TU Clausthal

# Power2X and Hydrogen Storage (and Transport)

## Unternehmergespräch ENERGIE

Alternative Energieträger für Wirtschaft und Mobilität: Von Wasserstoff bis Methanol

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14.09.2023

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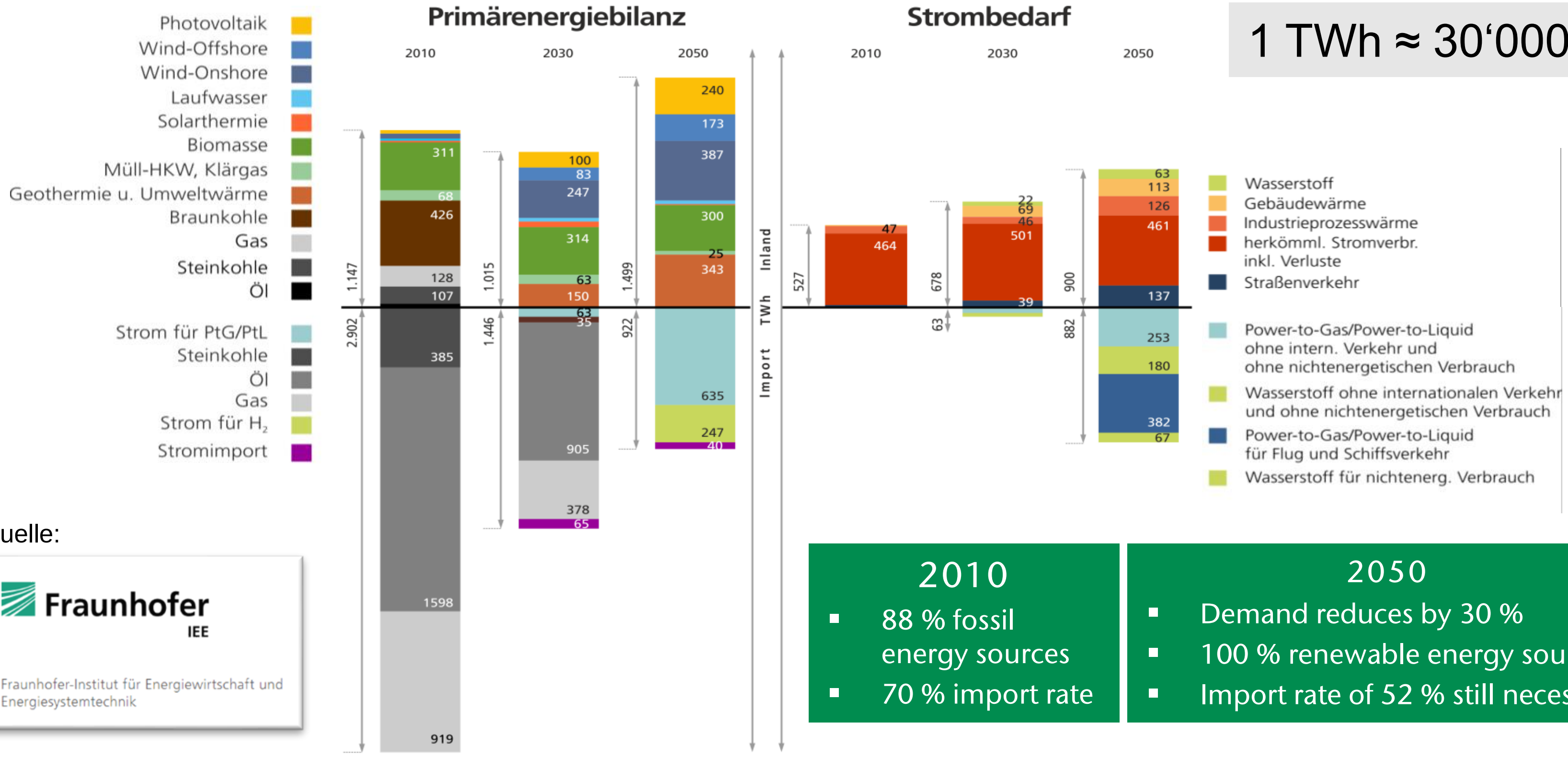
- **Thomas Turek**
  - W3 Chemische Verfahrenstechnik, Institutsleitung
  - Heterogene Katalyse, Elektrochemische Verfahrenstechnik

- **Jens Bremer**
  - W1 TT W3 **Chemische Energiespeicherung** (seit 3/2022)
  - Power2X Technologien
  - Multiskalenmodellierung, Simulation und Optimierung

# Energy Demand in Germany

(Barometer Energiewende – Fraunhofer IEE)

1 TWh ≈ 30‘000 $t_{H2}$




Quelle:

Fraunhofer IEE

Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik

**2010**

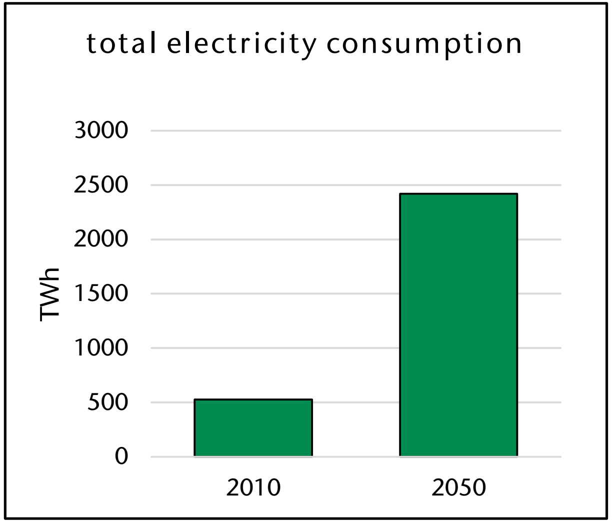
- 88 % fossil energy sources
- 70 % import rate

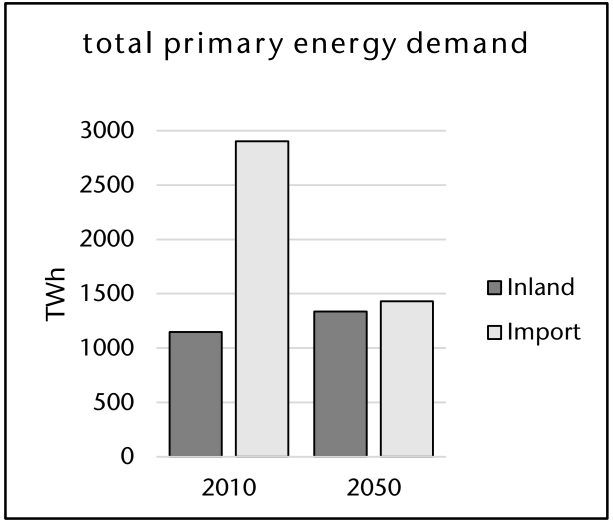
**2050**

- Demand reduces by 30 %
- 100 % renewable energy sources
- Import rate of 52 % still necessary

# Energy Demand in Germany

(Barometer Energiewende – Fraunhofer IEE)



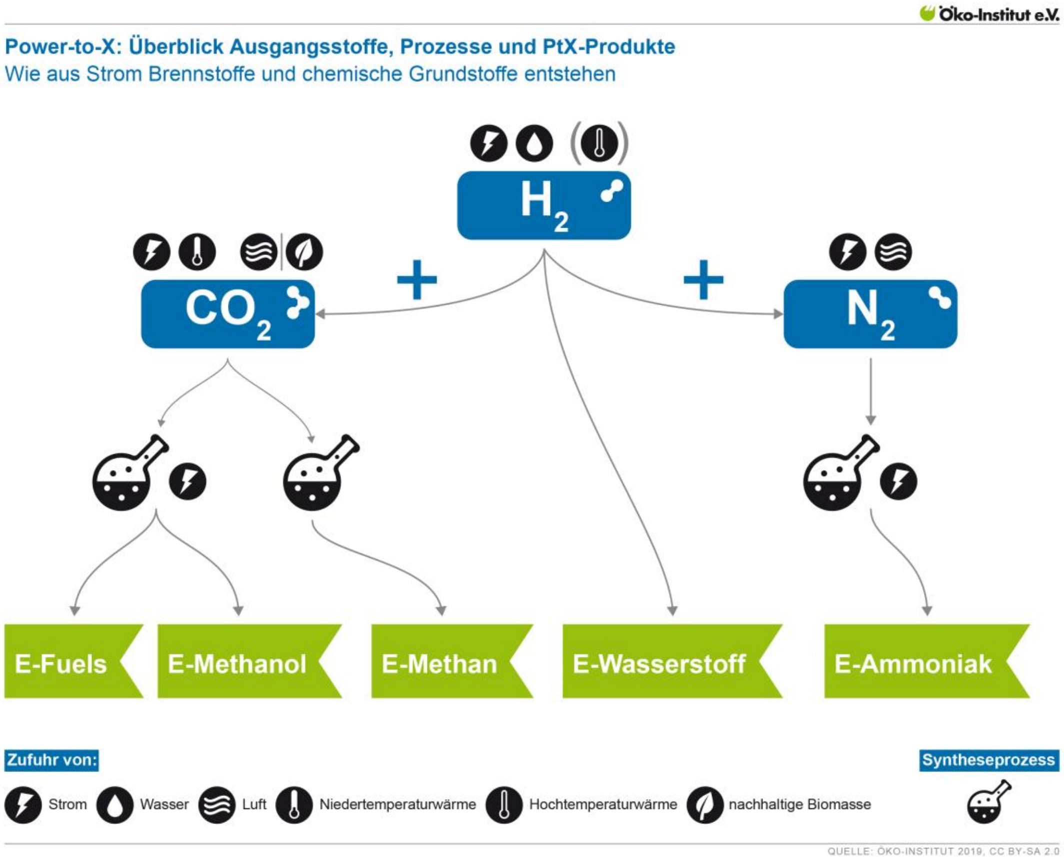




- Significant increase due to electrification of transport and heat sector
- Electricity becomes the main energy source

