STUDY P2X
BY FRAUNHOFER IMWS AND FRAUNHOFER IGB BIOCAT

Team IMWS

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February 11, 2019

Agenda

- Introduction Fraunhofer IMWS and IGB/CBP
- Study P2X : Green Hydrogen
- Study P2X : Green Ammonia

The Fraunhofer Gesellschaft at a glance

- Leading organization for applied research in Europe
- International collaborations with excellent research partners and innovative companies around the world

25 527 Staff

2,3 Billion Euro
Budget

72 Institutes and Research Facilities

Fraunhofer IMWS at a glance

- Director:
  - Prof. Ralf B. Wehrspohn

- Locations:
  - Halle (Saale)
  - Schkopau
  - Freiberg
  - Soest
  - Leuna (2019)

- Key Figures:
  - 284 Staff
  - 20,4 Mio. € Budget
  - 25,4 % direct industrial revenue
  - Quality Management ISO 9001-2017

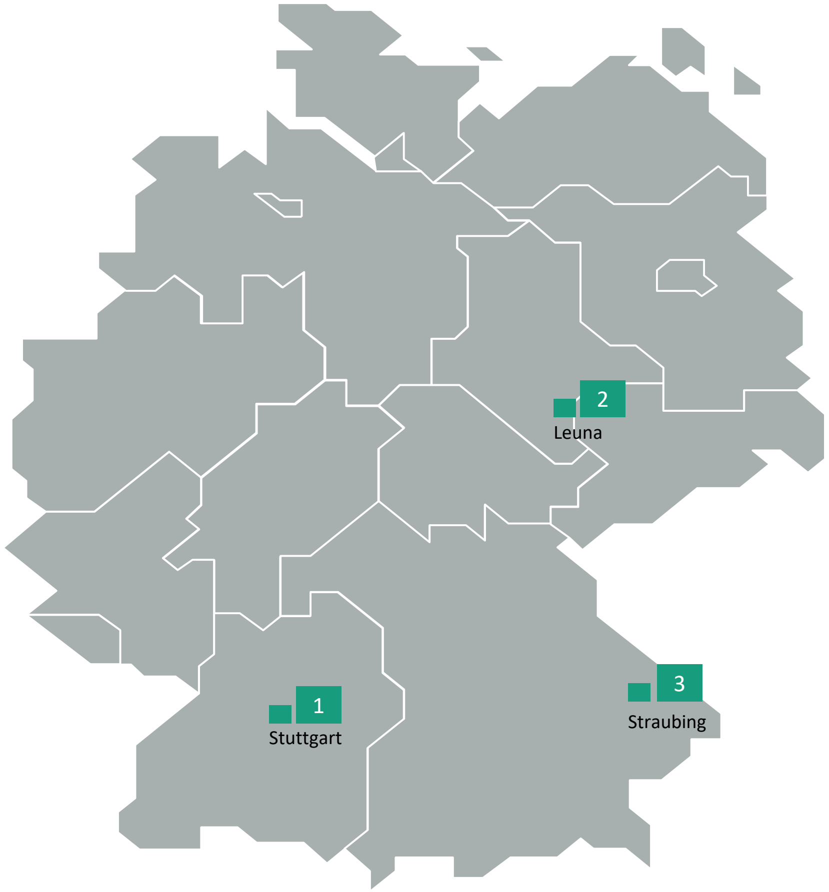
Fraunhofer IMWS Halle

Fraunhofer IMWS Schkopau

Fraunhofer IMWS Soest

Fraunhofer IGB

Director: Dr. Markus Wolperdinger



Fraunhofer IGB Stuttgart (HQ) TRL 1-5

Thermal storage
Power-to-X
Process engineering
Wastewater treatment

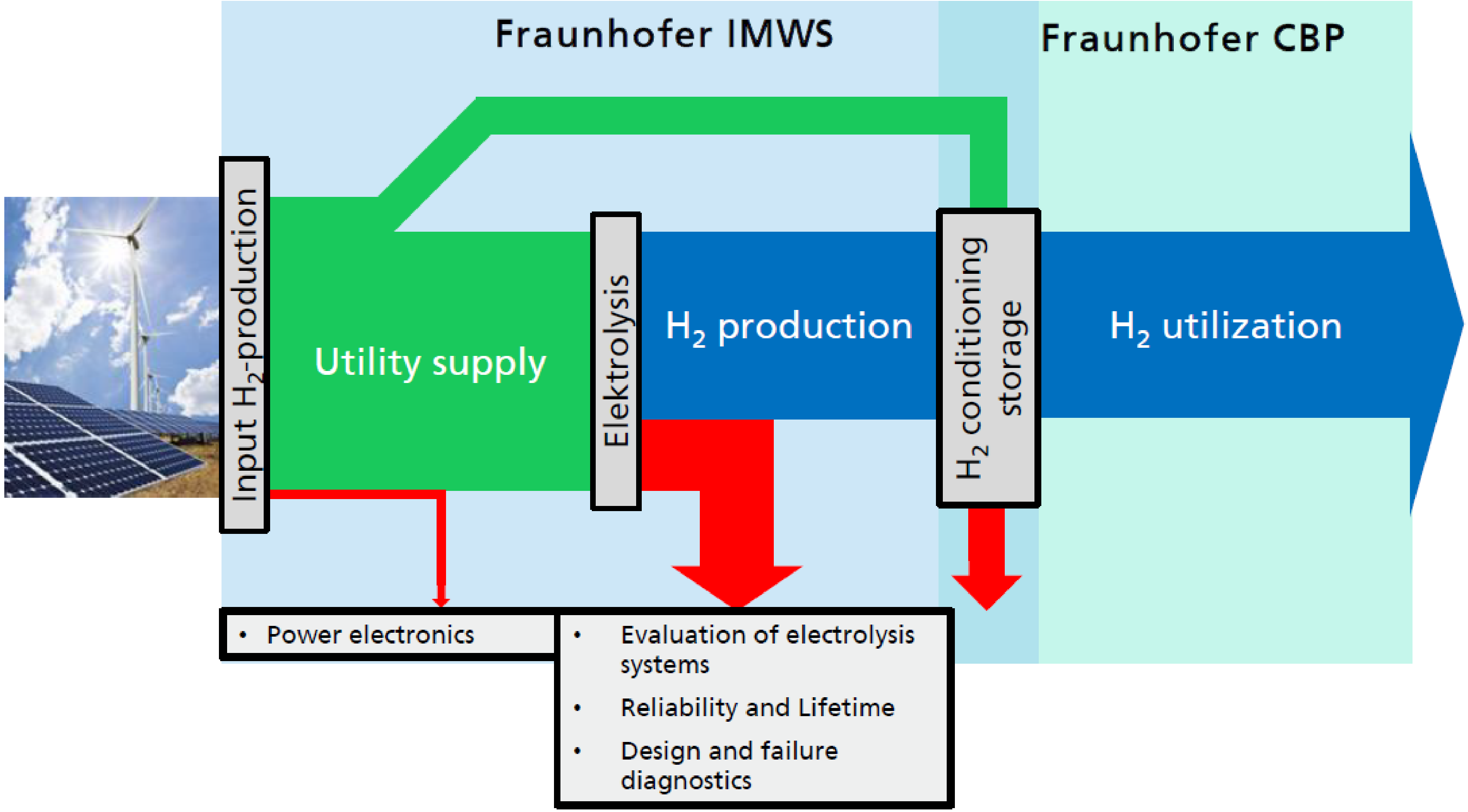
Fraunhofer CBP Leuna TRL 4-6

Chem&Bio processes
Power-to-X
Upscaling of synthesis processes
Biobased products

Fraunhofer IGB BioCat Straubing TRL 1-4

Power-to-X
