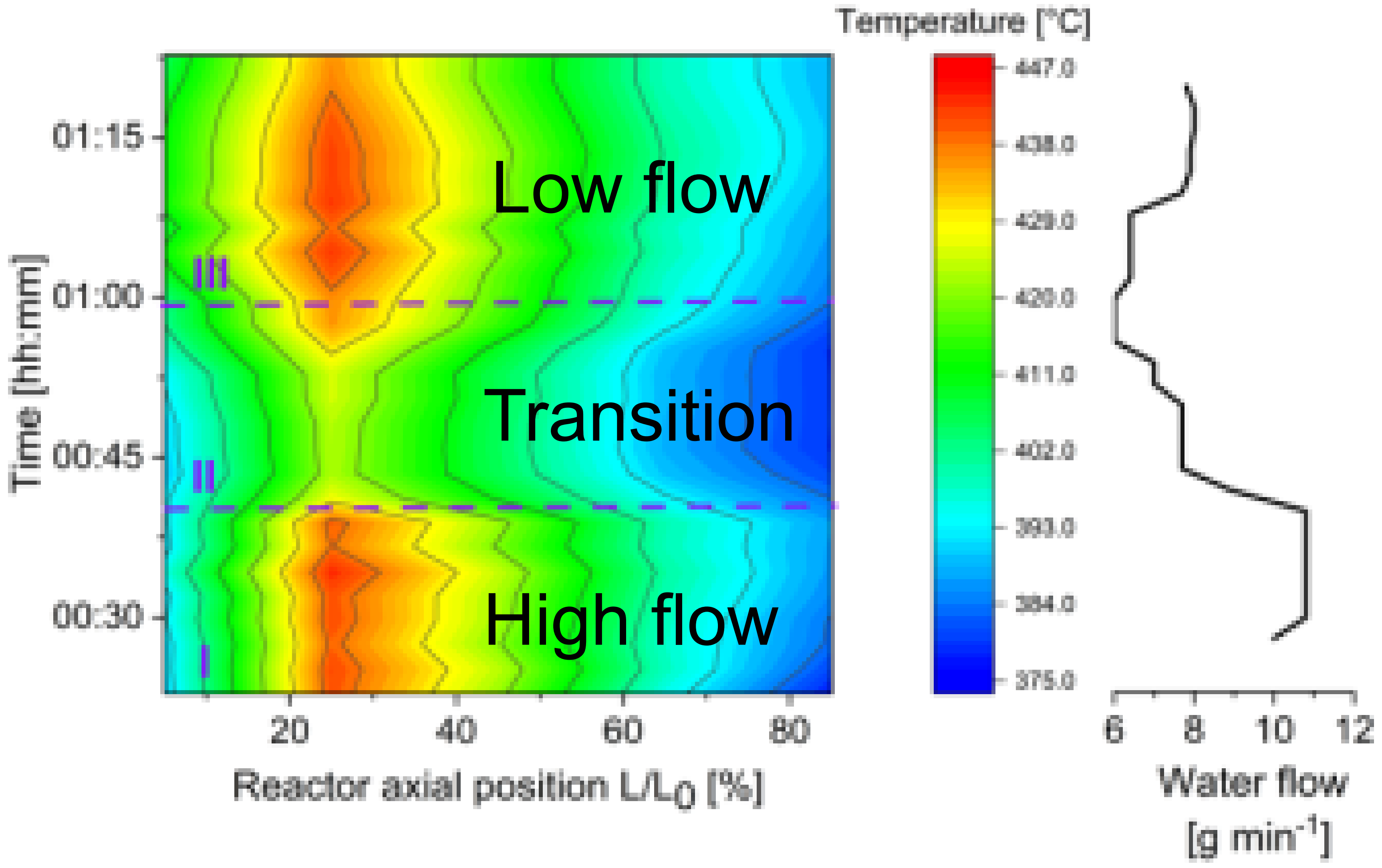
Heat transfer coefficient derived from cell model



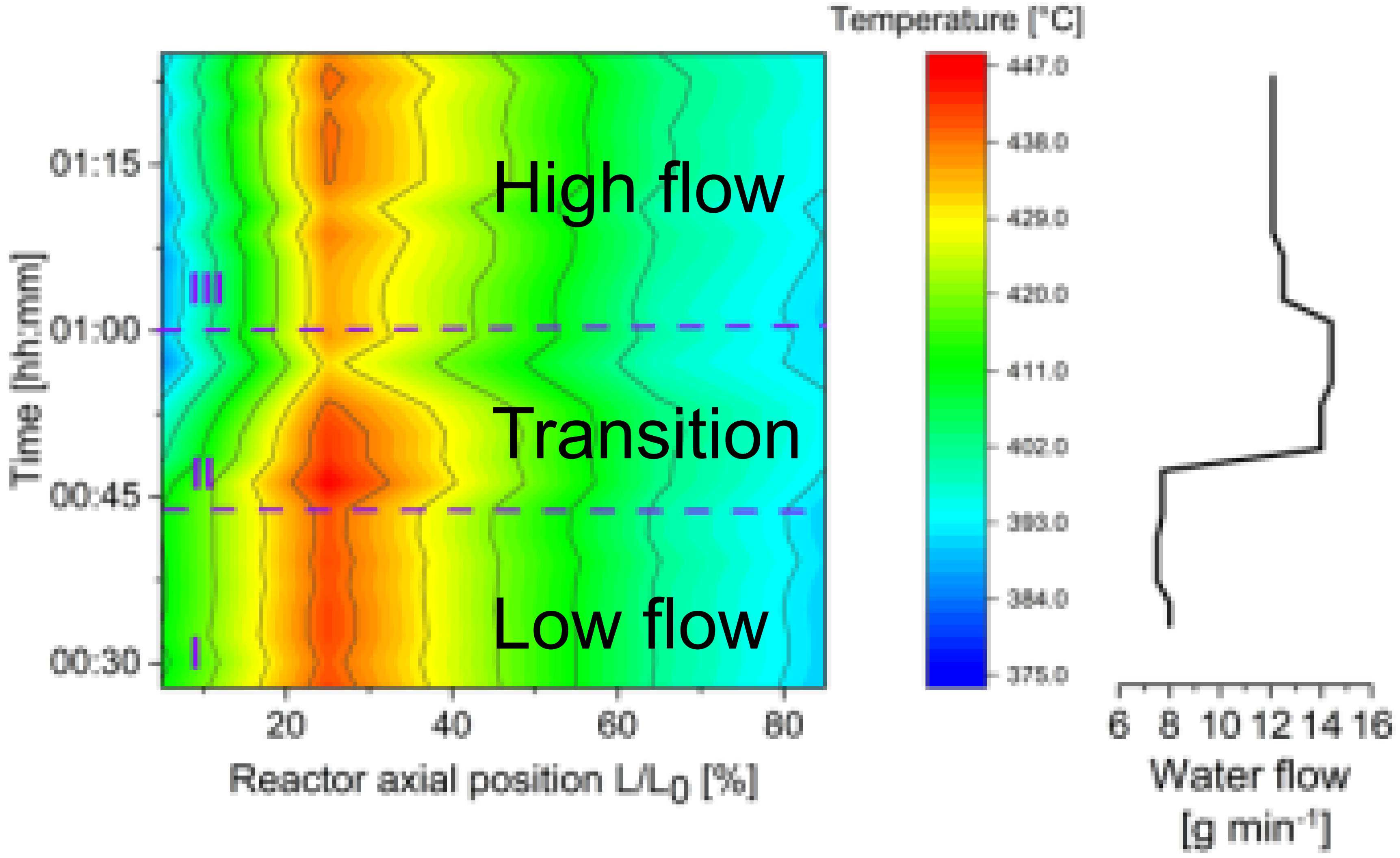
see also: Sarvenaz Farsi, PhD-Thesis, KIT, 2021