- Import of renewable energy is required (~1500 TWh)
  → No alternative to intercontinental transport using hydrogen

How to transport/ store hydrogen efficiently?
→ Carbon-based (SNG, MeOH, FT)
→ Nitrogen-based ($NH_3$)

# Power2X – Options



# Carbon vs. Nitrogen as $H_2$-Carrier

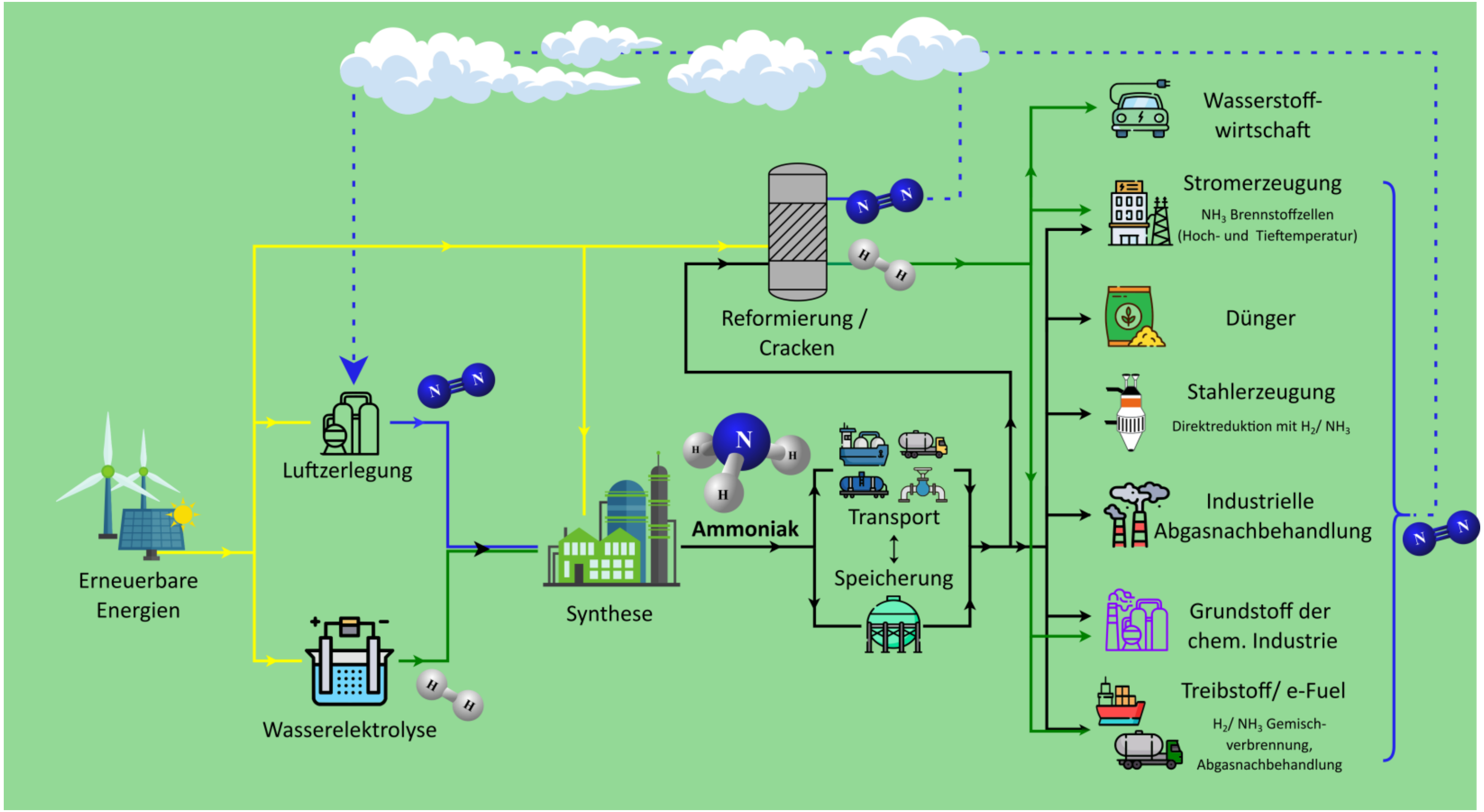
| Aspect | Carbon based (syn. Fuels) | Nitrogen based ($NH_3$) |
|---|---|---|
| Availability (Conc. in Air) → Assumption: Circular Economy | 0,04 % ($CO_2$) | 78 % ($N_2$) |
| Costs per kWh Electricity → PTX-Atlas (Fraunhofer IEE) | - (~ 300 €/MWh) | o (~ 200 €/MWh) |
| Storage Efficiency | o | (+) |
| Transport | + | + |
| Technical Maturity → CCU/ASU | (-) | + |
| GHG Potential | (-) / o | + |
| Toxicity | (-) / o | (-) |
| Environmental risk | o | o |
| Flammability | o | + |

Strong Arguments for Nitrogen as potential $H_2$-Carrier

CCU: Carbon Capture and Utilization
ASU: Air Separation Unit
GHG: Greenhouse Gas

+ positive / suitable
(+) rather positive / suitable
o ok
(--) rather negative / not suitable
-- negative / not suitable

# Power2X – Example E-Ammonia



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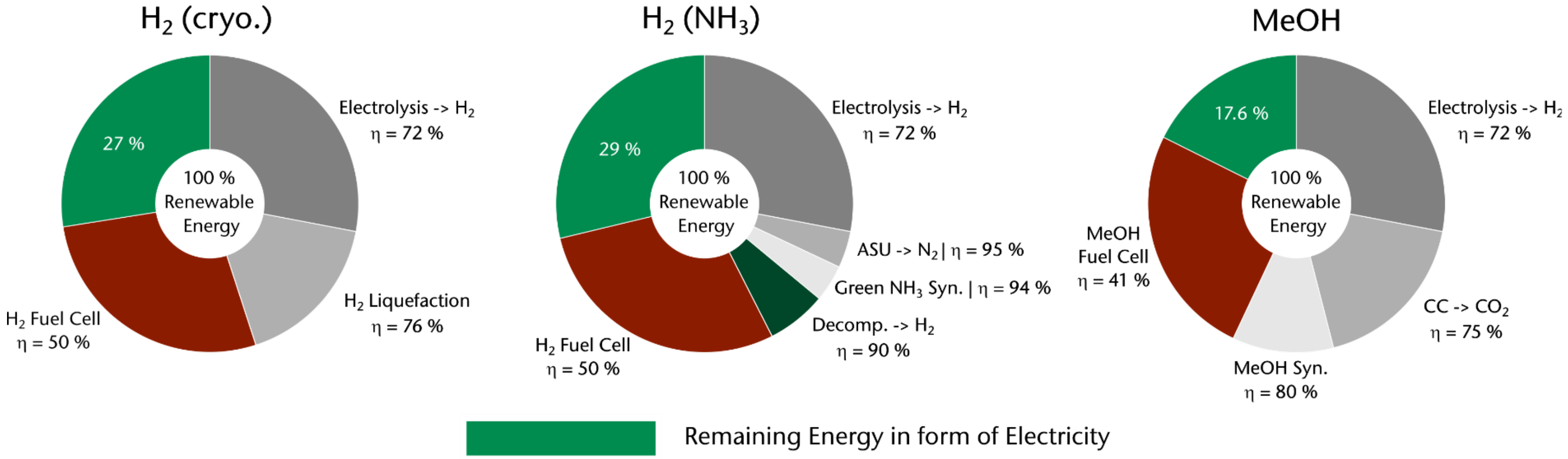
# Power2X - Round-Trip Efficiency




- Efficiency Calculations based on HHV of $H_2$ (141 $^{MJ}/_{kg}$)
- Pressure Storage of $H_2$ @ 700 bar, 25 °C | $\eta = 87.5$ %
- Up to 2% ($H_2$) boil-off losses per day for cryo. $H_2$ storage

# Ammonia – Equivalent Energy Storage Capacity

## Goldisthal Pumped-Storage

- Volume: 12 Mio. $m^3$
- Storage capacity: 8.5 GWh

[2]

## Liquid $NH_3$ (-33 °C) Storage Tank

- Equivalent storage capacity: 5300 $m^3$
  - @ 45 % efficiency $NH_3$ to power
- Tank dimensions (inner):
  - D = 21.3 m | H = 16.3 m