Chem&Bio processes
Recovery of elements
Biobased products

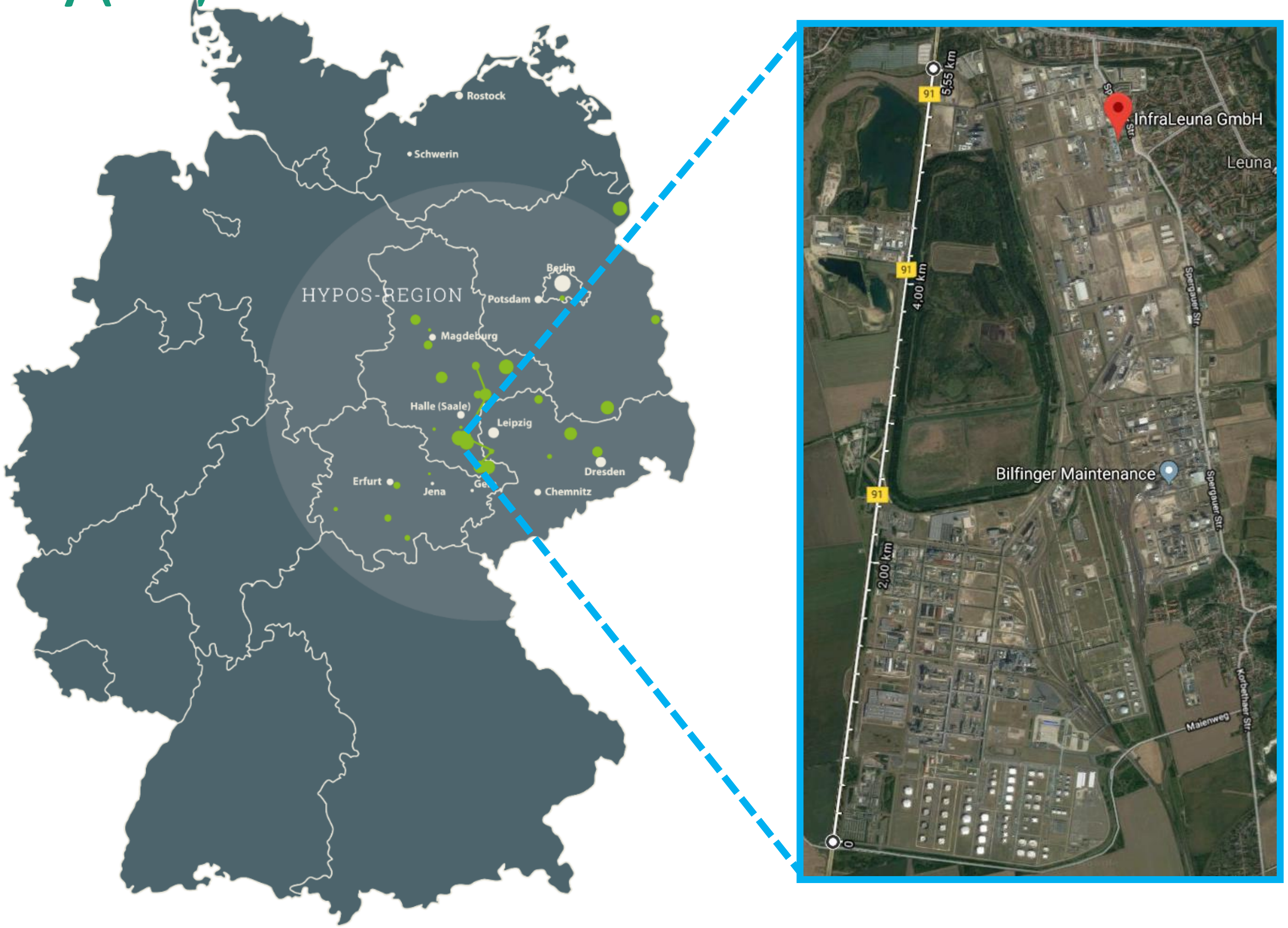
Fraunhofer IMWS –CBP – workshare



Fraunhofer IMWS Projects

Electrolysis research and test facility (ELP) Leuna

- Leuna Chemical Park operated by InfraLeuna
- Facts and figures:
    - 1,300 hectares
    - More than 10,000 employees
    - 600 km of pipeline network
    - 90 km of rail network



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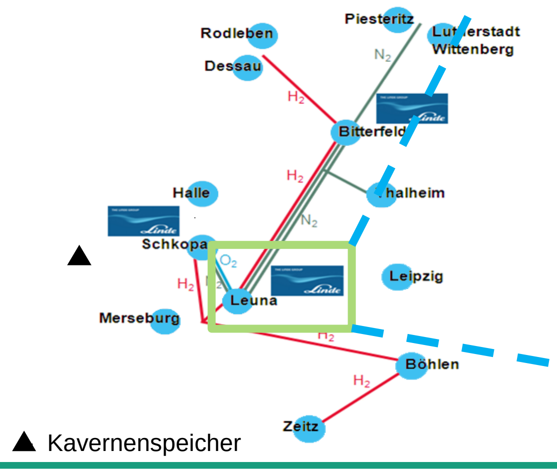
Electrolysis research and test facility (ELP) Leuna

Project outline

- Planned by the two Fraunhofer Insitutes IMWS & CBP and co-financed by the State of Saxony-Anhalt
- Research infrastructure with labratories, office space and technical center
- Outside test area for containerized electrolysis systems, each space with a max. capacity of 5 MW
- Integrated into the Chemical side and connected to a 150 km long hydrogen pipeline and Remote Operation Center both operated by LINDE AG
- Opened for all electrolysis technologies (alkaline, PEM and high temperature SOEC)
- Fully operational in 2020

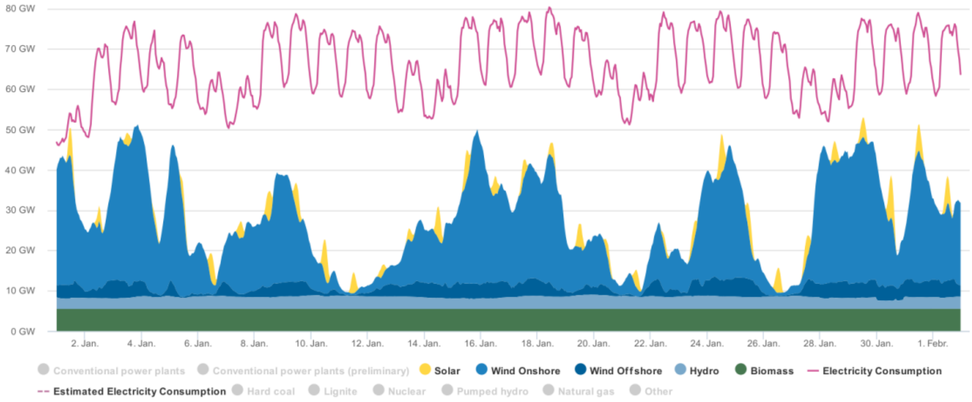


EUROPEAN UNION
European Regional Development Fund
Fraunhofer IMWS

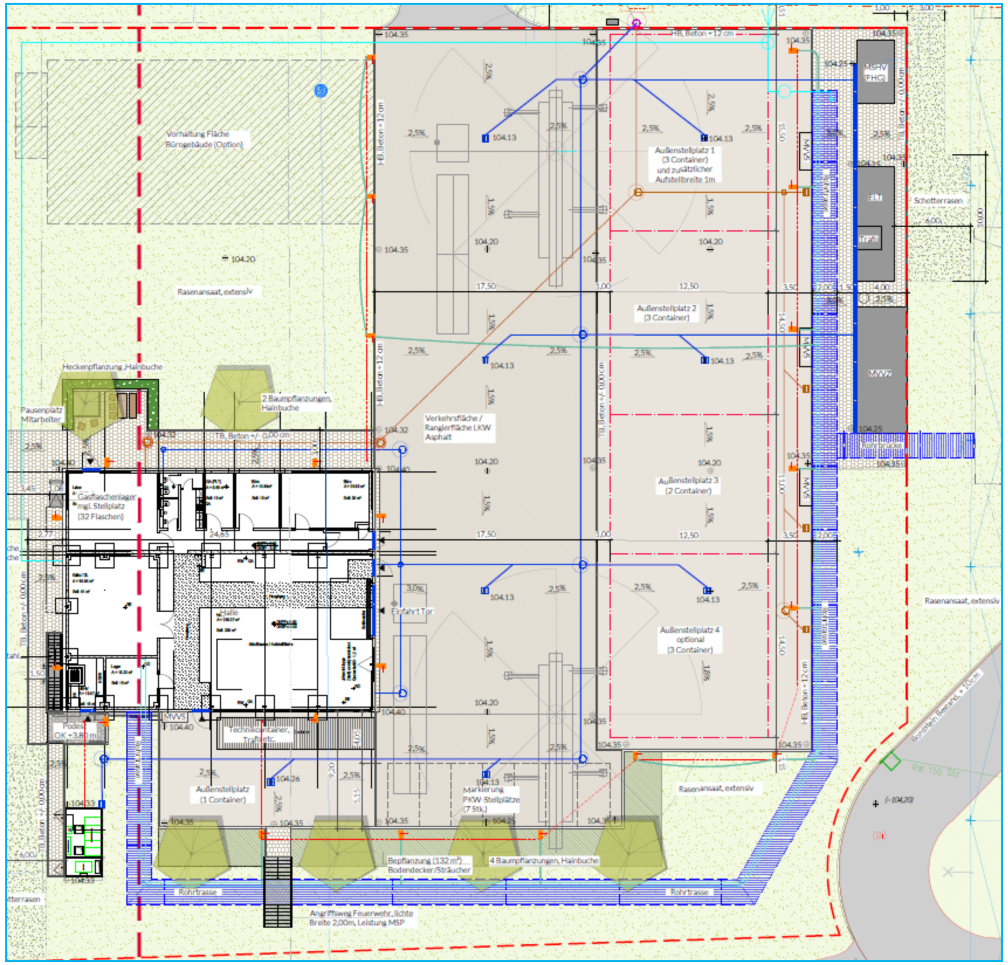
Electrolysis research and test facility (ELP) Leuna