Modulation of the feed flow

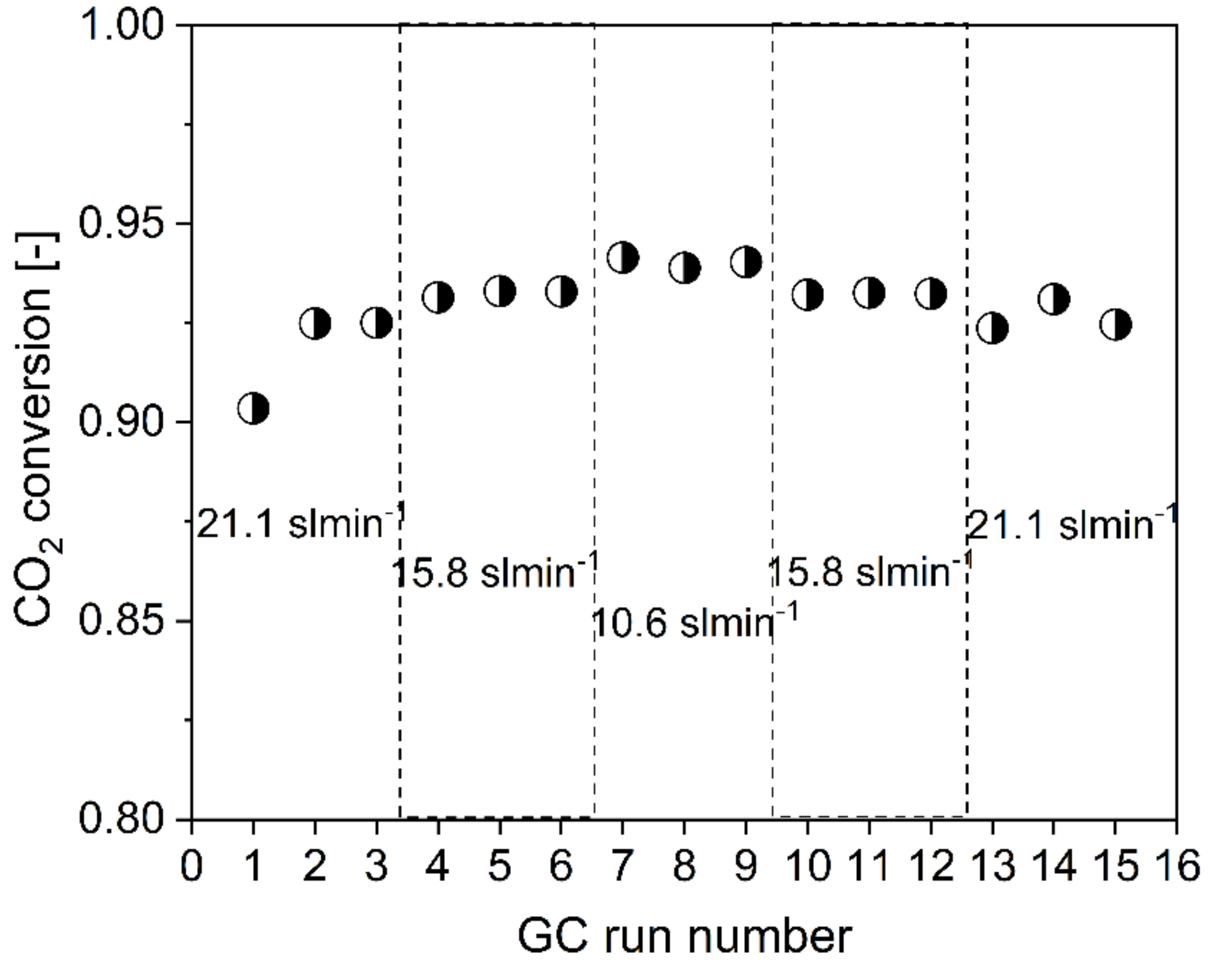
Feed flow reduction from 21.1 to 15.8 l/min



Feed flow increase from 15.8 to 21.1 l/min



CO_2 Conversion



$H_2 / CO_2 = 4$, $p_w = 10$ bar

see also: Sarvenaz Farsi, PhD-Thesis, KIT, 2021

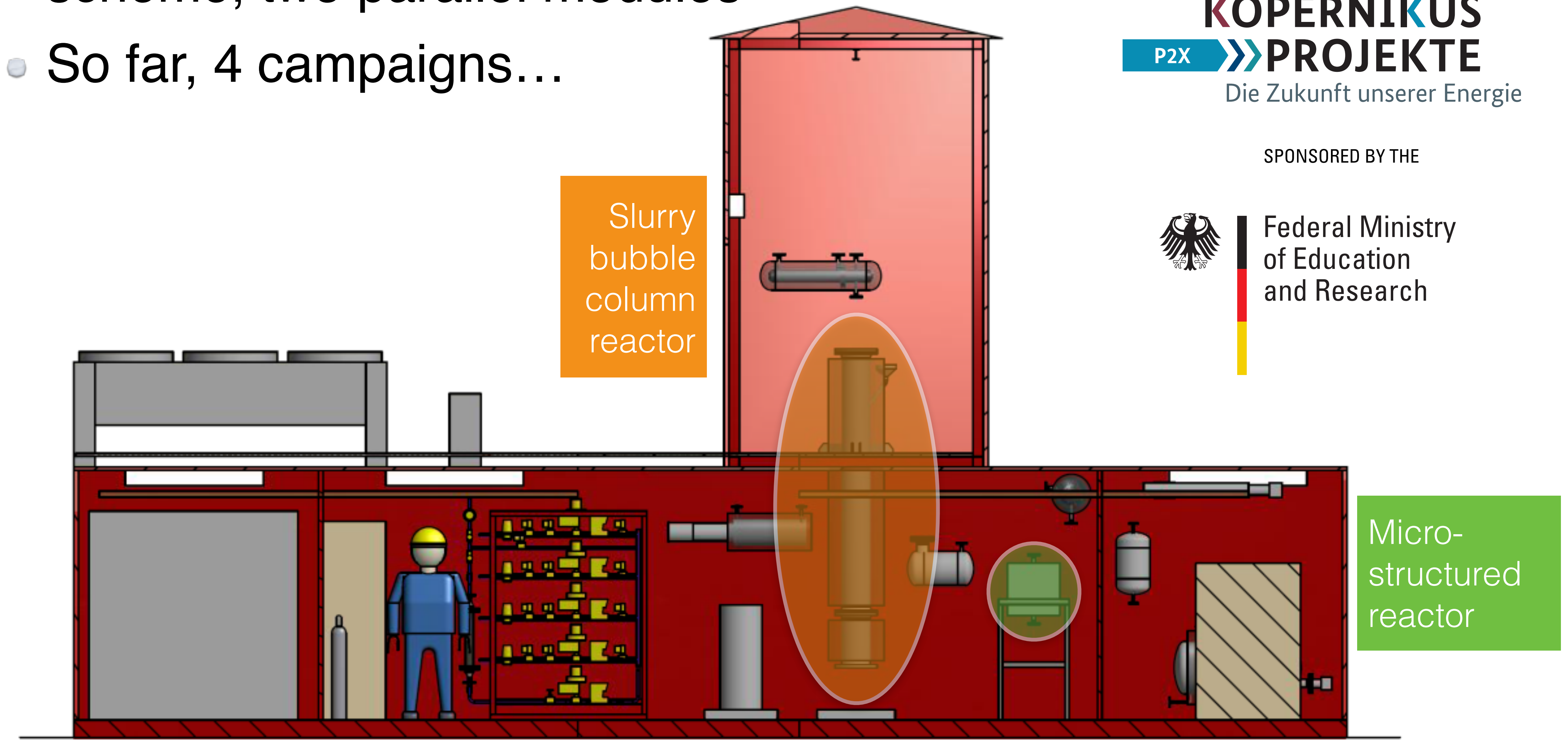
Validation and scale-up

- **Scale-up to 100 m_N^3/d together with INERATEC**
- Factor 5 larger than 2nd prototype, single stacking scheme, two reactor stages
- Successful start-up of power-to-gas pilot plant by gasNatural fenosa at a waste water treatment plant close to Barcelona, Spain (press release from May 31, 2018 at GNF website)

  http://www.prensa.gasnaturalfenosa.com/en/gas-natural-fenosa-launches-pilot-project-to-produce-renewable-gas-in-catalonia/

Synthetic Fuels – Combustibles Sintètics (CoSin), Grant No. COMRDI15-1-0037

- **Testing at 10 m_N^3/h scale in the Energy Lab 2.0**
- Factor 6 larger than gasNatural fenosa system, double stacking scheme, two parallel modules
- So far, 4 campaigns…