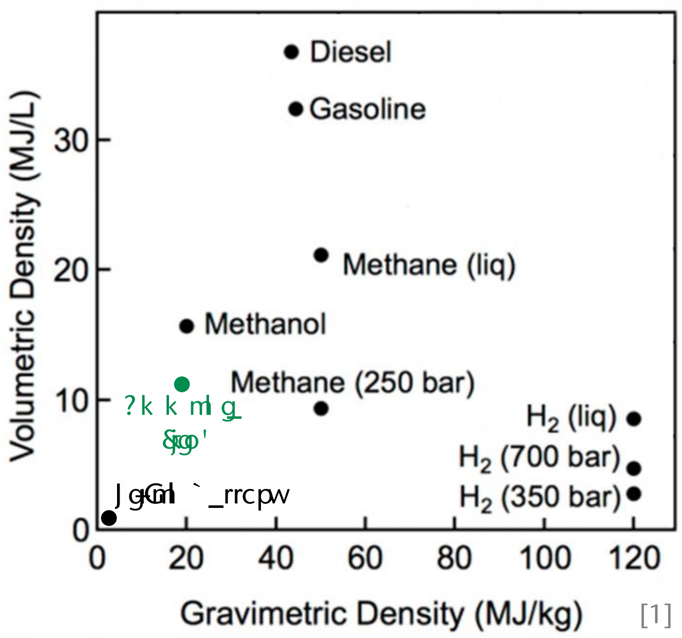
[3]

[2] Taken from: https://powerplants.vattenfall.com/de/goldisthal/
[3] Taken from: https://www.geldof.be/?portfolio=double-walled-ammonia-storage-tank-28372

# Power2X Fuels - Energy Content

- Liquid $NH_3$ @
  - - 33 °C | 1 atm
  - 25 °C | 10 bar
- Liquid $H_2$ @
  - - 253 °C | 1 atm

- Ammonia
  - ➢ Carbon free fuel source
  - ➢ Ammonia → Easy to store and transport (intra / intercontinental transport already established)
  - ➢ Proven safety history for over 75 years




[1]

[1] Adopted from: Rvarolo et. al (2019) "Clean Hydrogen and Ammonia Synthesis in Paraguay from the Itaipu 14 GW Hydroelectric Plant"

# Power2X - Import Pathways


Christoph Hank, Marius Holst, Connor Thelen, Christoph Kost, Sven Längle, Achim Schaadt, Tom Smolinka

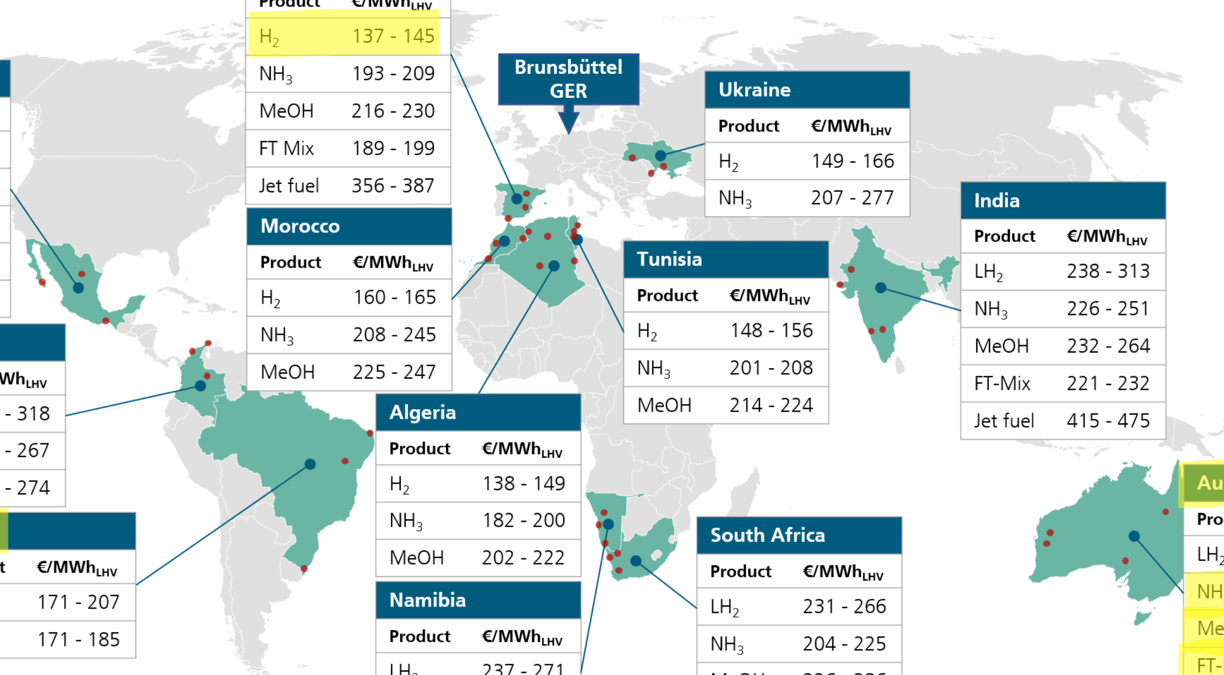
Site-specific, comparative analysis
for suitable Power-to-X pathways and products
in developing and emerging countries

# Power2X Import Pathways

- techno-economic comparison in 39 globally distributed regions
- production of green hydrogen, ammonia, methanol and jet fuel
- exclusively renewables for 100% green hydrogen production
- site-specific analyses (interaction of wind and photovoltaic production profiles, topography, infrastructural conditions, administrative conditions, transport distance)

- Low levelized cost of renewable electricity generation and associated high full load hours are decisive
- Favorable combined conditions for wind and PV power generation required
- Strong impact of low weighted average cost of capital

# Power2X Import Costs




**Spain**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $H_2$ | 137 - 145 |
| $NH_3$ | 193 - 209 |
| MeOH | 216 - 230 |
| FT Mix | 189 - 199 |
| Jet fuel | 356 - 387 |

**Mexico**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $LH_2$ | 242 - 285 |
| $NH_3$ | 217 - 231 |
| MeOH | 237 - 244 |
| FT-Mix | 210 - 212 |
| Jet fuel | 407 - 431 |

**Colombia**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $LH_2$ | 176 - 318 |
| $NH_3$ | 190 - 267 |
| MeOH | 190 - 274 |

**Brazil**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $LH_2$ | 171 - 207 |
| $NH_3$ | 171 - 185 |

**Morocco**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $H_2$ | 160 - 165 |
| $NH_3$ | 208 - 245 |
| MeOH | 225 - 247 |

**Algeria**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $H_2$ | 138 - 149 |
| $NH_3$ | 182 - 200 |
| MeOH | 202 - 222 |

**Namibia**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $LH_2$ | 237 - 271 |
| $NH_3$ | 206 - 213 |
| MeOH | 222 - 240 |

**Ukraine**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $H_2$ | 149 - 166 |
| $NH_3$ | 207 - 277 |

**Tunisia**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $H_2$ | 148 - 156 |
| $NH_3$ | 201 - 208 |
| MeOH | 214 - 224 |

**South Africa**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $LH_2$ | 231 - 266 |
| $NH_3$ | 204 - 225 |
| MeOH | 226 - 236 |

**India**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $LH_2$ | 238 - 313 |
| $NH_3$ | 226 - 251 |
| MeOH | 232 - 264 |
| FT-Mix | 221 - 232 |
| Jet fuel | 415 - 475 |

**Australia**

| Product | €/MWh$_{LHV}$ |
|---|---|
| $LH_2$ | 217 - 232 |
| $NH_3$ | 173 - 185 |
| MeOH | 192 - 200 |
| FT-Mix | 167 - 181 |
| Jet fuel | 299 - 334 |

Preisvergleich GER:

Benzin und Diesel:
1,70 €/L ≈ 170 €/MWh

Strom ≈ 350 €/MWh

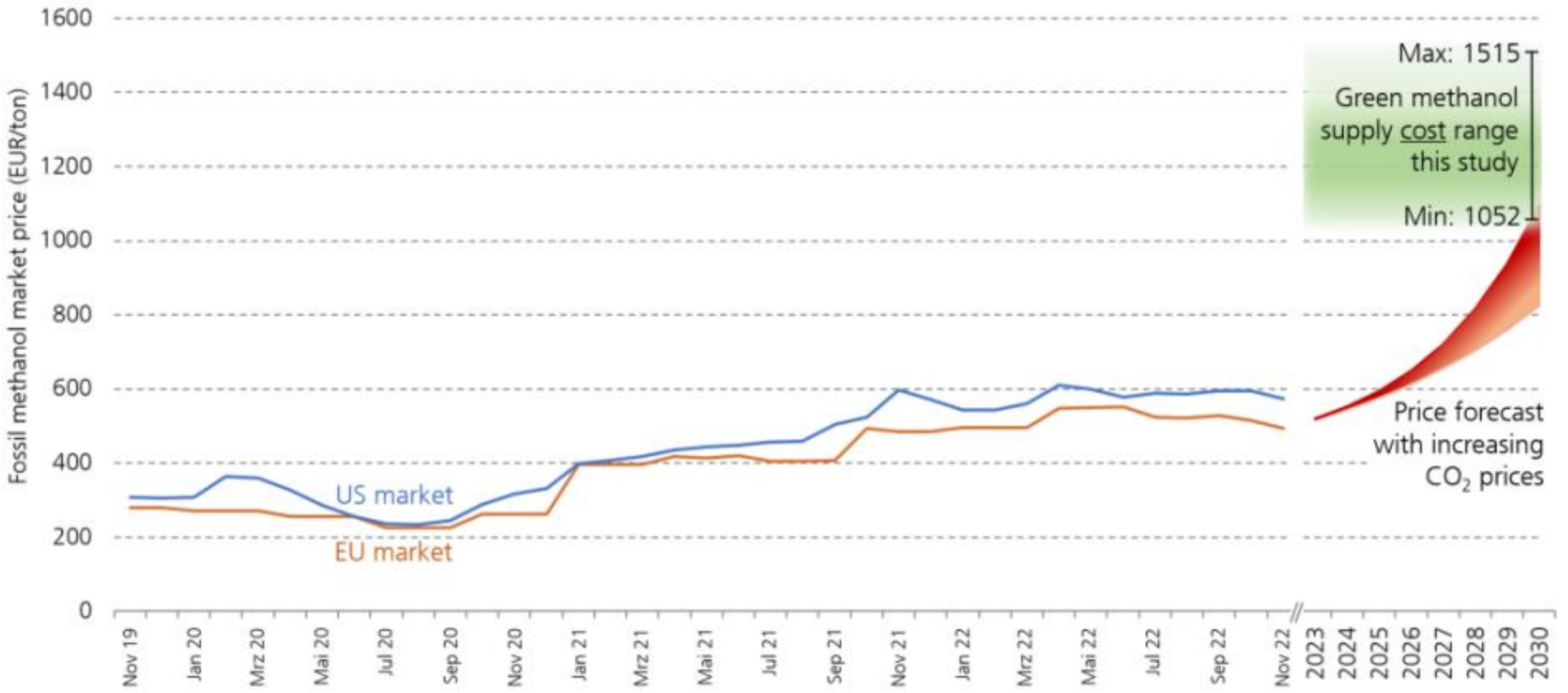
Erdgas ≈ 80 €/MWh

# Power2X – Hydrogen Price

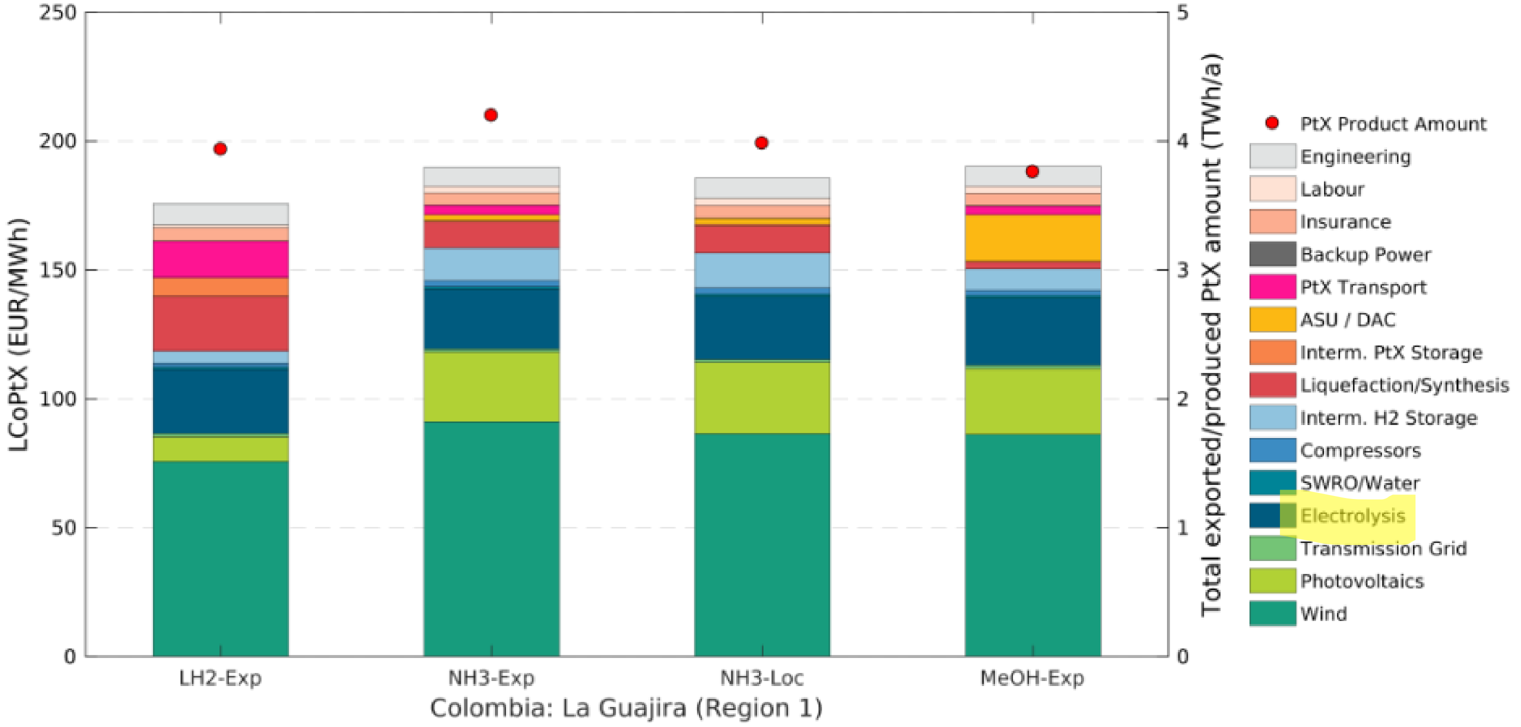
**Table 6-8: Published target values of national roadmaps and international price projections and scenarios for hydrogen in 2030.**

| **Communicator** | **Type of assessment** | **Price range per kg $H_2$** | **Reference** |
|---|---|---|---|
| This study | Scenarios | 3.21-5.33 EUR *(costs)* | *Power-to-X country analyses, 2023* |
| Hydrogen Council | Projection | 1.40-2.30 USD | *Hydrogen insights, 2021; [6]* |
| European Council | Target | 1.10-2.40 EUR | *Hydrogen strategy, 2020; [146]* |
| IEA | Scenarios | 1.50-3.50 USD | *Net Zero by 2050, 2021; [147]* |
| IRENA | Scenarios | 1.40-2.00 USD | *Low RE cost scenarios in Green H2 cost reduction, 2020; [148]* |

# Power2X Import Pathways



# Power2X Import Pathways



# Power2X - Key Challenges



“Therefore, it is important to promote the development of a manufacturing industry for water electrolysis and to scale up the current small-scale hardware manufacturing and move towards gigawatt-scale manufacturing capacities.”

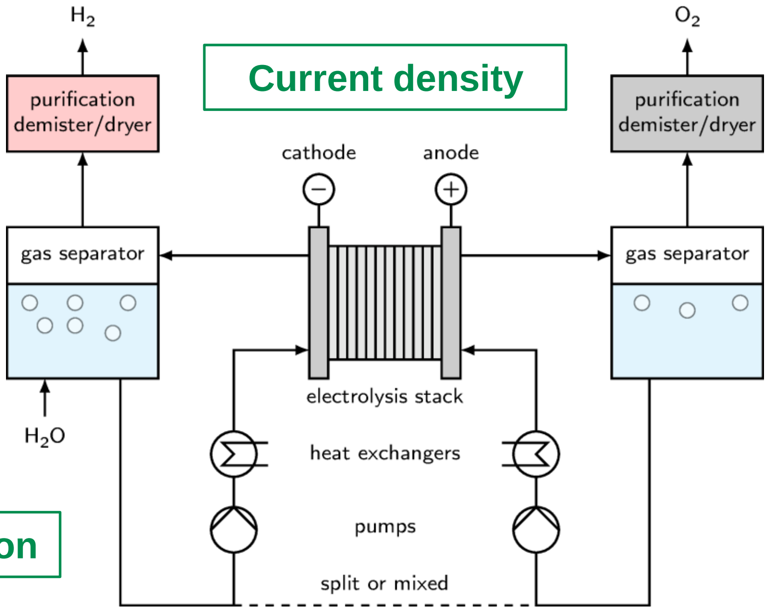
→ One main research area at TU Clausthal / ICVT + WEW WATER ELECTROLYSIS WORKS

# Stack is the Heart of an Alkaline Water Electrolysis System!

Current density

Temperature

Pressure




Electrolyte concentration

Electrolyte flow mode

J. Brauns, T. Turek, Processes 8 (2020) 248.

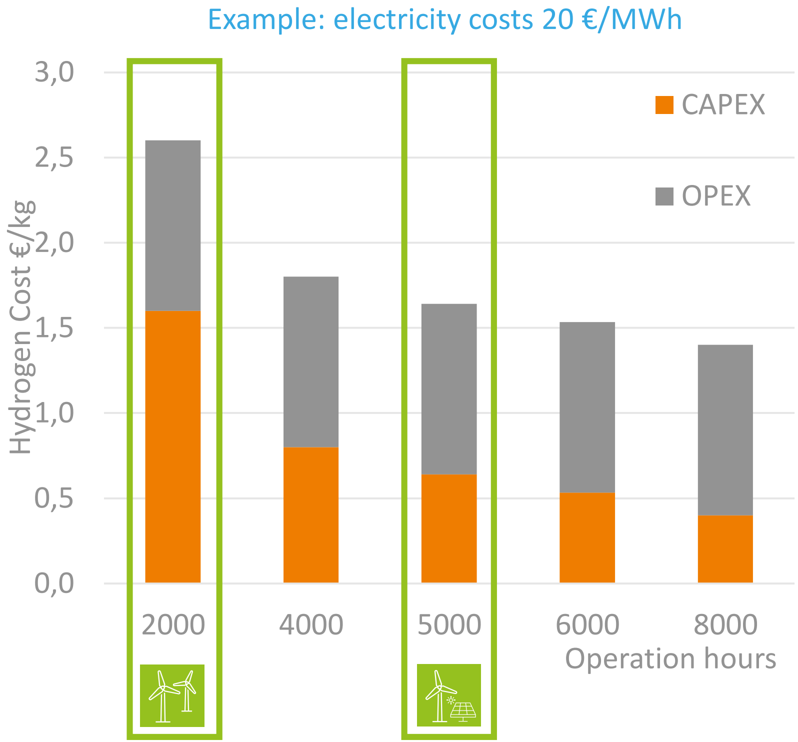
# Challenges in Hydrogen Business

- Hydrogen production costs are composed of CAPEX and OPEX, whereby the respective shares can vary drastically.
- CAPEX dominates when power generation costs are low and/or annual full-load hours for electrolysis operation are limited.