Scope

- Testing and evaluation of electrolysis systems up to 5 MW
- Demonstration of downstream processes for the use of H_2 (e.g. methanol synthesis)
- Creating energy and material balances in correlation with load profile
- Price of H_2 based on load profile
- Determine future research focus based on gathered data



Agora Energiewende; Current to: 12.02.2018, 16:45



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AGENDA STUDY P2X : GREEN HYDROGEN

1) Market development: PtX / Green Hydrogen
2) Technology comparison
3) Efficiency
4) Economy: CAPEX / OPEX analysis
5) combination with renewable energy (RE)
6) Requirement for Pilot Installation

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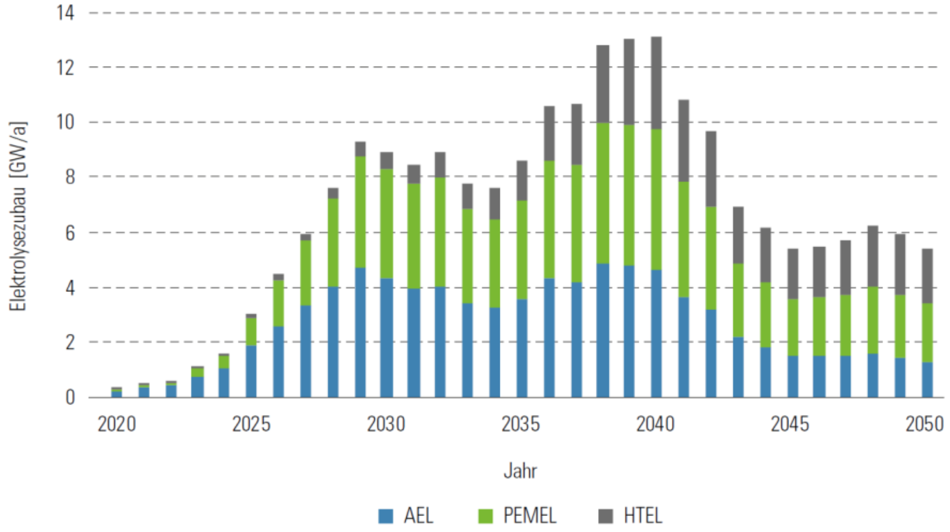
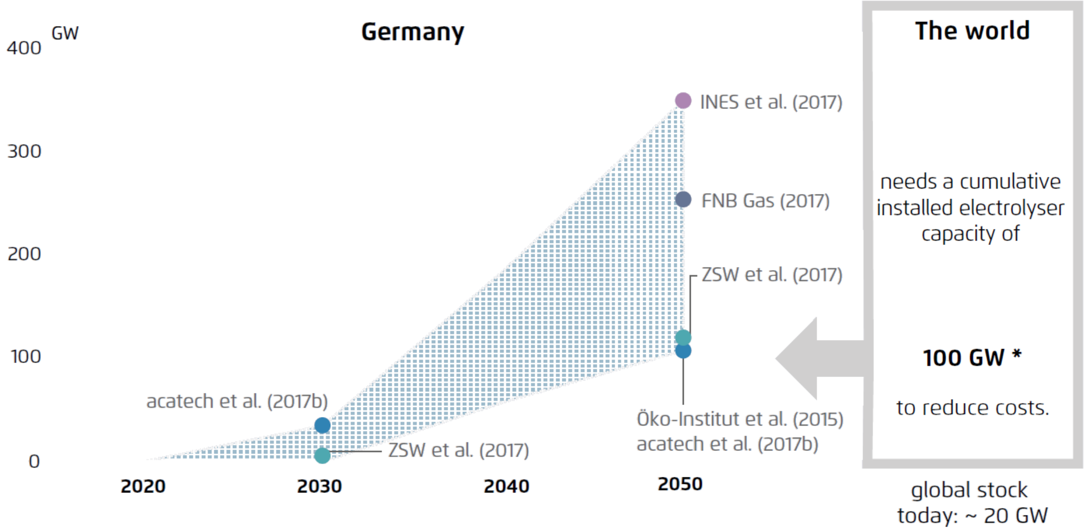
Market





- 170 – 400 GW installed in 2050
- after 2030: 8 - 13 GW p.a. capacity increase

- 2050: capacity of 3000 - 6000 GW (including syn. fuels)
- Germany alone 100 - 350 GW

- PtX: multi GW technology in 2020-2030; significant variation of expected capacity
- Strongly dependent on applications (and regulatory framework in Germany)
- Hydrogen technologies in general and electrolysis are market ready
  - can be implemented into industrial applications

sources: [1], [2]