KOPERNIKUS PROJEKTE
Die Zukunft unserer Energie

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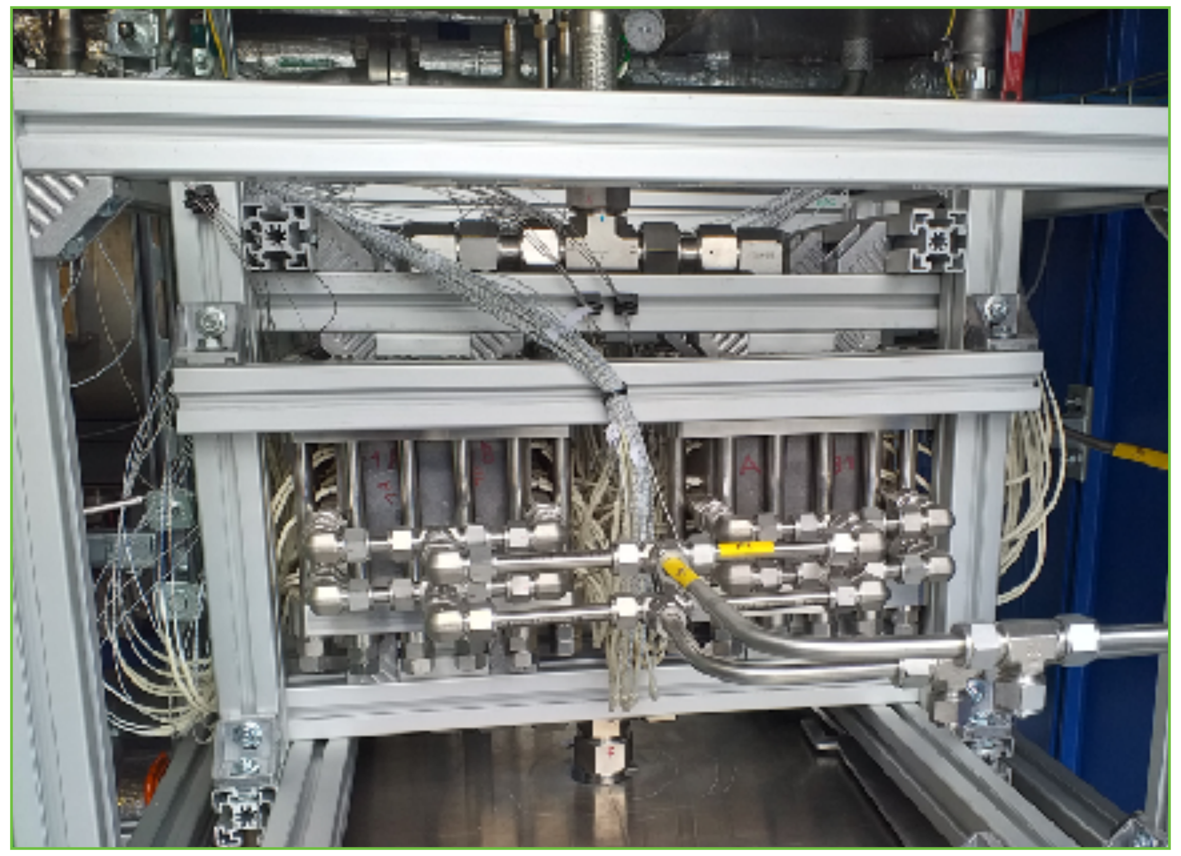
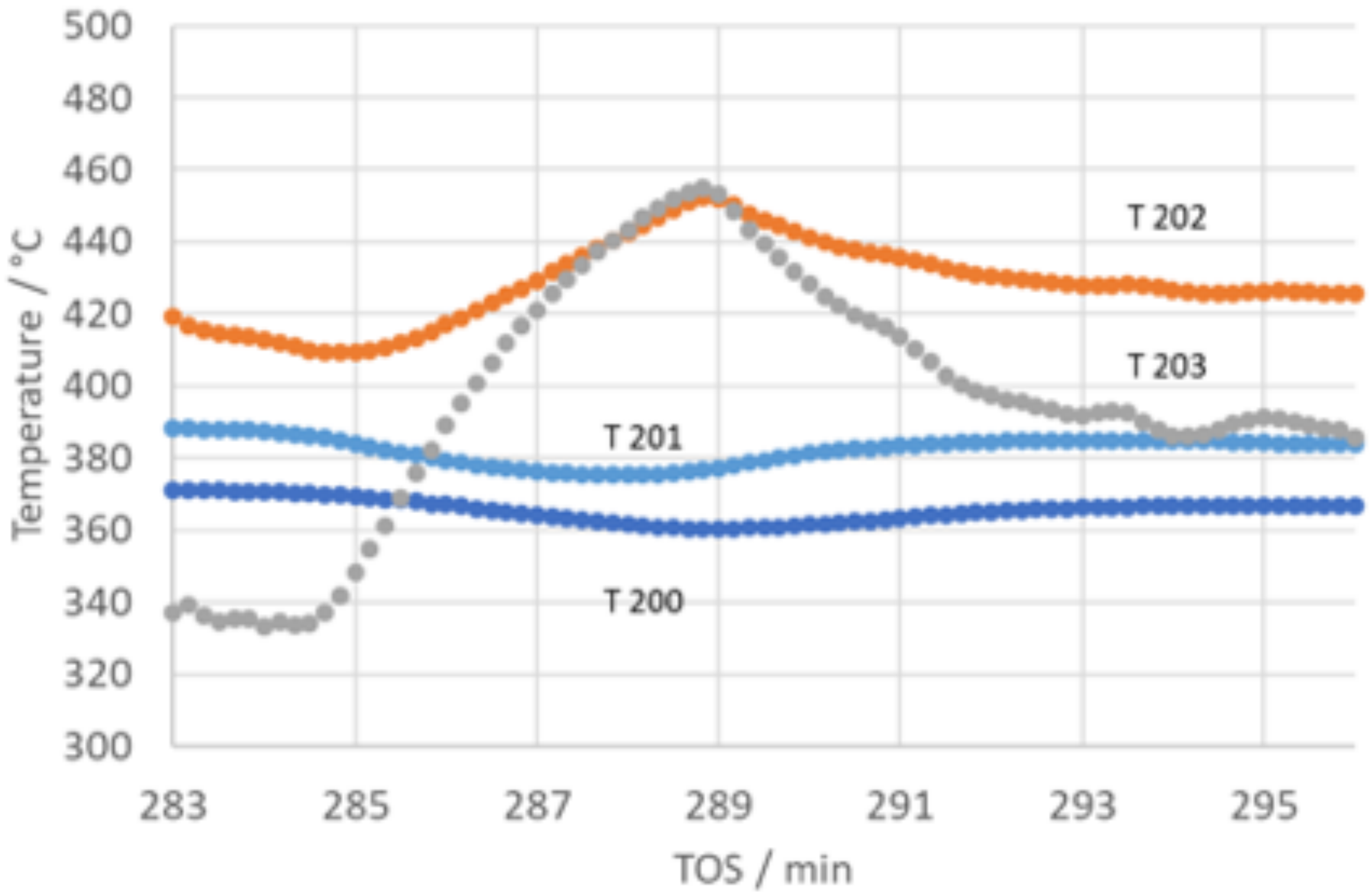
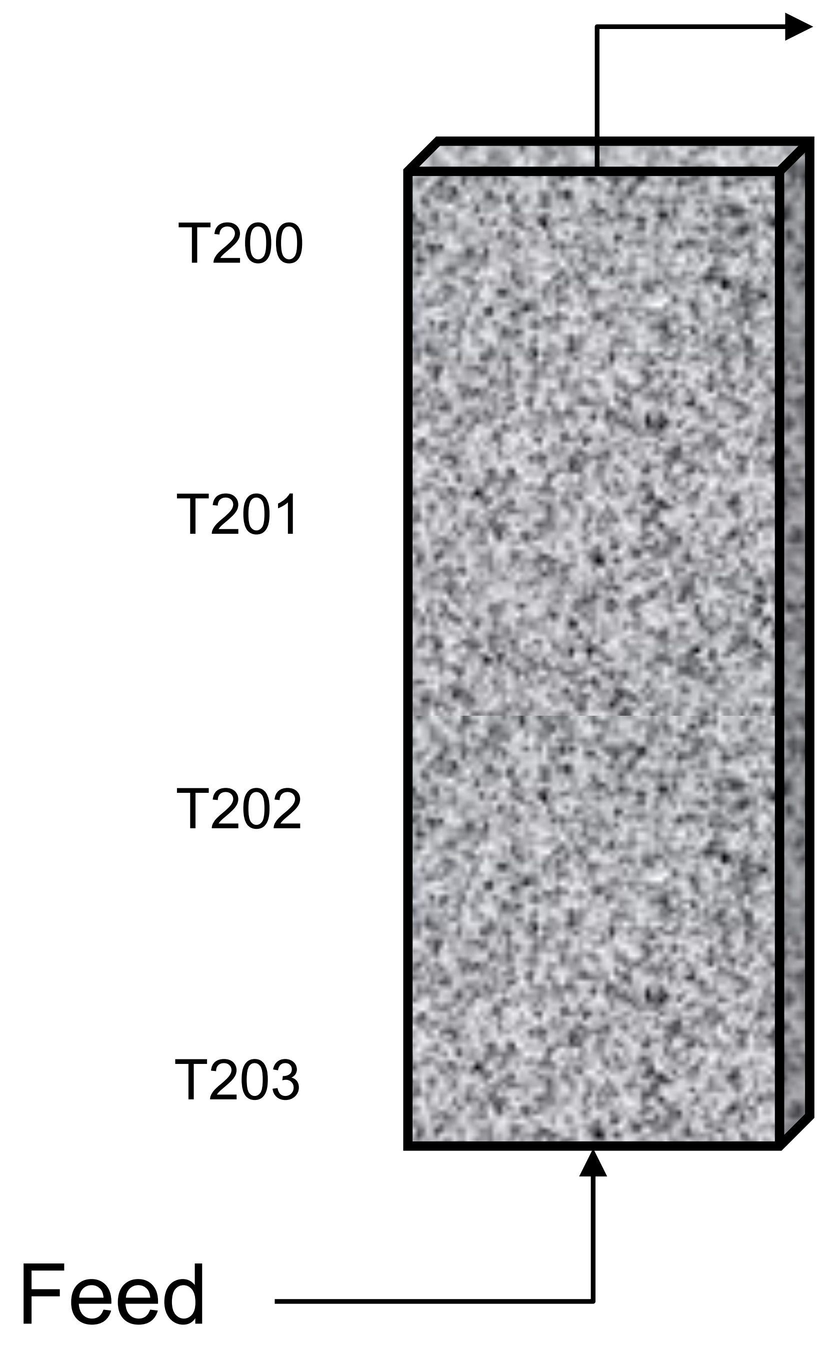


100 kW Prototype - first operation campaign (1/3)