2000 full-load hours

5000 full-load hours

8000 full-load hours




Exemplary calculation based on Smolinka et. al, 2018, IndWEDe study; CAPEX 575 €/kW excl. land, power connection, maintenance

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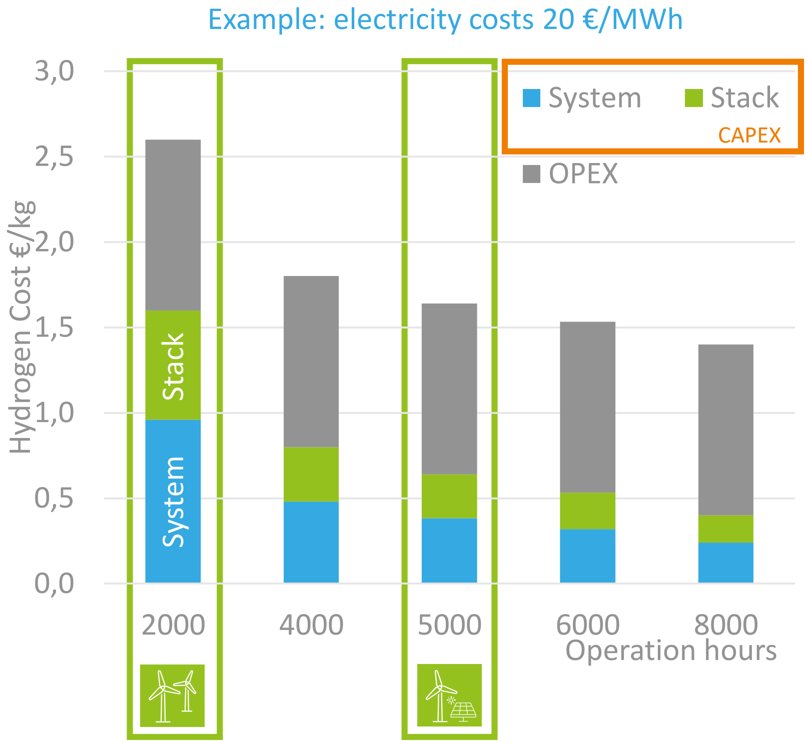
2000 full-load hours


5000 full-load hours


8000 full-load hours

- Stack is largest system component with highest innovation/cost-down potential

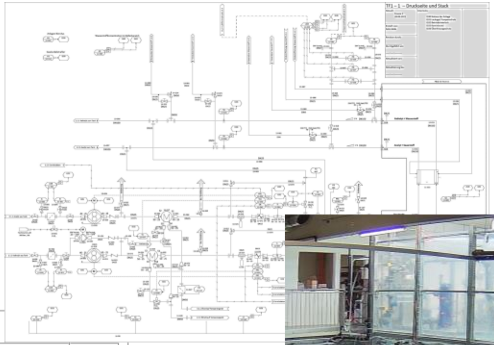


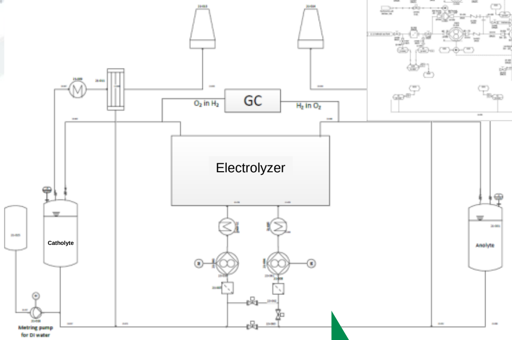

Exemplary calculation based on Smolinka et. al, 2018, IndWEDe study; CAPEX 575 €/kW excl. land, power connection, maintenance

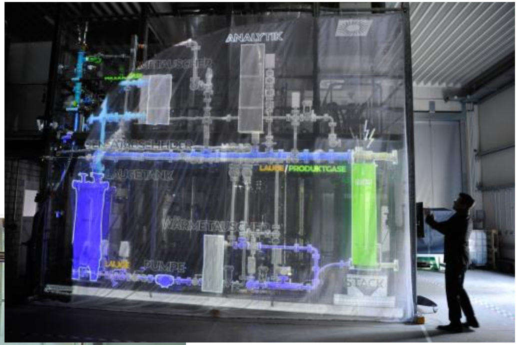
# Erection of the Pilot Plant

H2Giga


Bundesministerium
für Bildung
und Forschung






| Kickoff | Basic- & Detail-Engineering | Procurement | Construction | Commissioning |
|---|---|---|---|---|
| April 2021 | May 2021 | August 2021 | January 2022 | June 2022 |

# Erection of the Pilot Plant

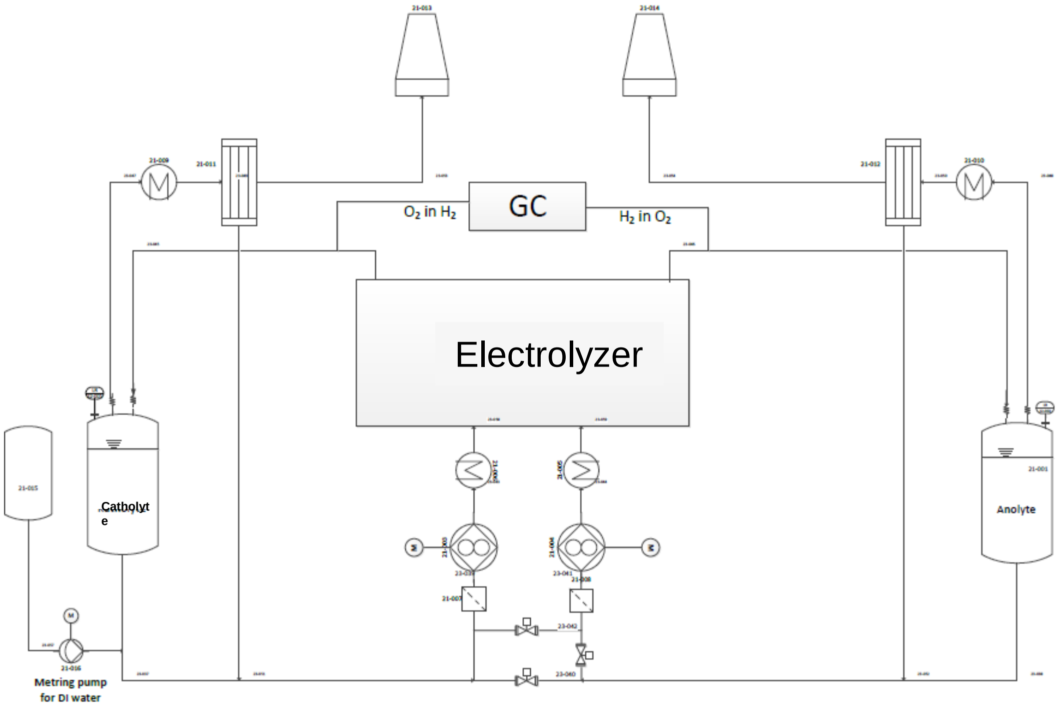
# Pilot Plant Details

## Specifications

- Atmospheric pressure (max. 500 mbar overpressure)
- Temperature: max. 90 °C
- Current max. 4000 A
- Up to 150 kW (3 kg $H_2$ / hour)
- Separated or mixed electrolyte cycles
- Shortstacks, full electrode area