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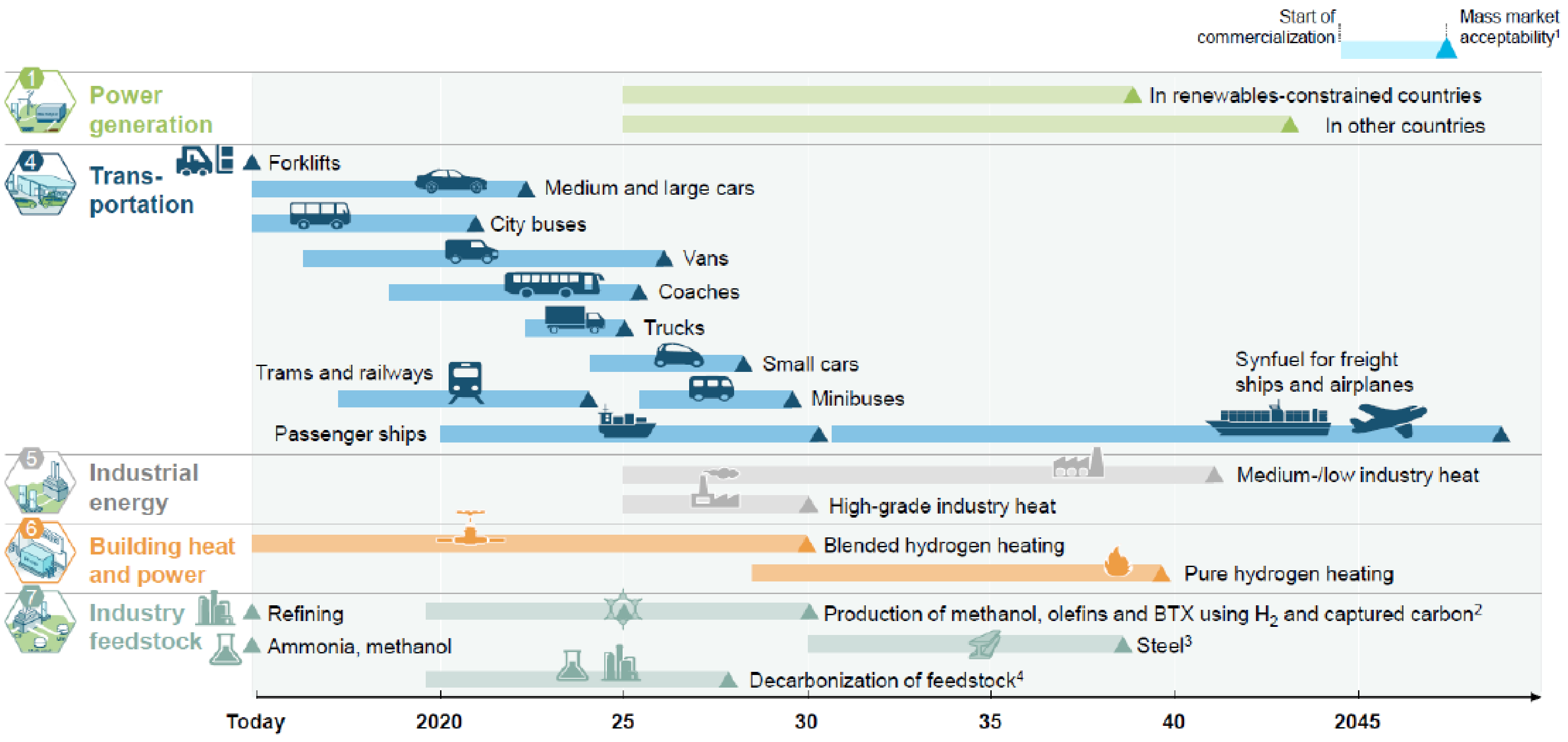
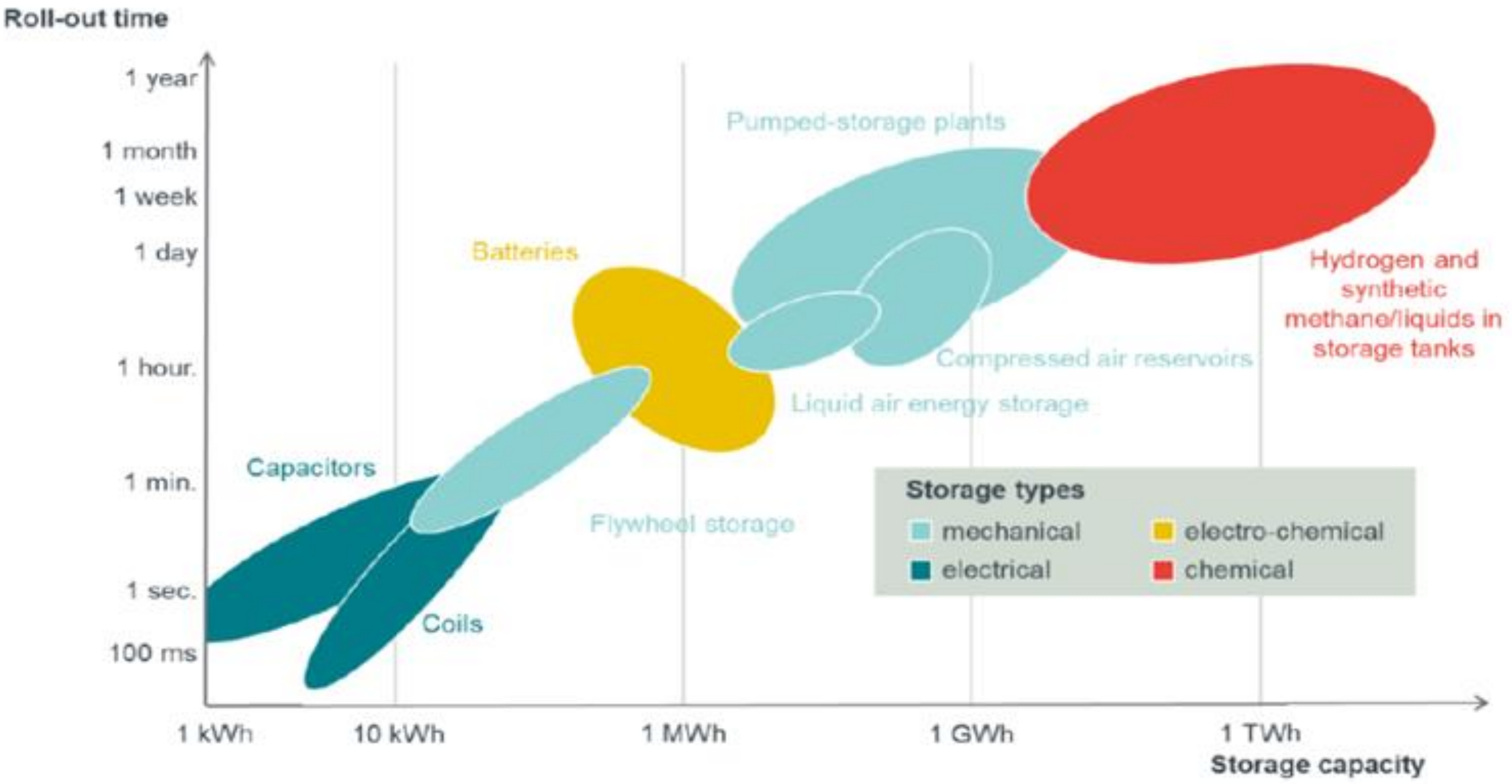
Applications



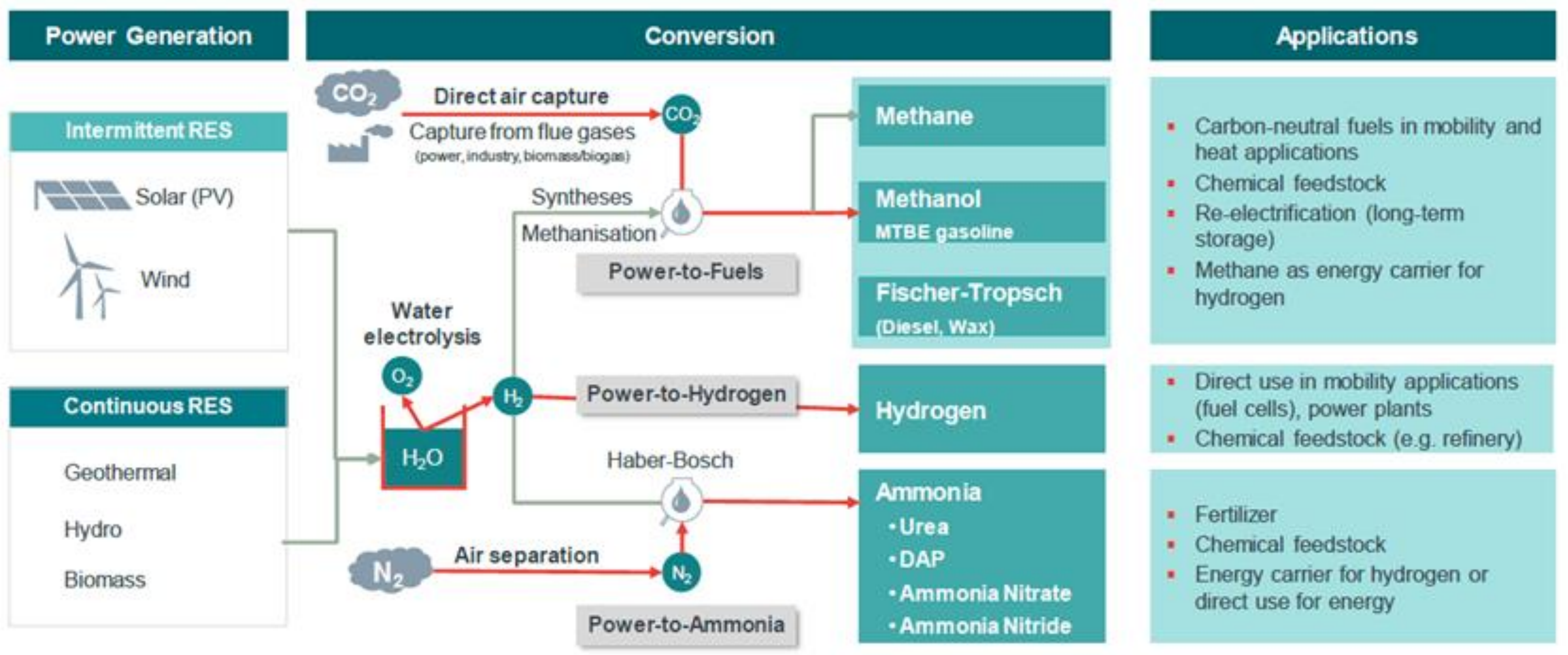
- Applications in industry (Refining, Ammonia, …) at initial phase
- Long term energy storage (>1 year): No technologies except hydrogen available

sources: [3]