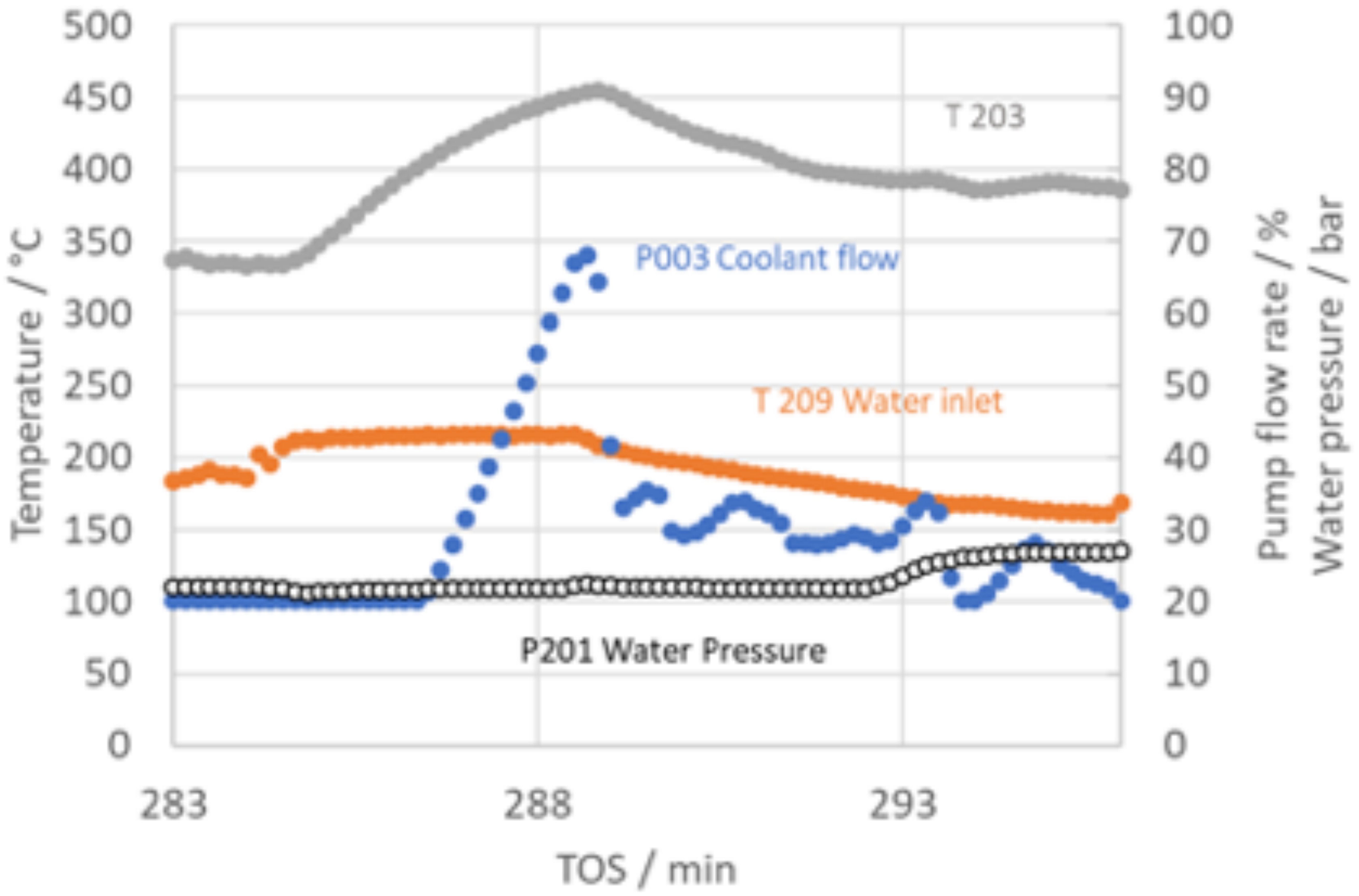


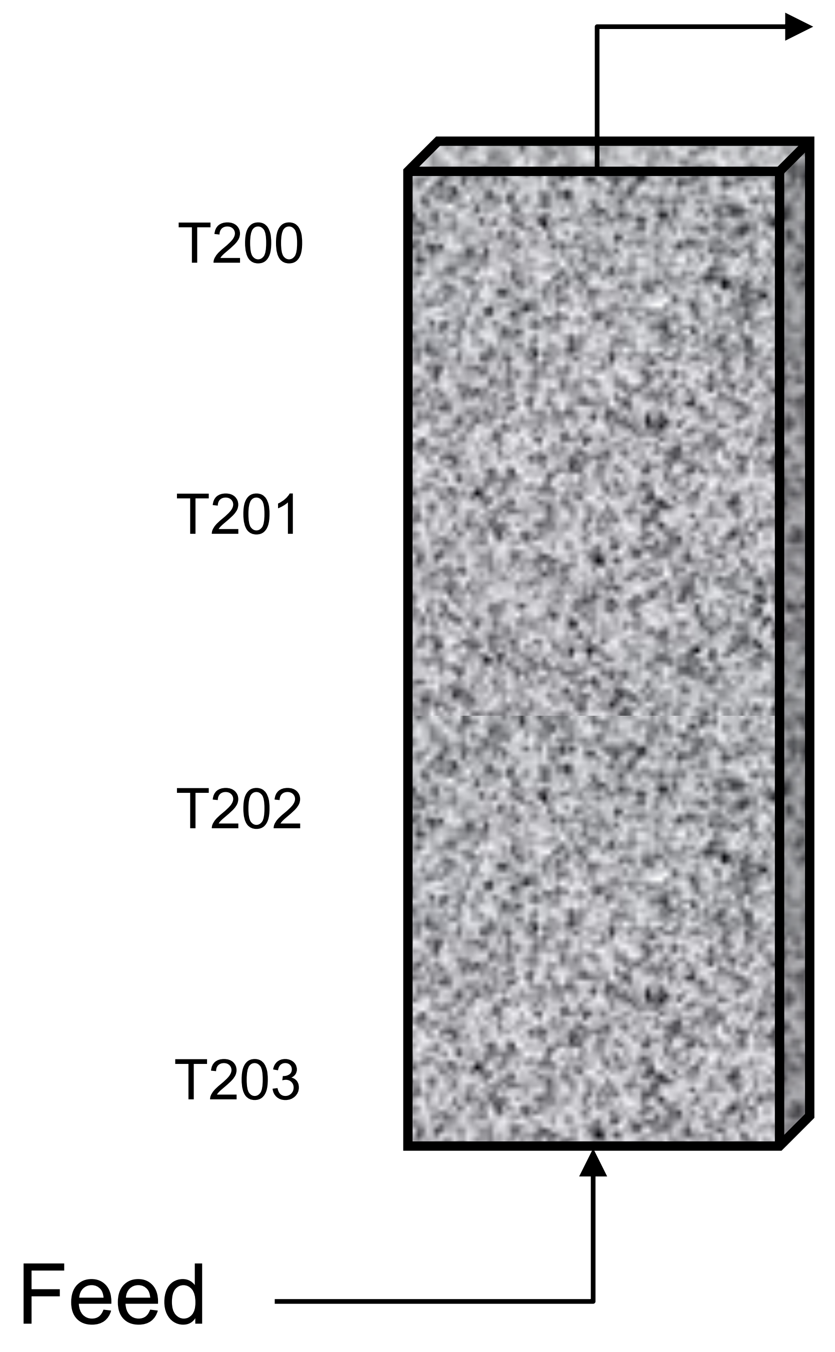


- 5 bar
- 5 m^3/h CO_2
- 20 m^3/h H_2
- 3 m^3/h N_2

- Module 1 operated in normal condition
- Module 2 did not ignite (~ 380°C)

100 kW Prototype - first operation campaign (2/3)