## Operation

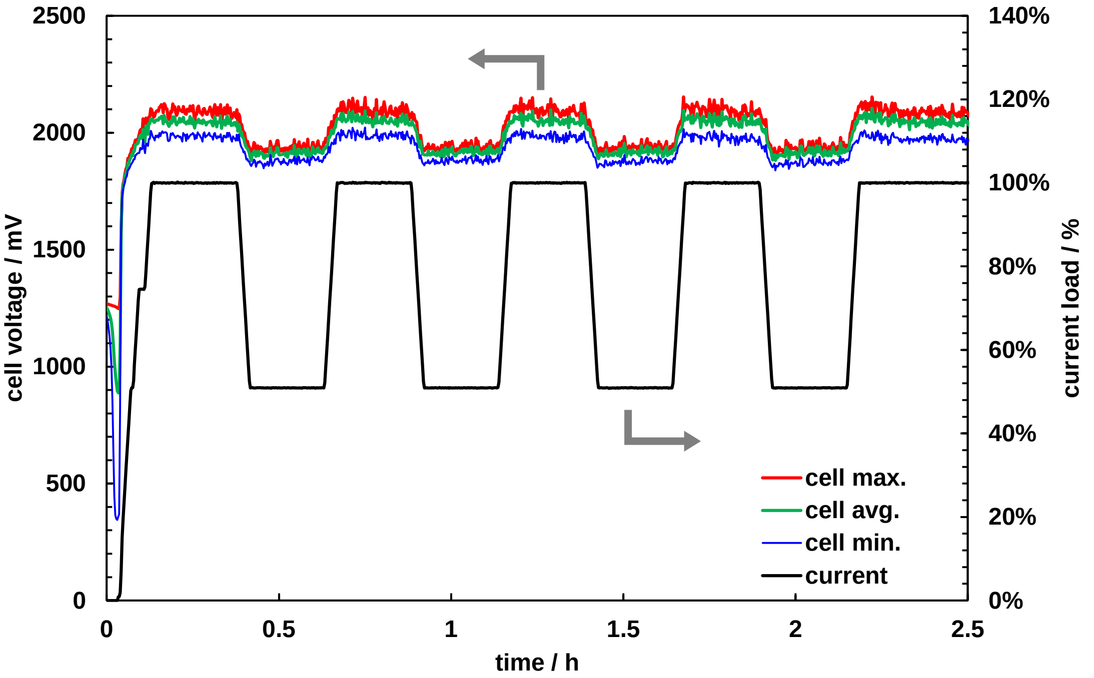
- Fully automated test protocols
- Main focus on operating strategies, dynamics, lifetime



# Dynamic Operation

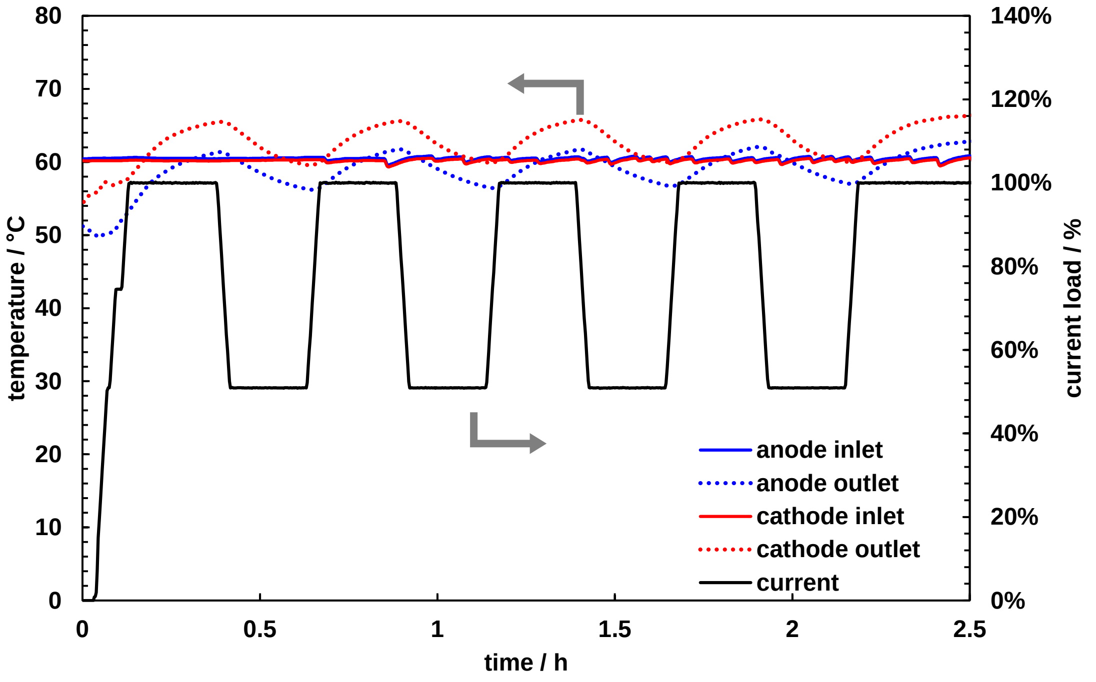
- Two cycles per hour
- Quick response of cell voltage on current
- Slight increase of voltage for low currents
- Slight decrease of voltage for high currents

→ Temperature effect

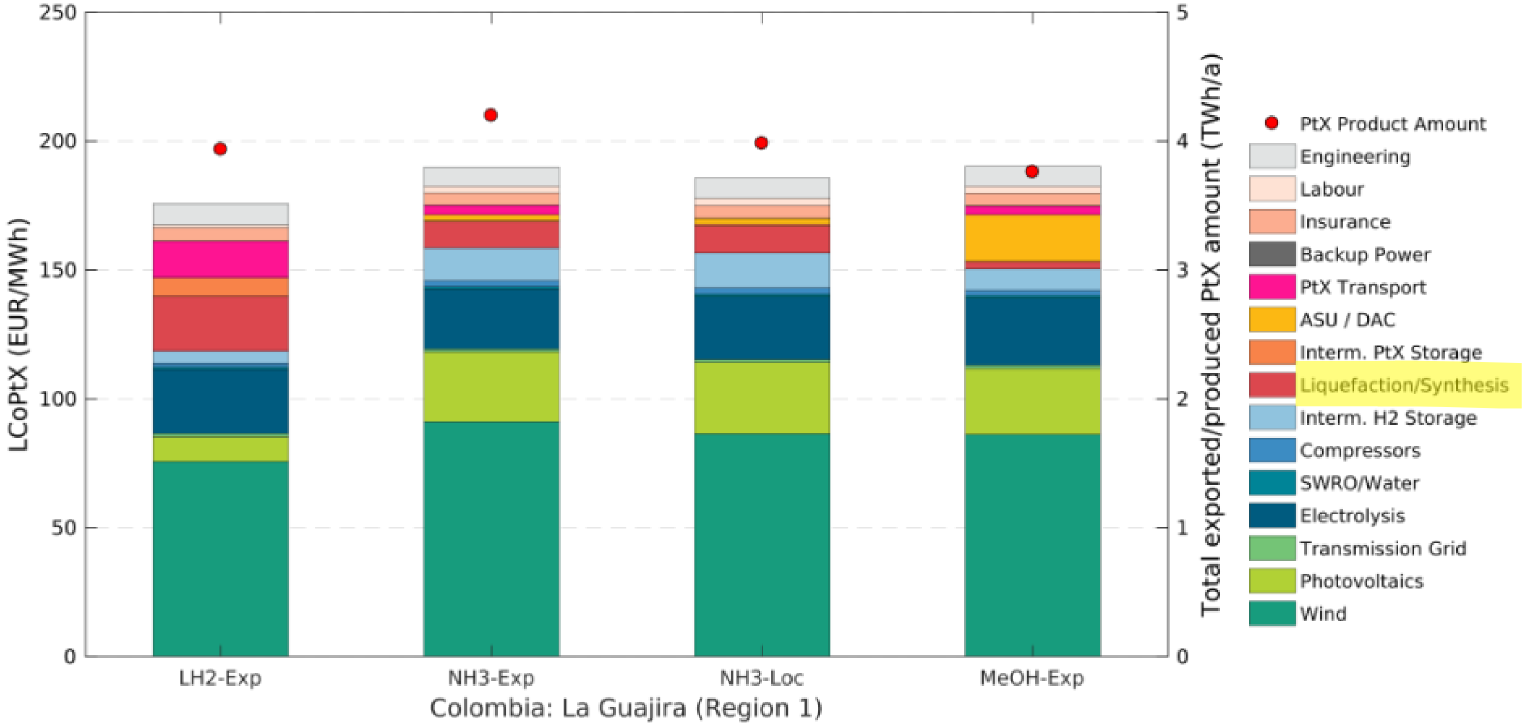


# Dynamic Operation – Temperature effects

- Inlet temperature controlled to 60°C by BoP
- Outlet temperature changes more slowly (heat capacity of stack and parts of the BoP)