Technologies to store energy



Power-to-X:
Conversion of renewable power into various forms of chemical energy carriers



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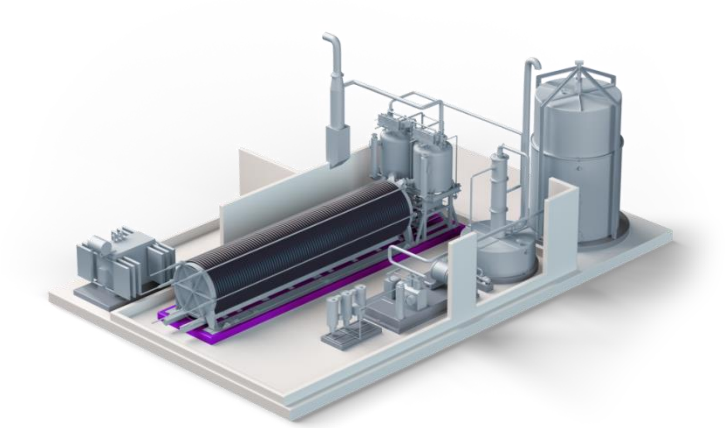
Electrolysis

Alkaline water electrolysers atmospheric

- Liquid electrolyte KOH
- Atmospheric pressure
- Proven technology in industrial scale

156 MW_{el} Hydrogen production for fertiliser plant completed in 1963 at the Assuan Dam in Egypt (source: ht-hydrotechnik)



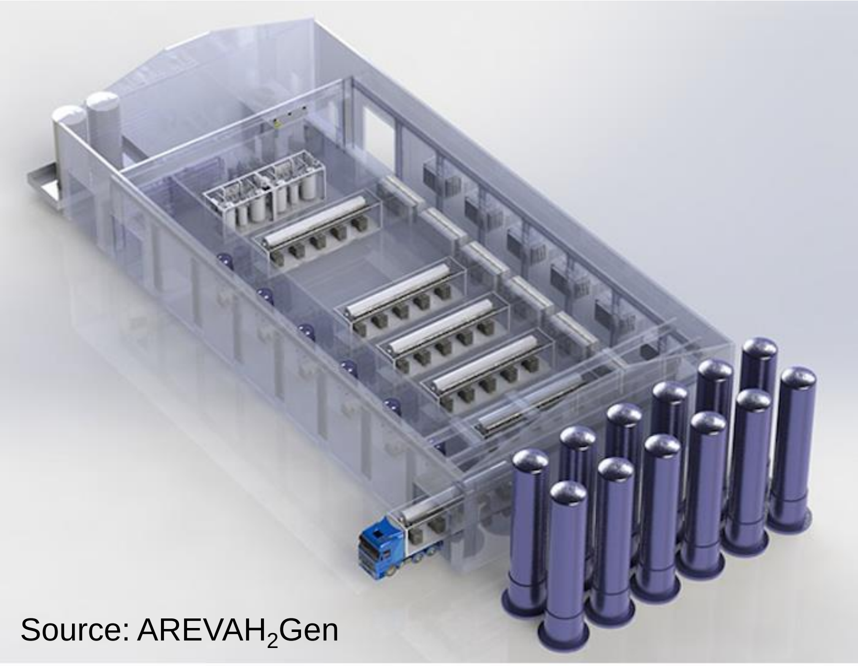
NEL Hydrogen 485 Nm^3/h

Plans for 400 MW

ThyssenKrupp from chlor-alkaline electrolysis to water electrolysis

Electrolysis

Proton Exchange Membrane electrolyser



Source: AREVAH_2Gen

- Membrane as electrolyte
- High current desity
- Flexible from 0 – 200 %
- High pressure and atmospheric

Source: Siemens

Silyzer 300

Source: Giner Inc.

Allagash

2 MW 400 Nm^3/h

Source: Hydrogenics

HyLIZER 600

3 MW 620 Nm^3/h

Source: Proton OnSite

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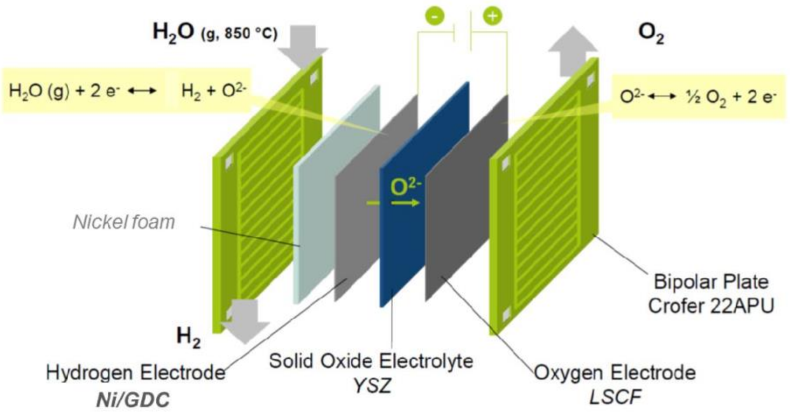
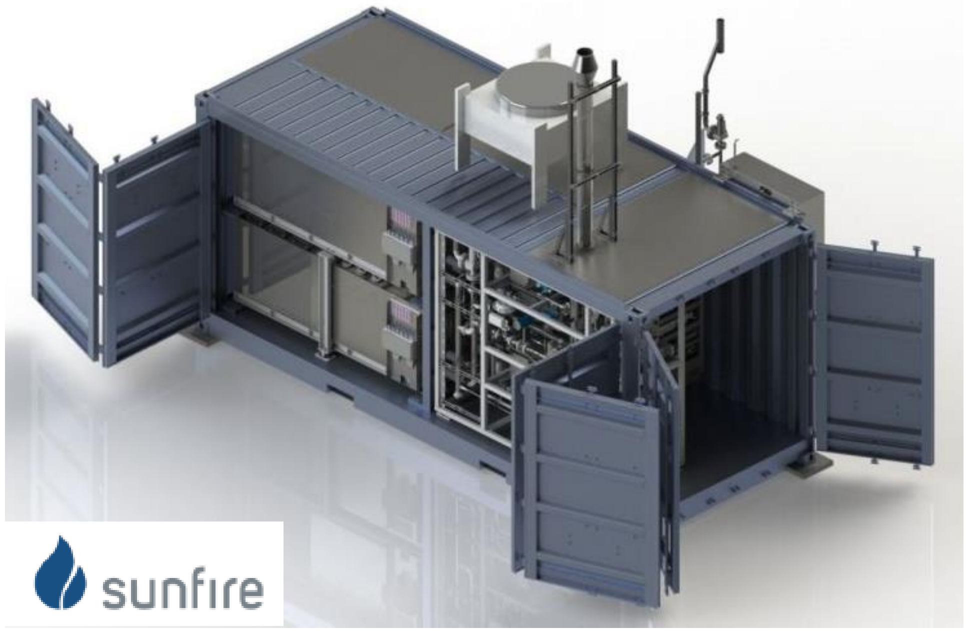
Electrolysis
Solide Oxide electrolysis (SOEC)

- Solid Oxide as electrolyte
- High temperature process 750 – 1000 °C
- Steam as input media
- Reversible system possible