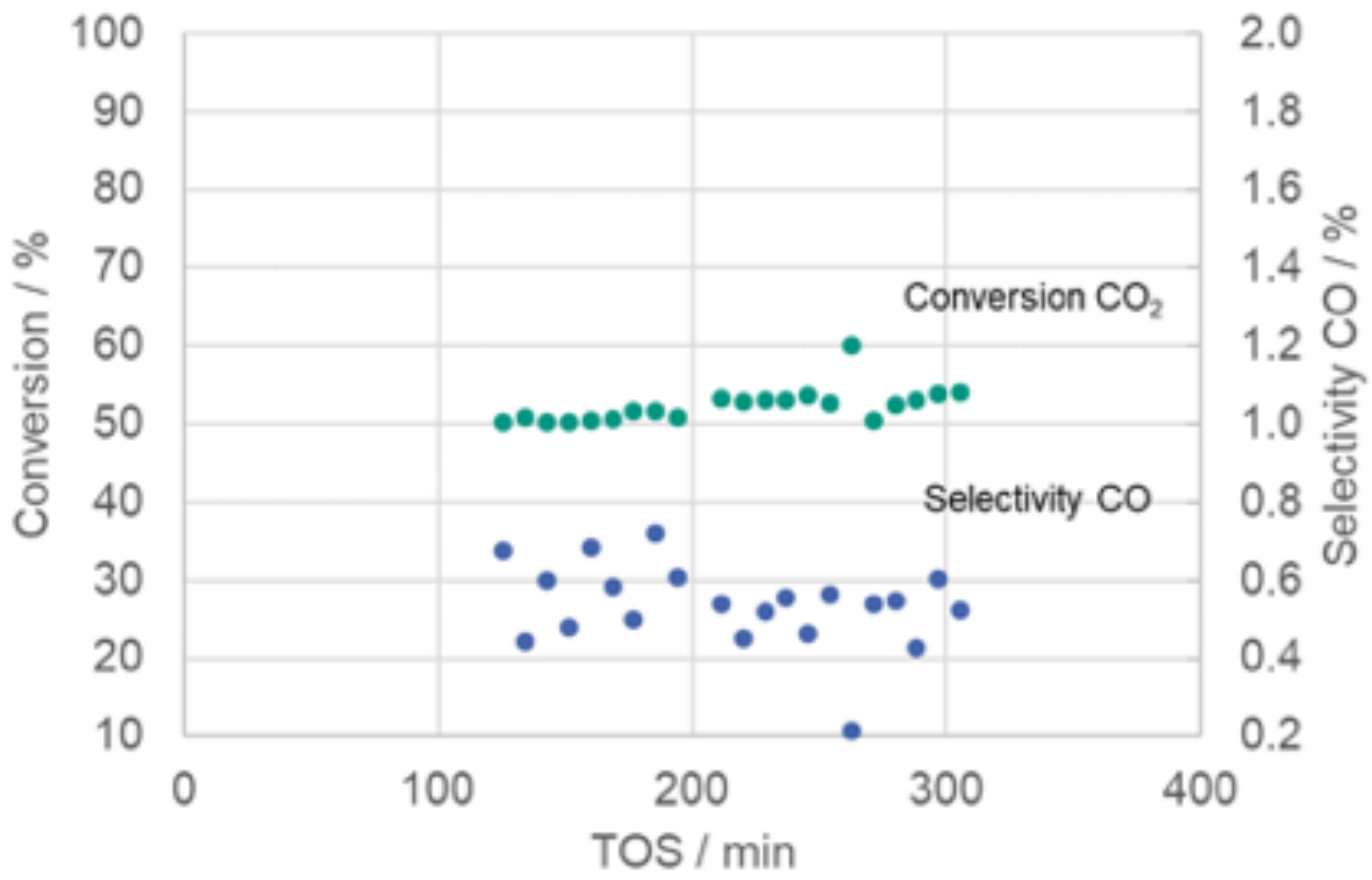




- 5 bar
- 5 m³/h CO_2
- 20 m³/h H_2
- 3 m³/h N_2

- Control of Module 1 within very short time possible; similar ignition behavior like original reactor

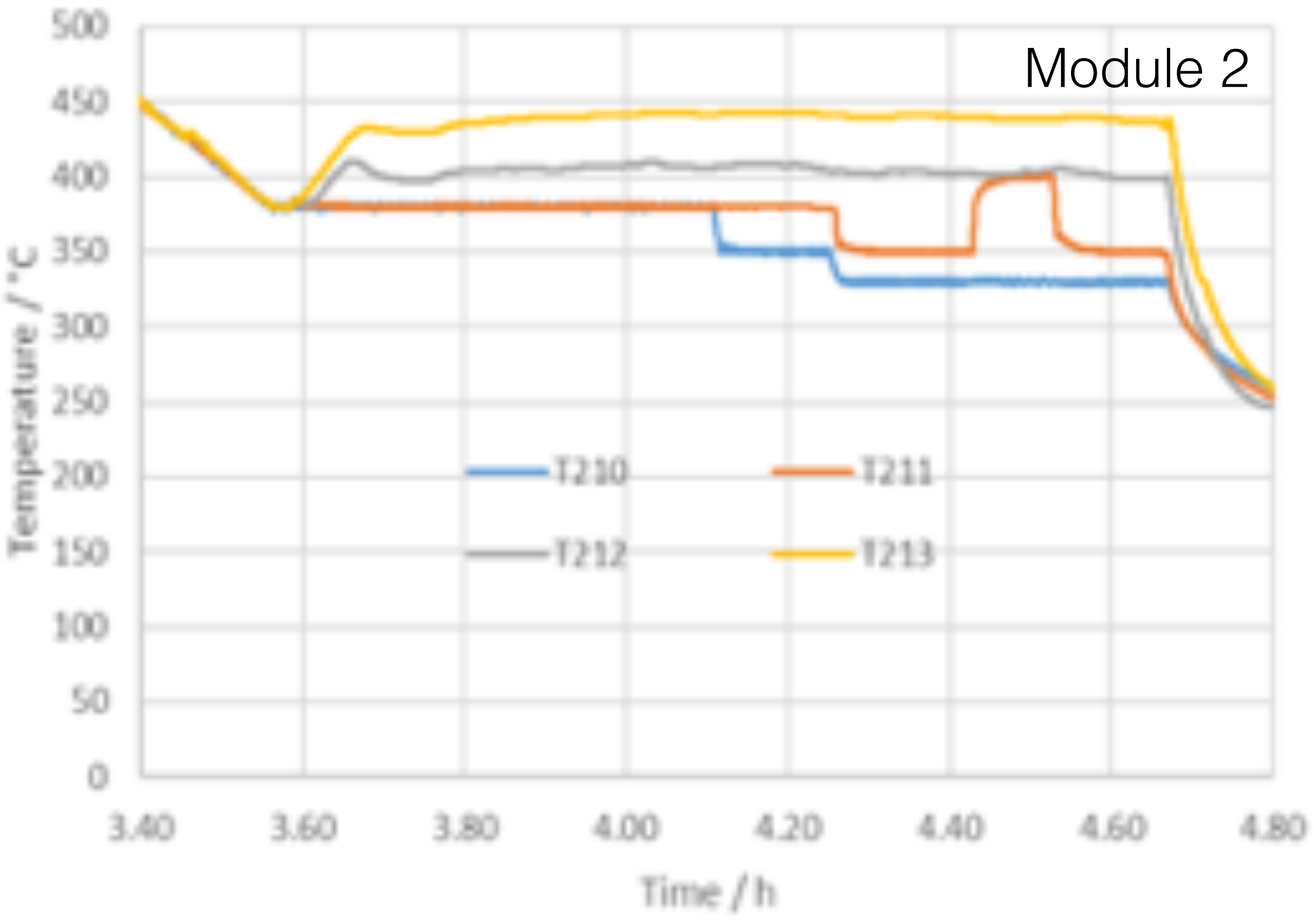
100 kW Prototype - first operation campaign (3/3)