# Power2X Import Pathways

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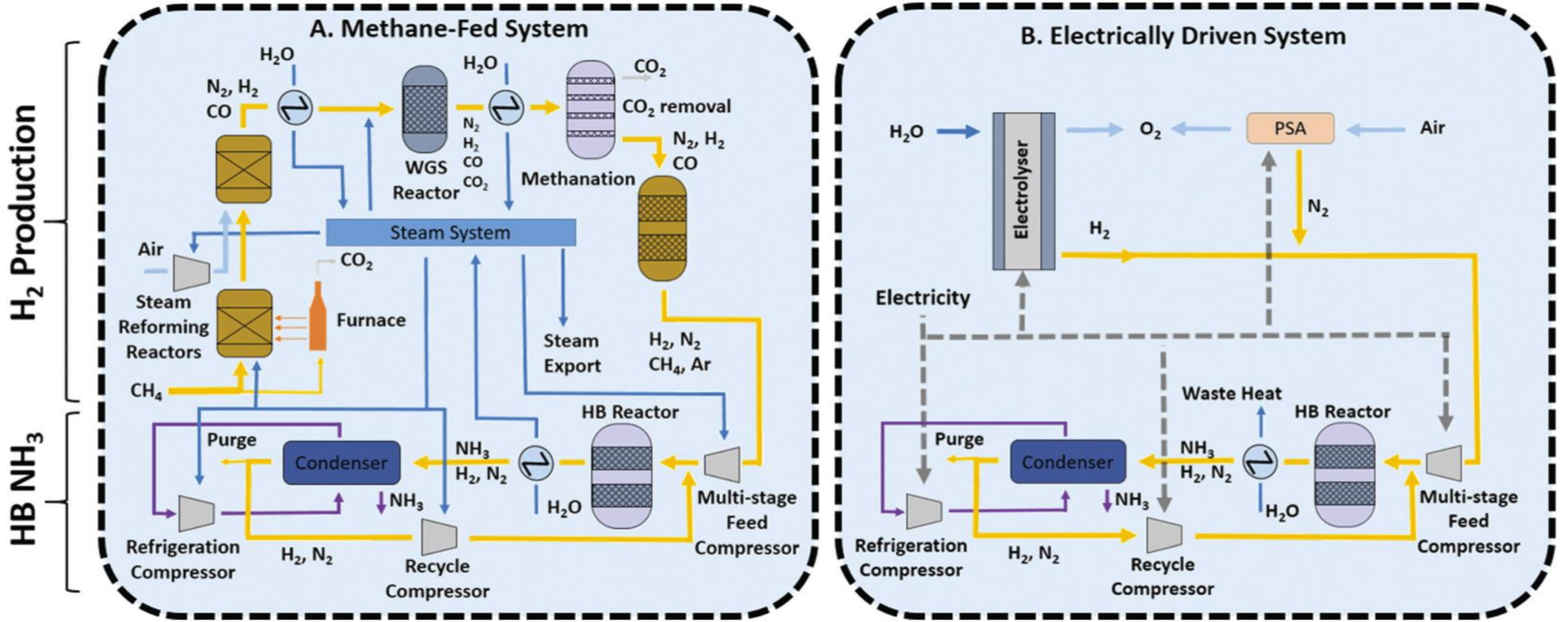
# $NH_3$ Synthesis – Process options

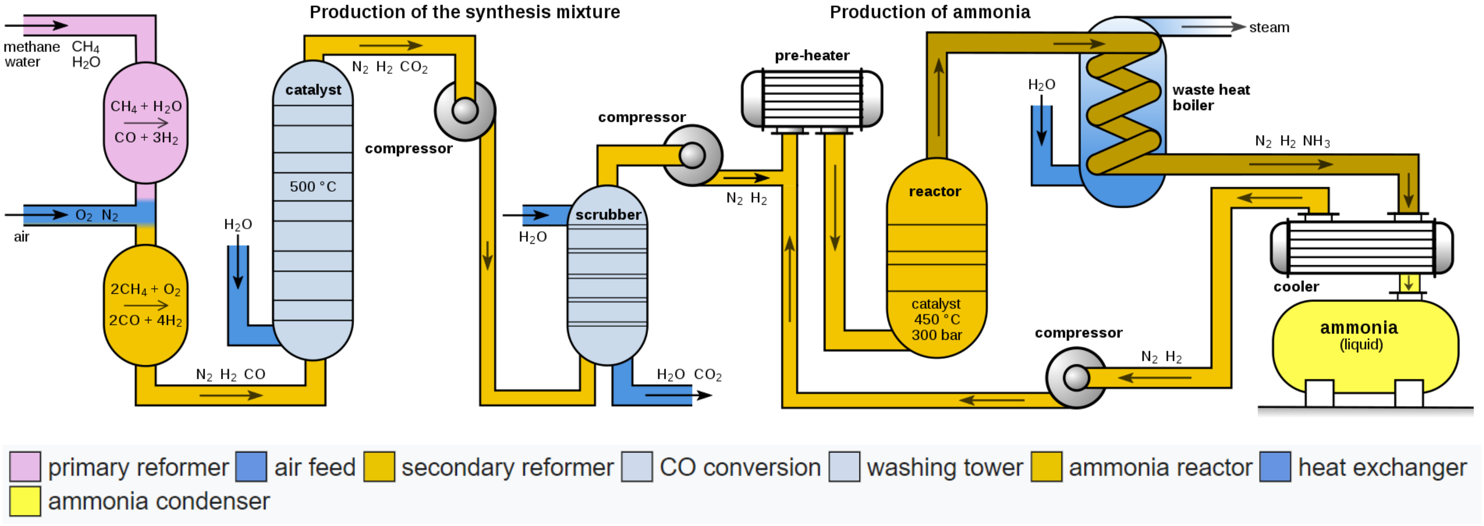



**conventional**

**next generation**
(zero carbon emission)

C. Smith, A. K. Hill und L. Torrente-Murciano, „Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape," *Energy Environ. Sci.*, Jg. 13, Nr. 2, S. 331–344, 2020, doi: 10.1039/C9EE02873K.

# Ammonia Synthesis (Haber Bosch Process)




https://en.wikipedia.org/wiki/Haber_process

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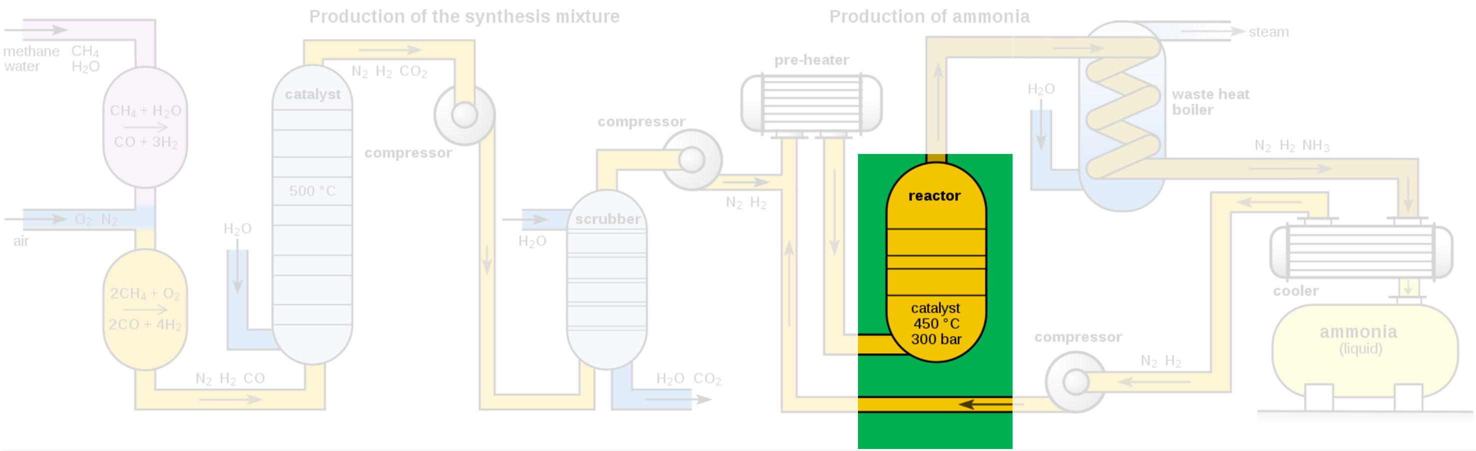
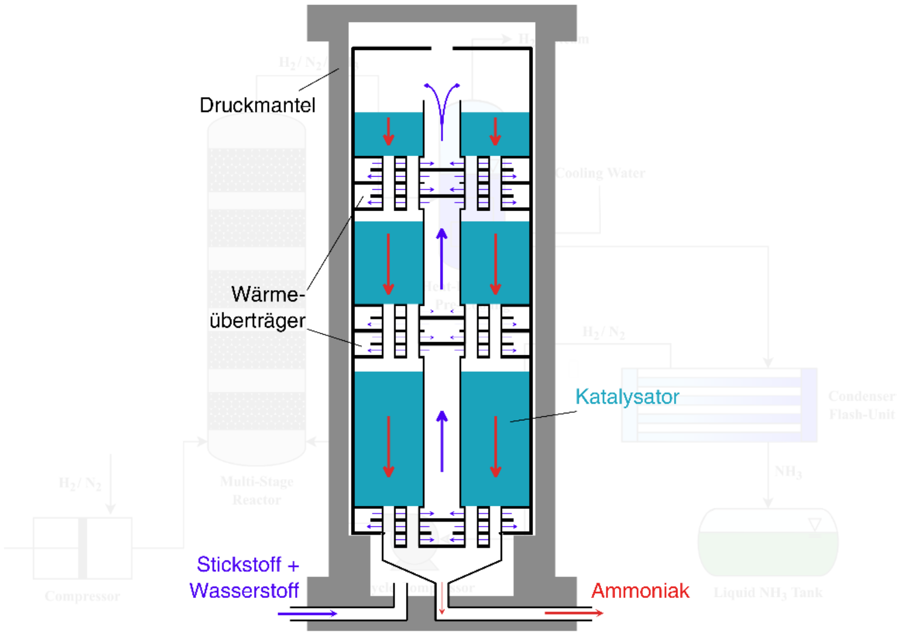



primary reformer, air feed, secondary reformer, CO conversion, washing tower, ammonia reactor, heat exchanger, ammonia condenser

$$N_2 + 3\,H_2 \longrightarrow 2\,NH_3 \quad \Delta H^\circ = -46.1\ \mathrm{kJ/mol}_{NH_3}$$

https://en.wikipedia.org/wiki/Haber_process

# Ammonia Synthesis (Haber Bosch Process)

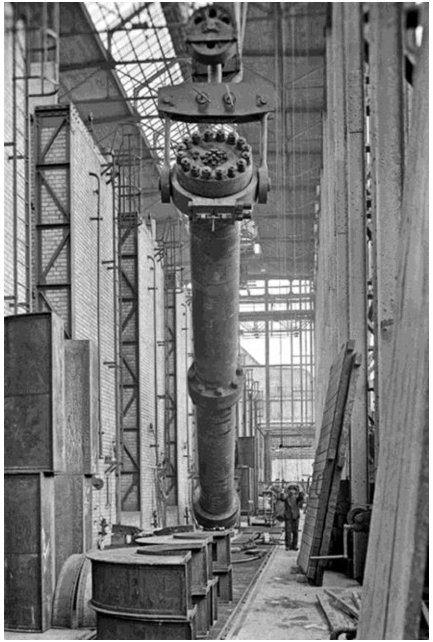



- State-of-the-art: Highly optimized fossil fuel based steady state process.