Source: Sunfire GmbH

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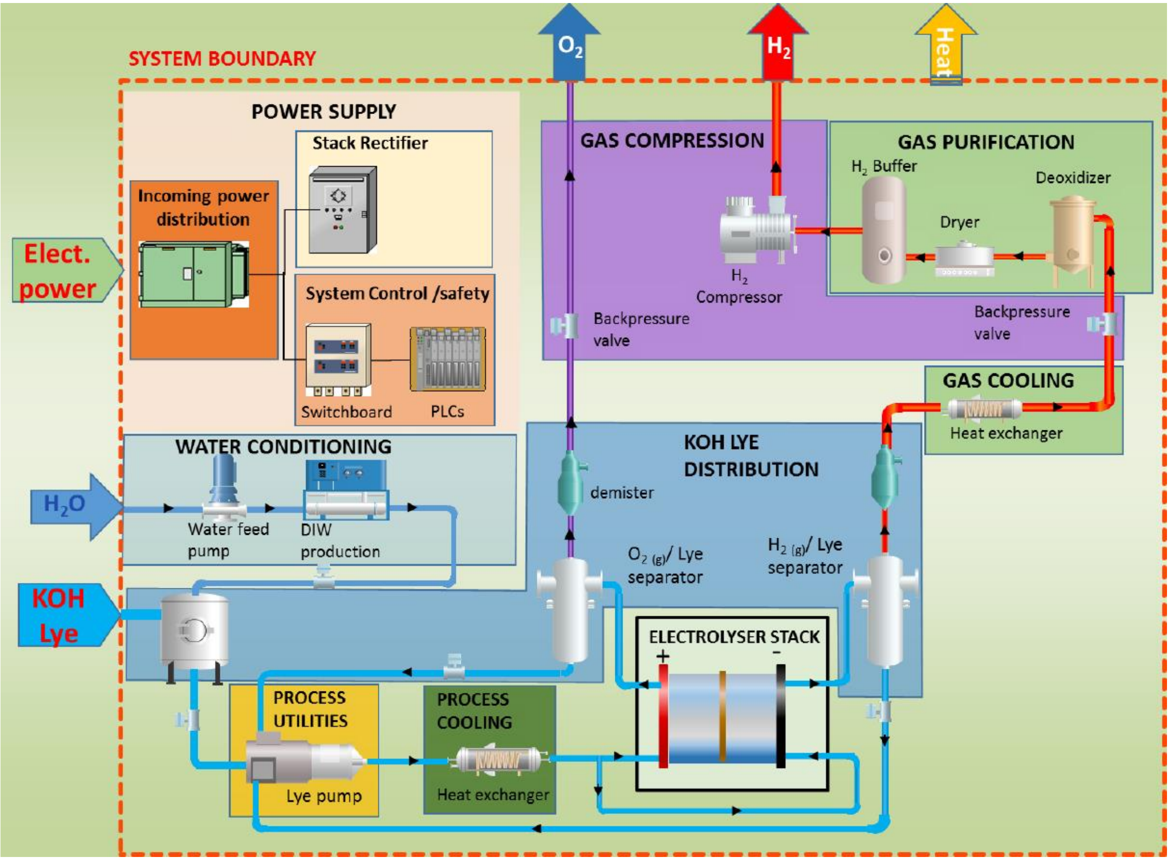
Technology

- electrolysis plant requires moderate complex system
- gaining experience of component interaction and system behavior essential for good plant management
  - especially for supply with RE
- significant part of total cost stems from system components besides electrolyzer stack

Example of alkaline electrolysis system



sources: [4]

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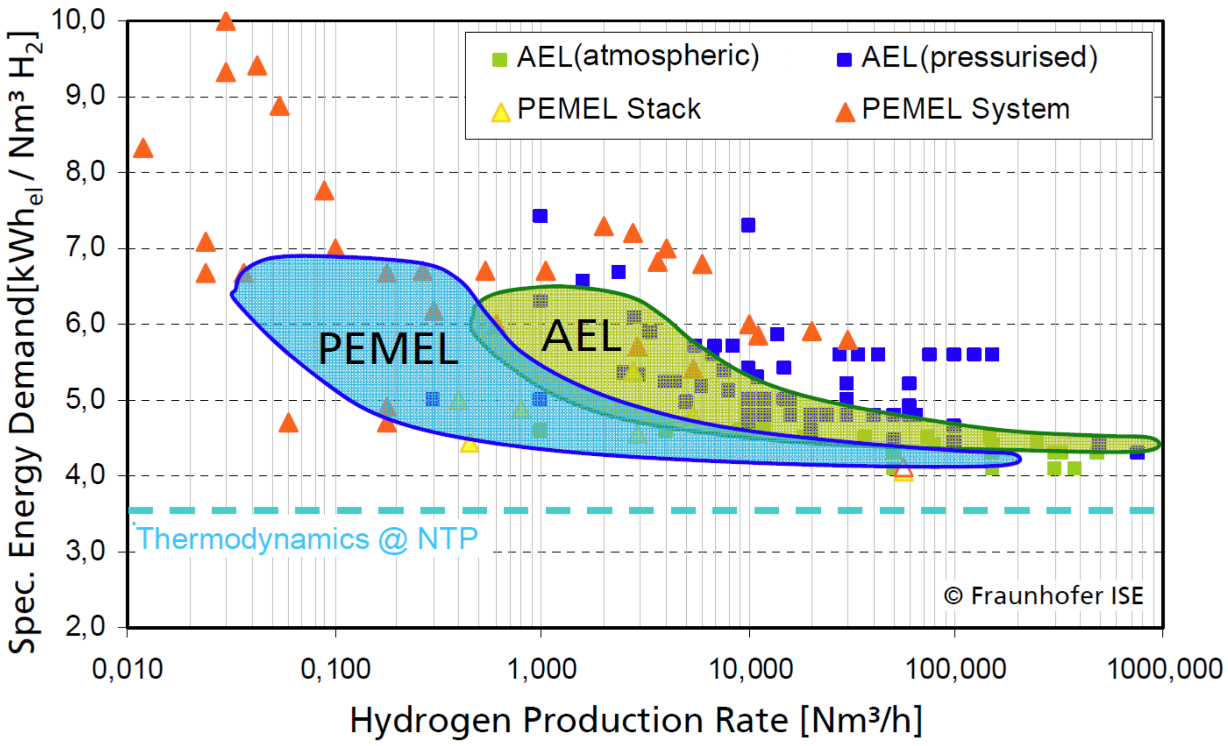
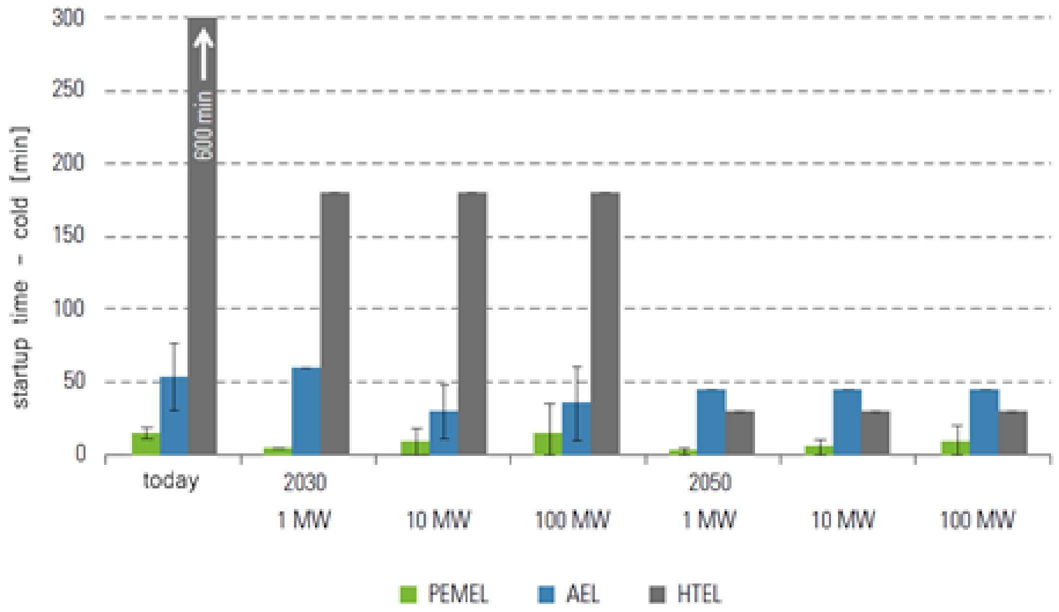
Efficiency