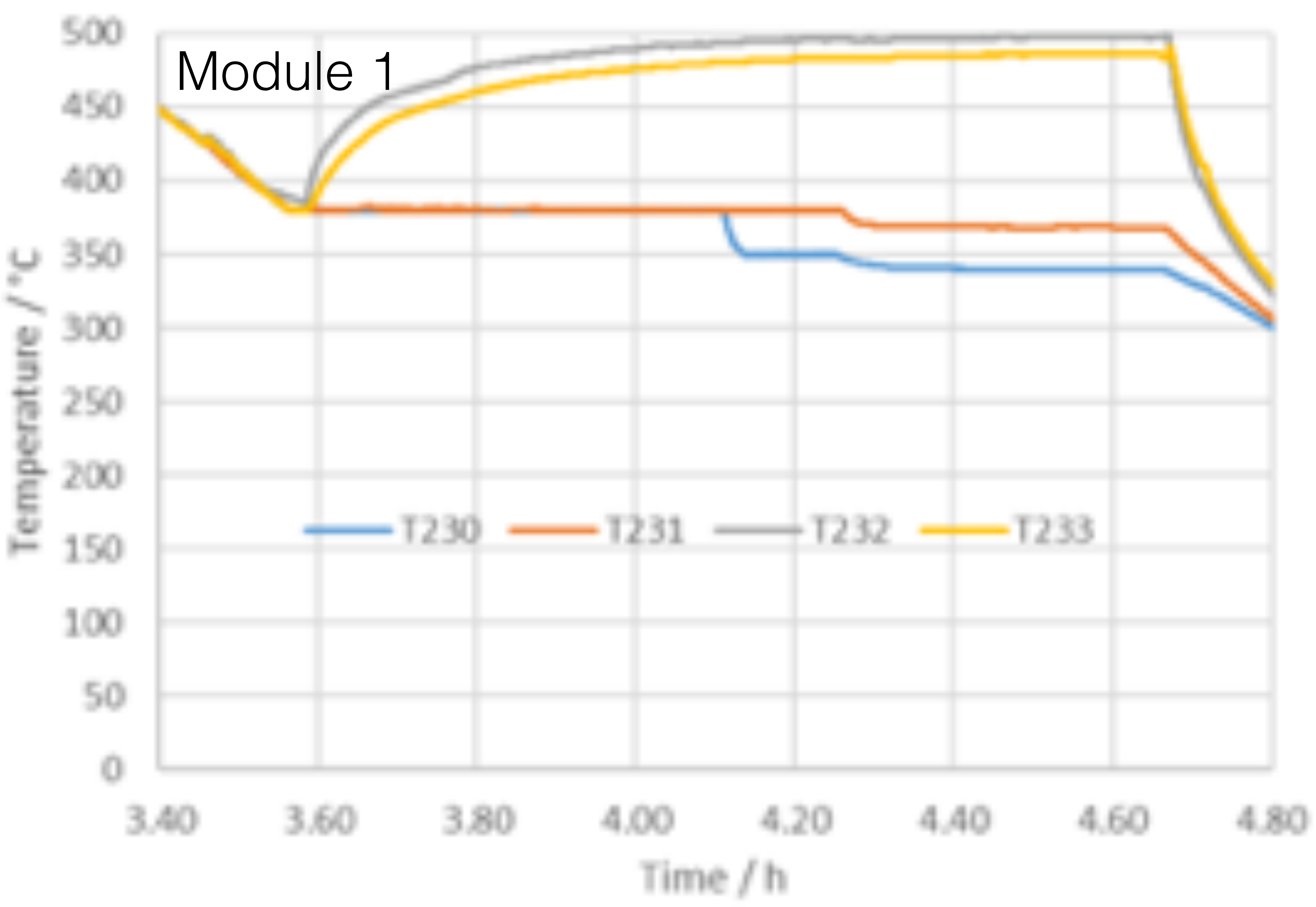


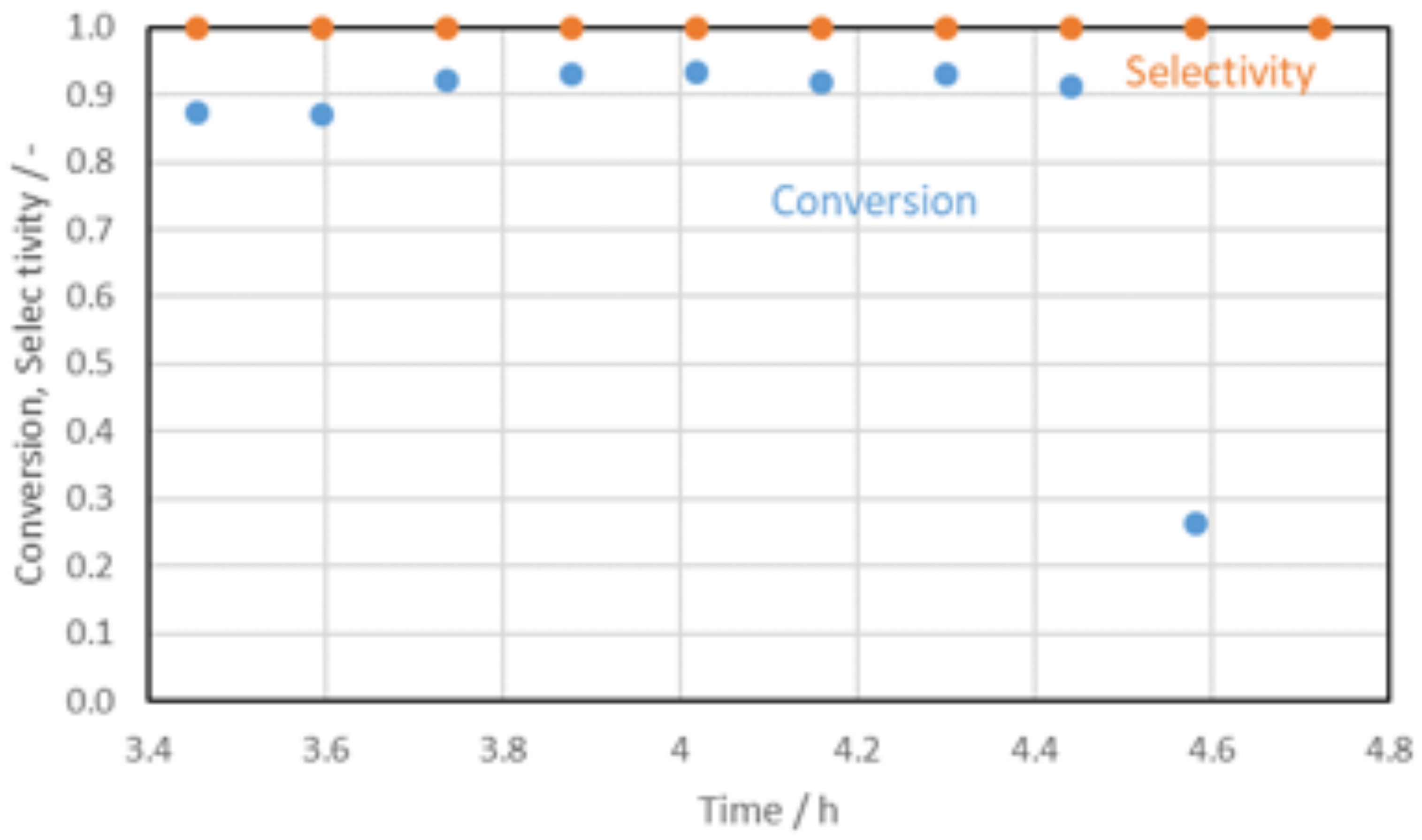
- 5 bar
- 5 m^3/h CO_2
- 20 m^3/h H_2
- 3 m^3/h N_2

- Module 1 contributed mainly to conversion; parameters still to be optimized
- Module 2 did not ignite (~ 380°C) and behaved like a bypass
  - most reasonably due to failed reduction or oil droplets from slurry bubble
  - column (problems with aerosol formation in product line)