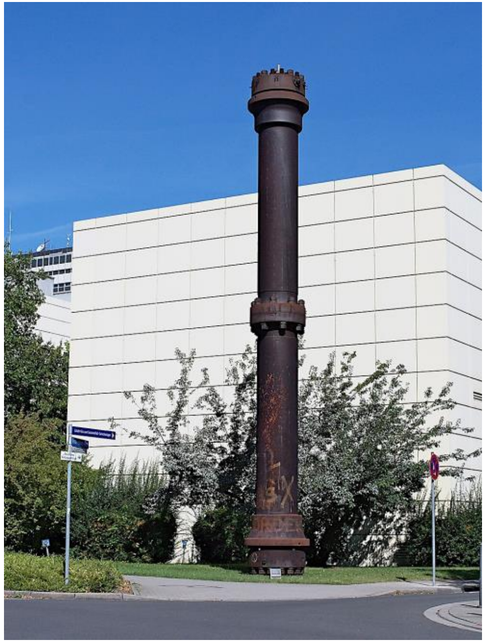
- New challenges for "green" synthesis:
  - Intermittent reactor and process operation
  - Fast start-up and shut-down required
  - Catalyst degradation during dynamic operation
  - Reactor runaway

# Reactors from the past

A historical high-pressure steel reactor for the production of ammonia via the Haber process



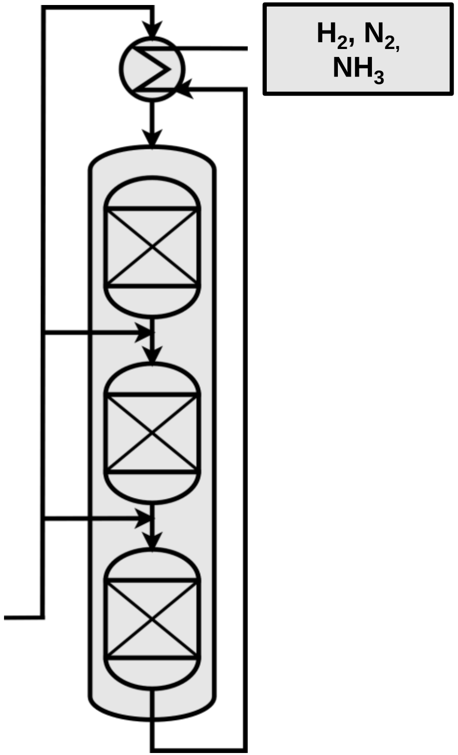
**1913**, First reactor at the Oppau plant



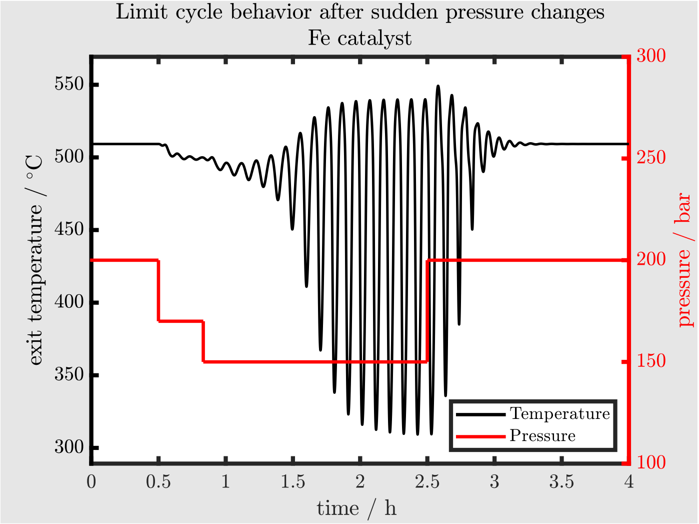
**Today** displayed at the Karlsruhe Institute of Technology, Germany

# Influence of changing $H_2$ flow

(Axial flow, quench gas reactor)




**Germany 1989:** A sudden **pressure drop** caused by a temporary **reduction of feed flow** resulted in **unstable behavior** of an industrial scale multistage axial flow, quench gas $NH_3$ reactor.



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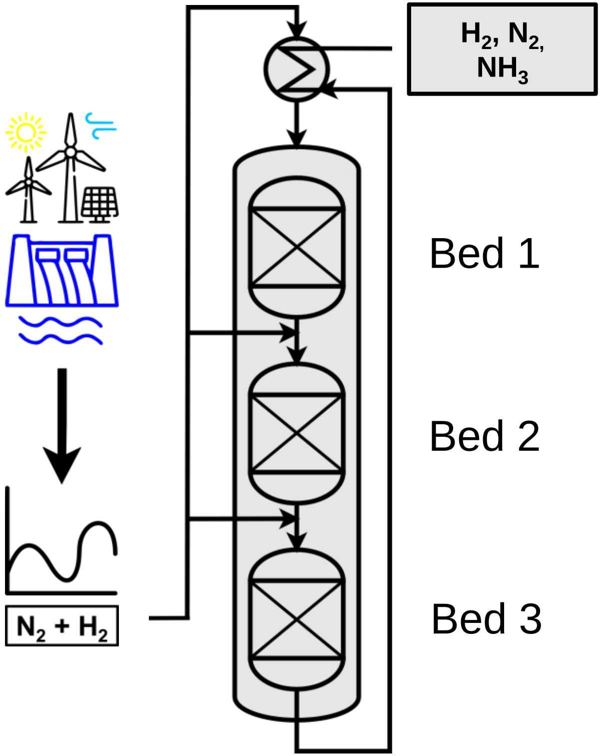


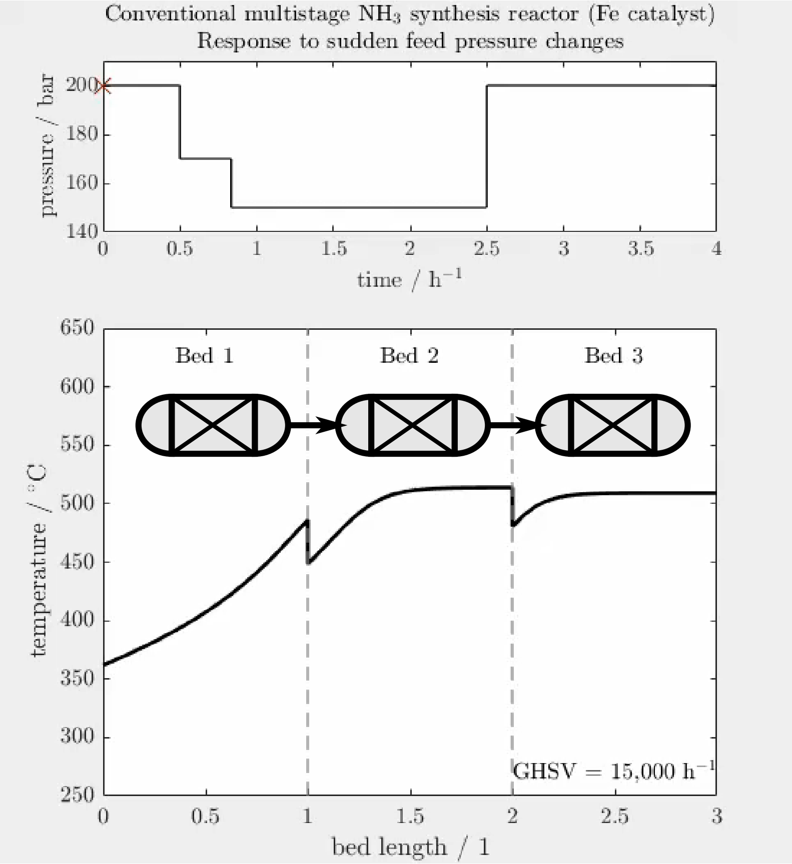

# Summary

- There is still a long way to go for reaching our climate goals
  - We need to start now!

- There is no way around Power2X technologies and green energy carriers
  - A huge market is opening right now!

- Costs for Power2X technologies and green energy carriers must go down

- There many possibilities for innovation and Development

**Many thanks for your attention!**