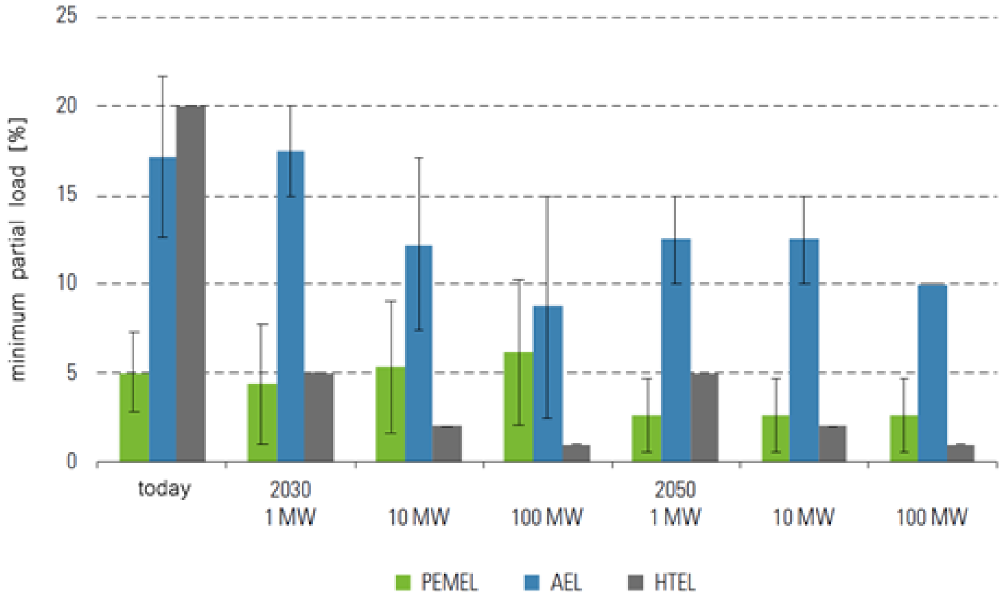
- Both technologies AEL and PEM at approx. same level of efficiency
- No significant future improvement of efficiency expected
  - technologies in pilot test, are also suitable for future production



sources: [5]

Parameters relevant for combination with fluctuating energy

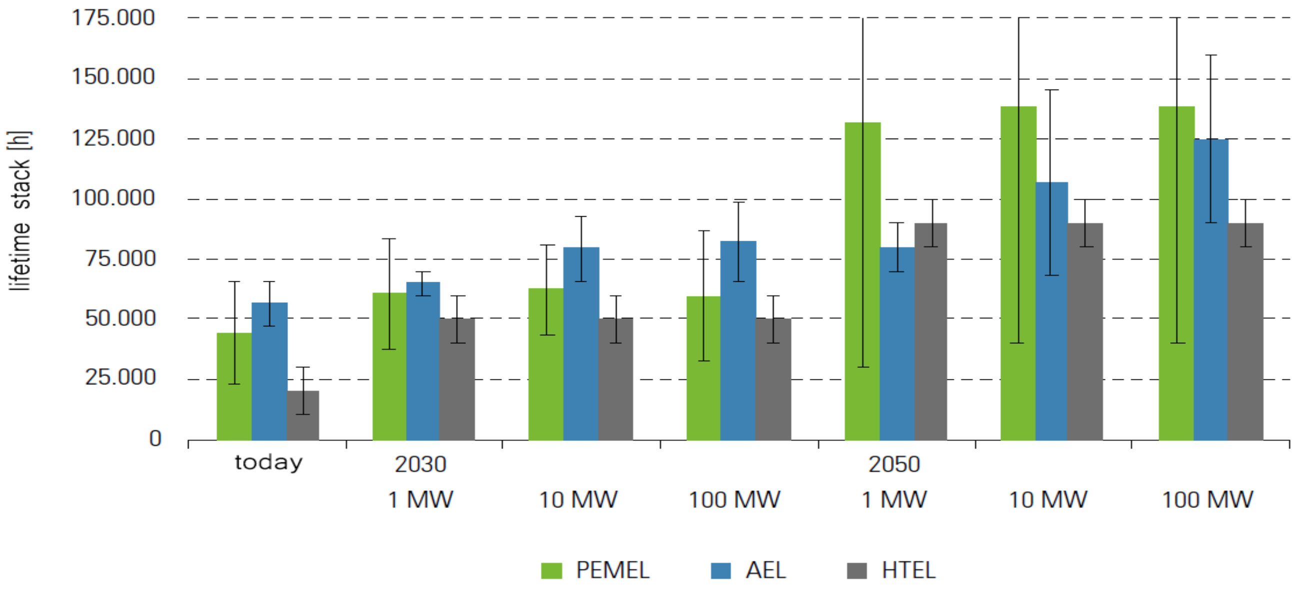




- time to start AEL and PEM from cold stack
- PEM < AEL < HTEL
- significant reduction for HTEL in future
- PEM is only technology with short start-up time

- capability of stack to run based on partial load
- today PEM lowest minimum partial load
- AEL & HTEL will lower current minimum values in the future

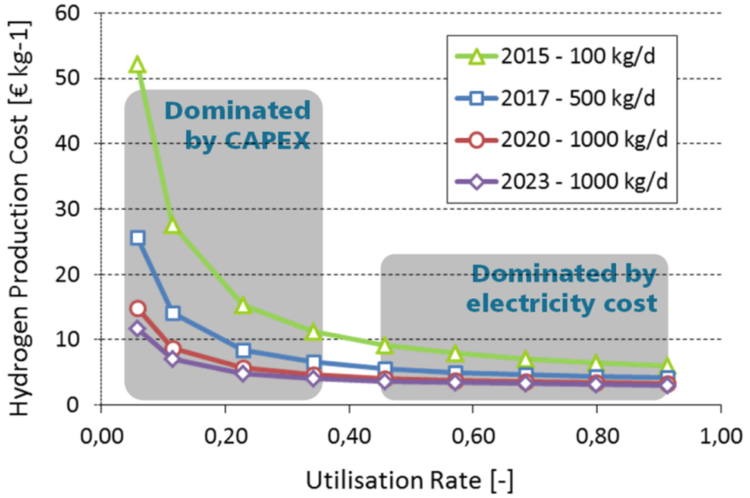
Reliability based of electrolysis system

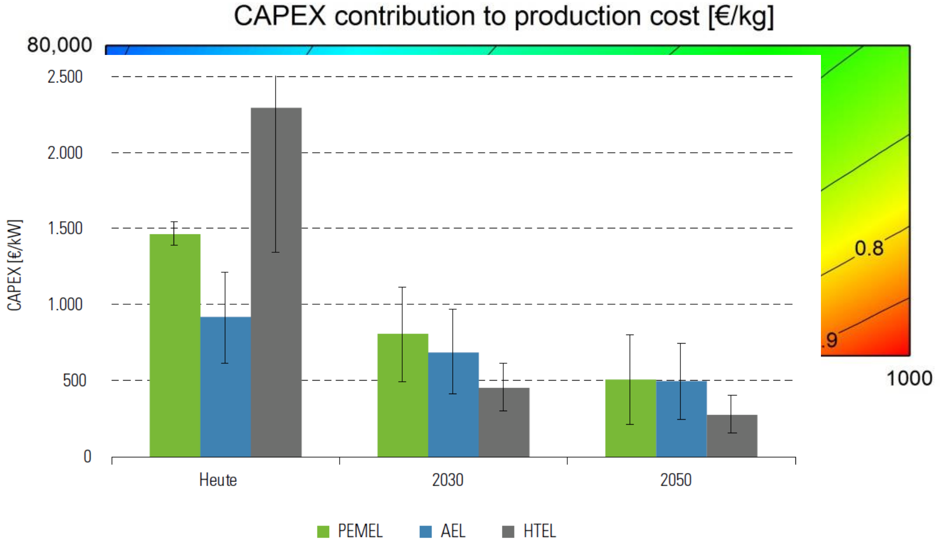


- currently AEL has highest lifetime
- 2030:
  - increase in lifetime for all technologies
  - nearly equal lifetimes for small scale systems in all technologies
- 2050:
  - AEL further increases lifetime for large scale systems
  - PEM may become technology with highest reliability on all scales (high uncertainty)

Cost aspects - CAPEX

- CAPEX especially relevant for low utilization
- CAPEX today 900 - 1400 €/kW, expected minimum values of 500 €/kW (2020+, larger system)
- example calculation:
  - Energy for hydrogen production: 4.5 kWh/Nm³
  - Investment cost for a EL-system: 500 €/kW
  - lifetime of EL-system: 60,000 h
  - ➢ CAPEX contribution to production cost ➔ 0.42 €/kg
- CAPEX will decrease with further capacity build up / economy of scale





sources: [1], [6]