100 kW Prototype - Second operation campaign - reactivation of module 2

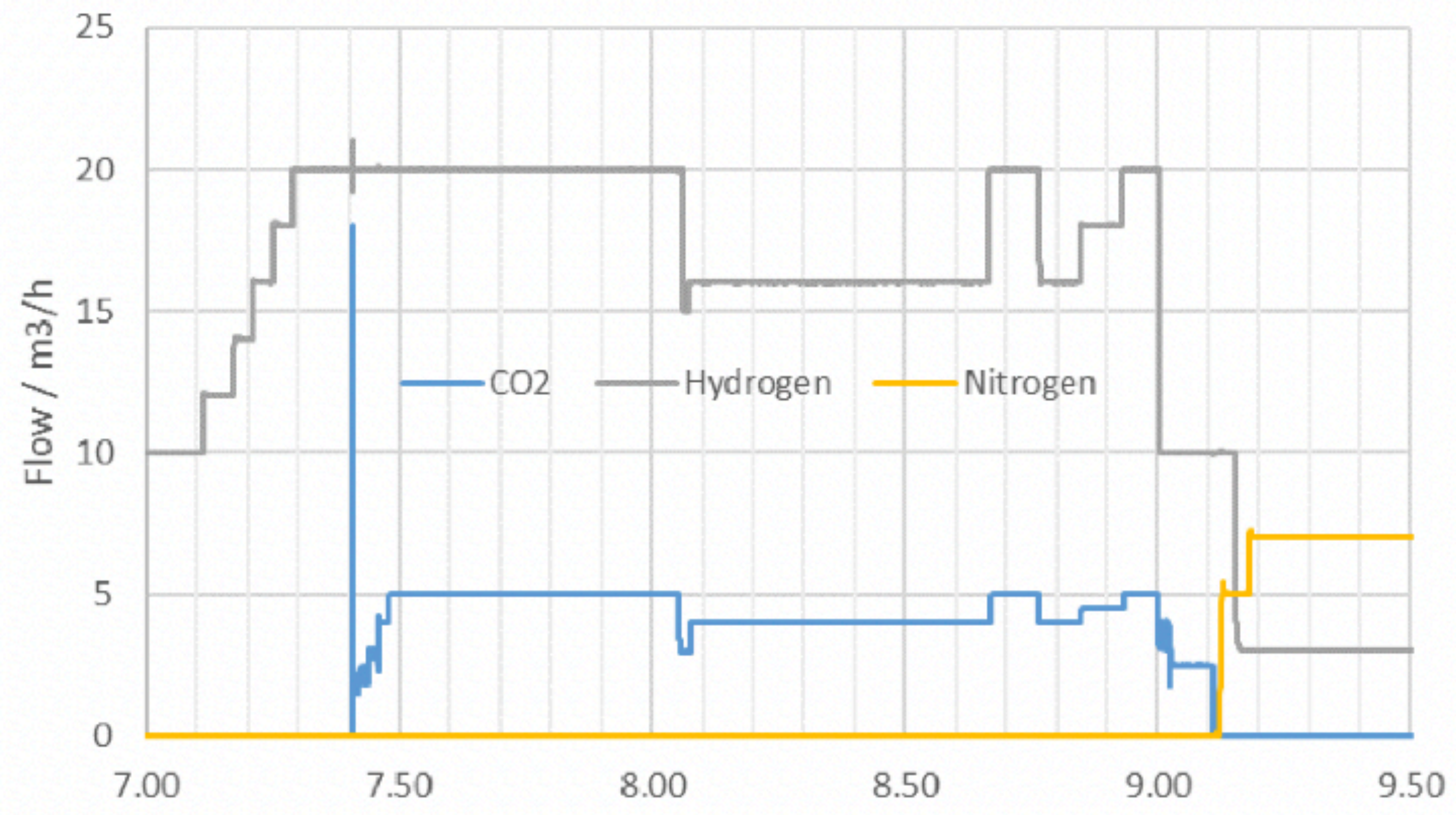


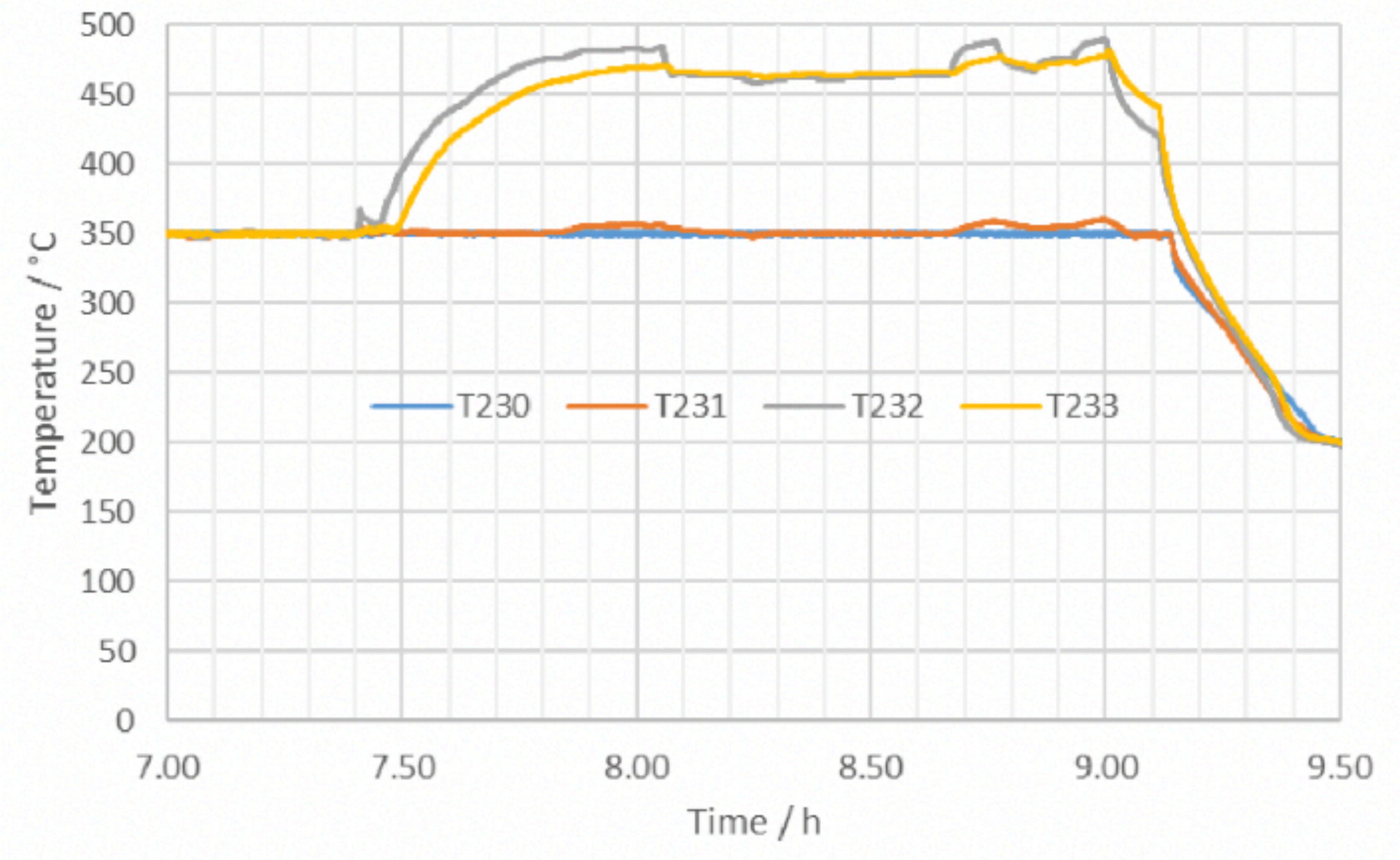


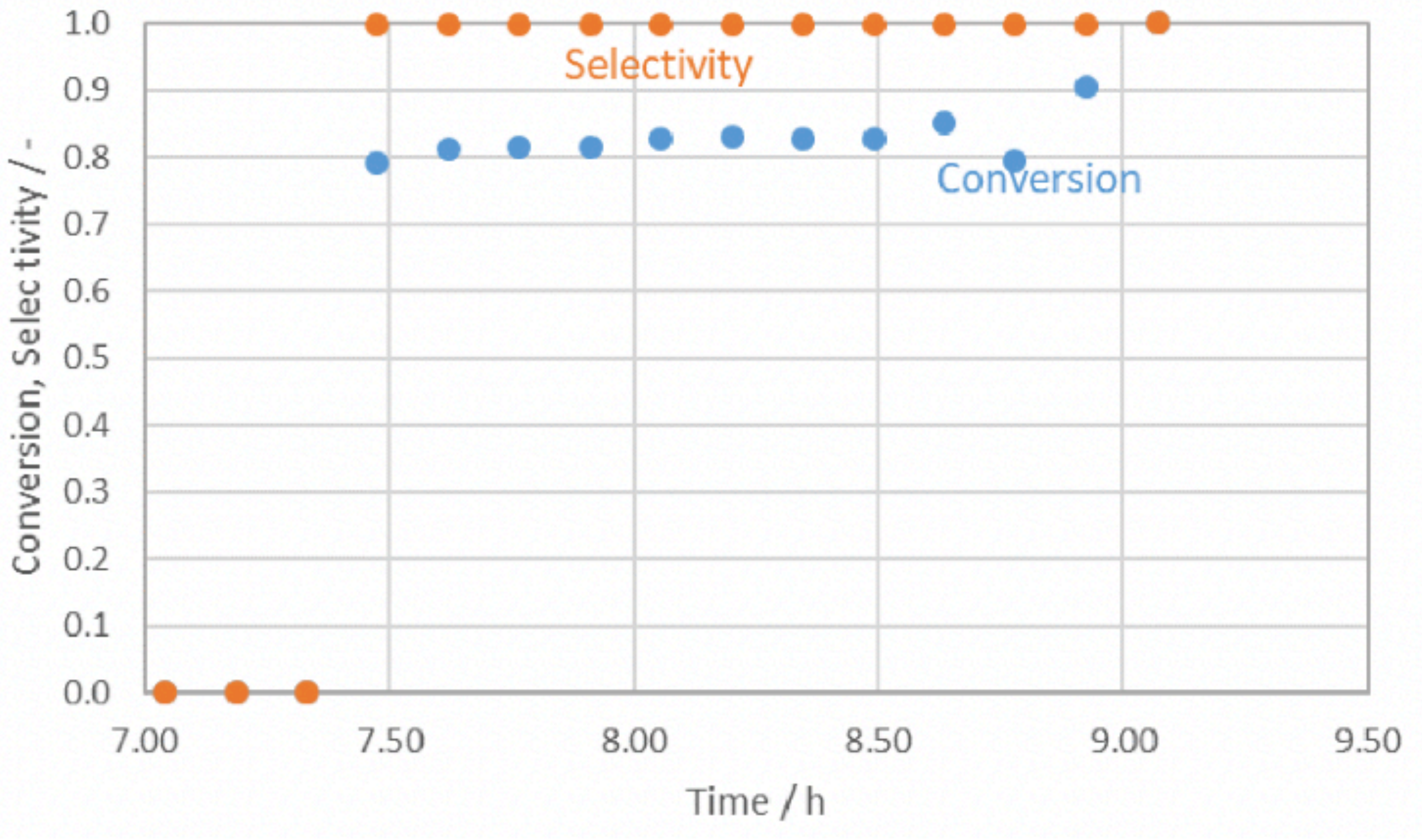


- Both modules ignited (~ 400°C), partly approval of re-reduction process
- Although different absolute temperature good control over temperature
- Selectivity for Methane 100% (no CO found)

100 kW Prototype - Third operation campaign - flow modulation

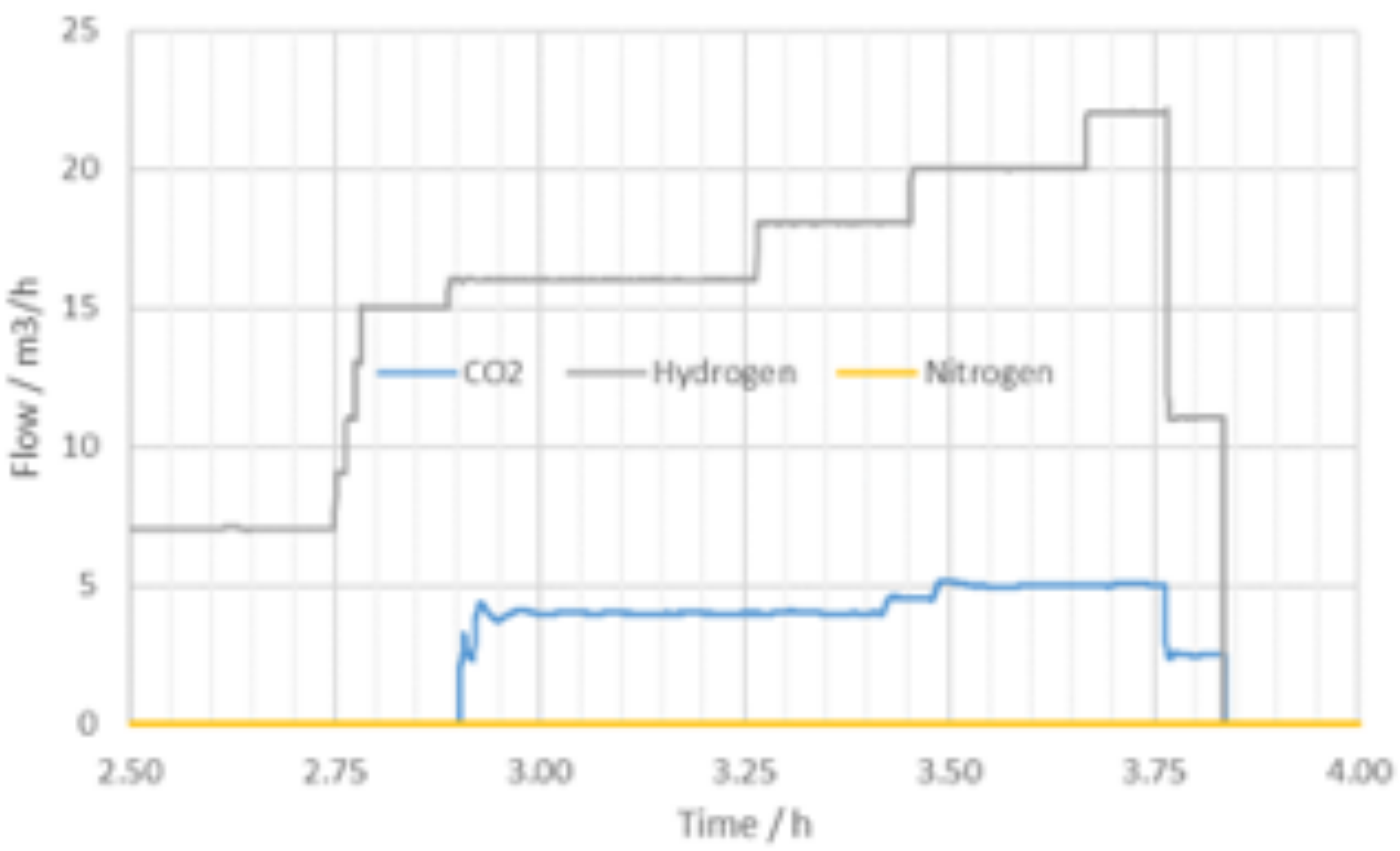


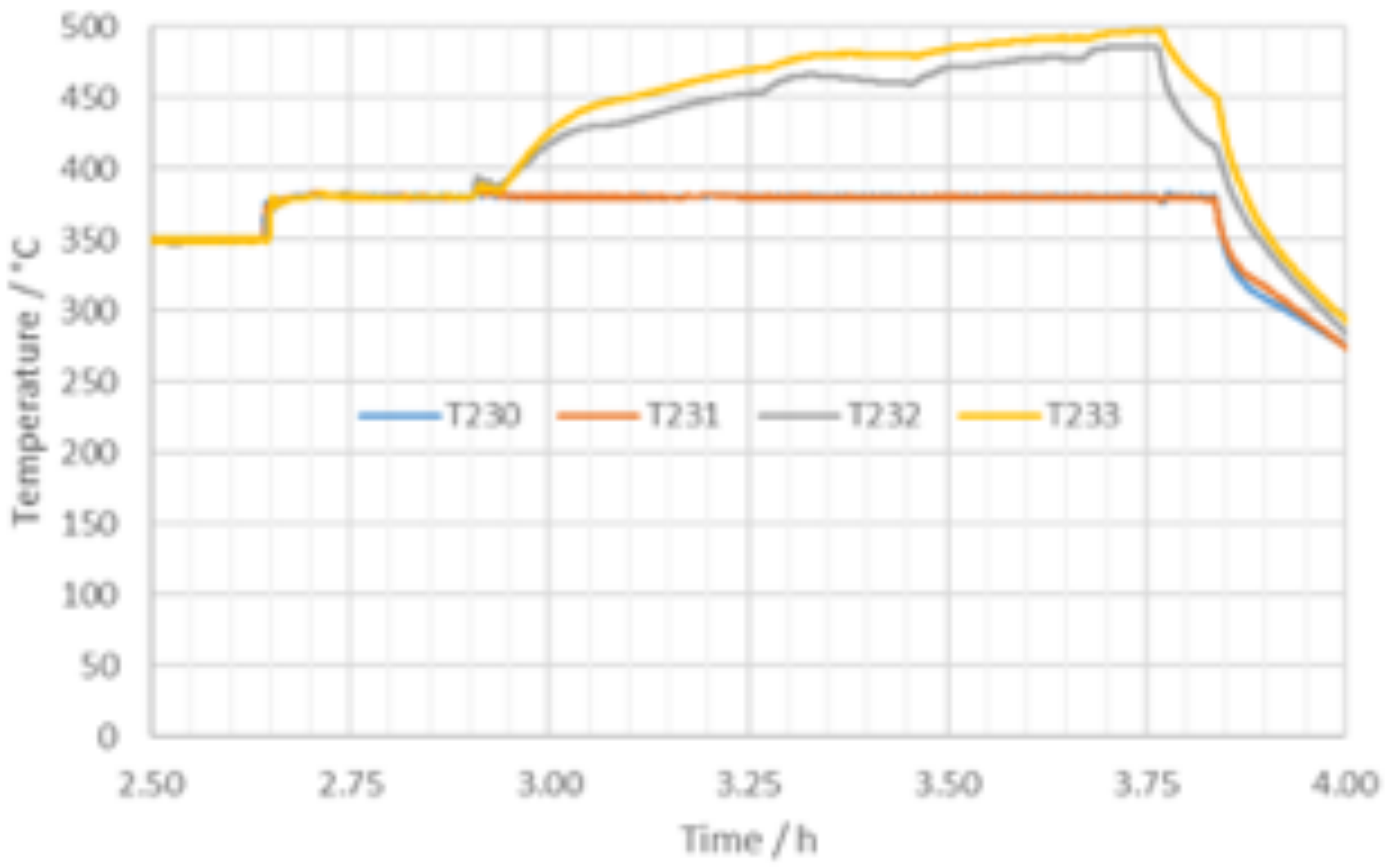


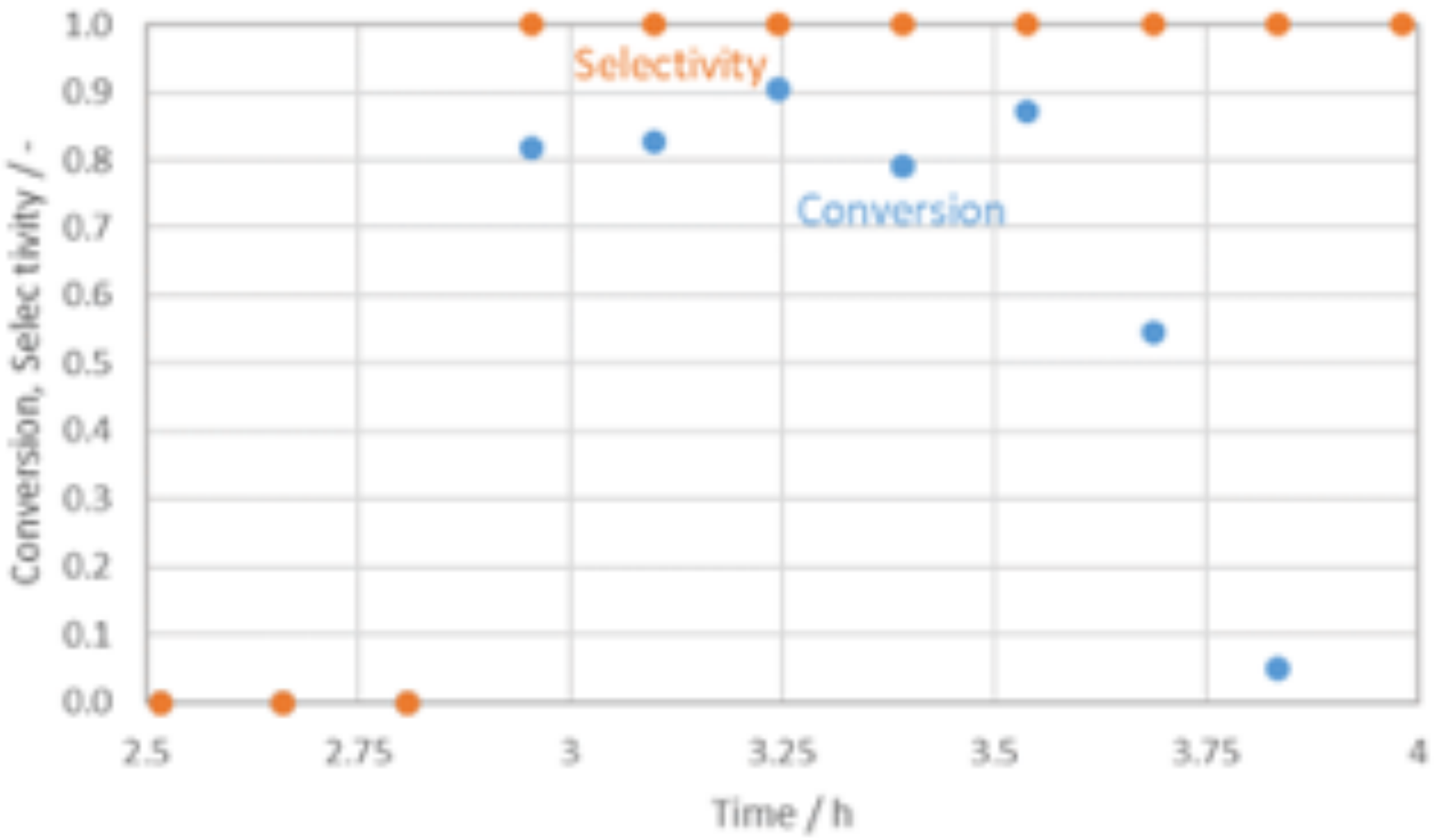


- Successful approval of flow modulation

100 kW Prototype - Fourth operation campaign - water cooling only on 2nd inlet







- Control almost possible, however, long adaptation times and final exceeding of set points
- Further validation and/or design improvements needed
- Work in progress…

INERATEC

Summary / Outlook

Status of PtG

- Technology is more or less ready for commercial use, but economics are difficult and still have to be improved
- PtG, like all types of PtX, only makes sense (from a CO_2 emission reduction point of view) if CO_2-free electrical power is used
- Current R&D addresses catalyst improvements, advanced reactor designs, and process integration (heat, material flows) with a focus on higher efficiency, lower cost, capability of transient operation, increased long-term stability all targeting lower production cost and higher operational flexibility

Uncertainties regarding the commercial implementation of PtG

- Future role of gas in domestic and industry heating ?
- Future role of gas in electric power generation (cold dark doldrums, security of supply) ?
- Future of the gas grid: methane or hydrogen, both, or (partial) deconstruction ?
- Role of CRG/LRG in transport ?
- Business model for PtG ?