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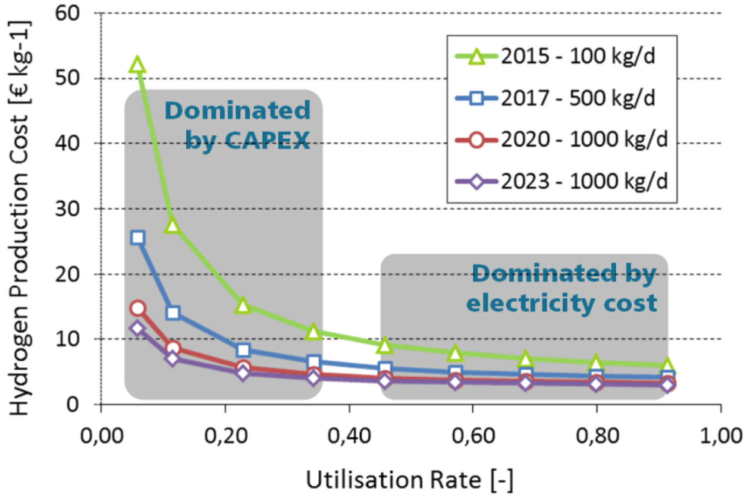
Cost aspects - OPEX



- Main parameter: electricity cost
- Recent auction prices for RE:
  - Morocco: 4.8 ct/kWh (PV), 3 ct/kWh (wind)
  - Saudi-Arabia, Mexico: 1.8 ct/kWh
- calculation for hydrogen price (assuming 4.5 kWh/m³ for energy need):

Power source	Electricity price [ct/kWh] [7]	Calculated OPEX [€/kg] Electricity
wind and PV in North Africa in 2020	5	2.5
PV in North Africa 2020	3.5	1.7
PV in North Africa 2050	2	1.0

➔ high load factor for the EL system is essential (PV alone will not suffice)

➔ complete system setup has to be considered

sources: [6], [7]

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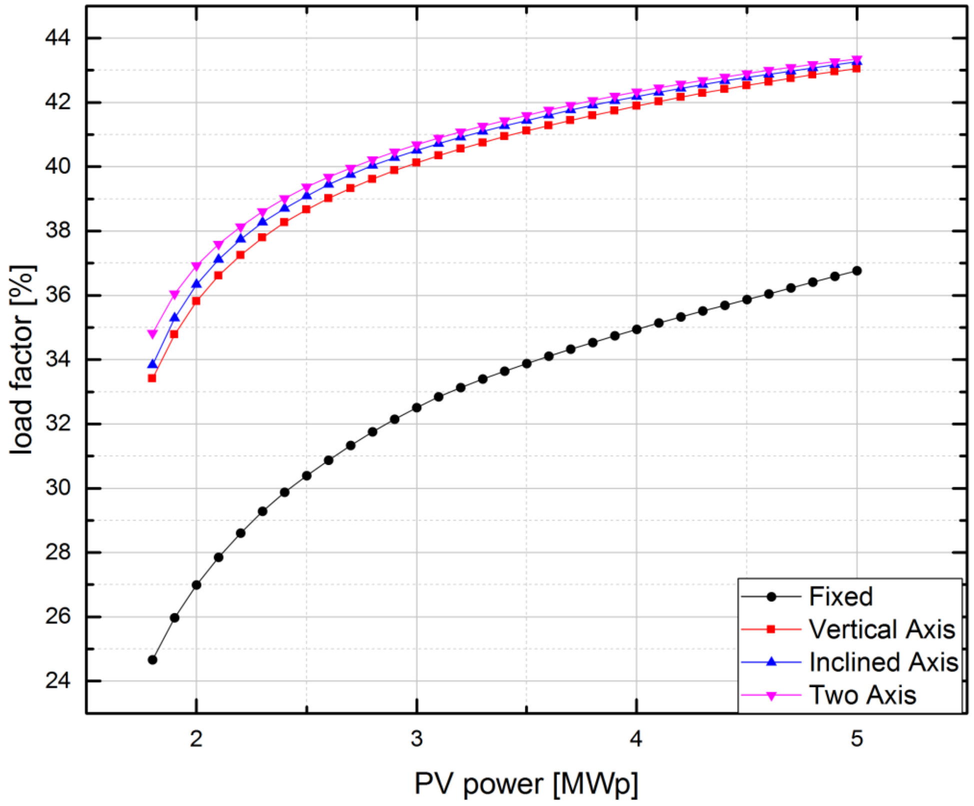
Combination w. PV / renewable energy – a view on load factor

- economic operation requires high load factor
- simulation with PV data from [8] for Morocco (1.6 MW electrolysis plant)
- 1.6 MW PV (with tracking): load factor of ~34%
- combine PV and wind for more balanced power production throughout the day
  - wind power: prime energy source
  - PV plant serves as backup



sources: [8]

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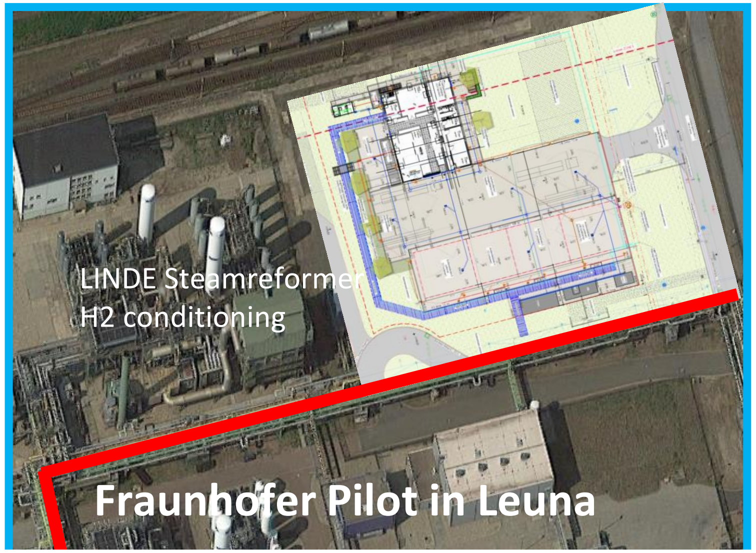
Advantage of pilot installation



- invest in pilot will ensure:
  - right time for scale-up can be taken
  - technology with highest ROI (return on invest) can be taken
  - IP situation is well understood and secured
  - combination with RE is controlled
  - skill build up before major invest
- Future decisions for invest based on experience instead of assumptions.
- Experience in combination of hydrogen generation by electrolysis based on RE: define the best setup of the energy system
- future situation of Morocco regarding energy system can be taken into account

sources:

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Opportunity for Morocco

- Morocco could have an excellent position in future P2X industry, based on availability of RE

Hyped Potentials

- At centre of PtX debate in Europe with strong PtX potential
- Energy partnerships with Europe foster political support
- ➢ Potential to lead technology development; may depend strongly on solid political facilitation

Morocco – the "hyped potential"

- Today: Strong RES potential identified by every study
- Short-term: Potential for larger-scale pilot projects
- Long-term: PtX development strong if politically facilitated

Snapshot of the world's strongest RES potentials

sources: [2]

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Thank you for your attention!

Fraunhofer Institute for Microstructure of Materials and Systems

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AGENDA STUDY P2X : GREEN AMMONIA

1) Reviewing ammonia synthesis technologies
2) Catalysts, thermodynamics
3) Energy efficiency
4) Economy: CAPEX / OPEX analysis
5) Intermittent operation :combination with renewable energy (RE)
6) Requirements for plant installation

Overview of ammonia synthesis technologies

- Haber-Bosch process
- direct electrochemical reduction of nitrogen to ammonia
- photocatalytic reduction of nitrogen to ammonia and
- plasma-enabled reduction of nitrogen to ammonia

Reaction "drivers"	H_2 needed from external source	No H_2 needed from external source	Reaction "drivers"
Temperature, pressure catalyst	Haber-Bosch Synthesis	Direct electrochemical reduction of N_2	Electrons, H_2O, electrocatalyst
Non-thermal plasma, catalyst, (temperature)	Plasma-enabled reduction	Photochemical reductionof N_2	Photons, H_2O, photocatalyst

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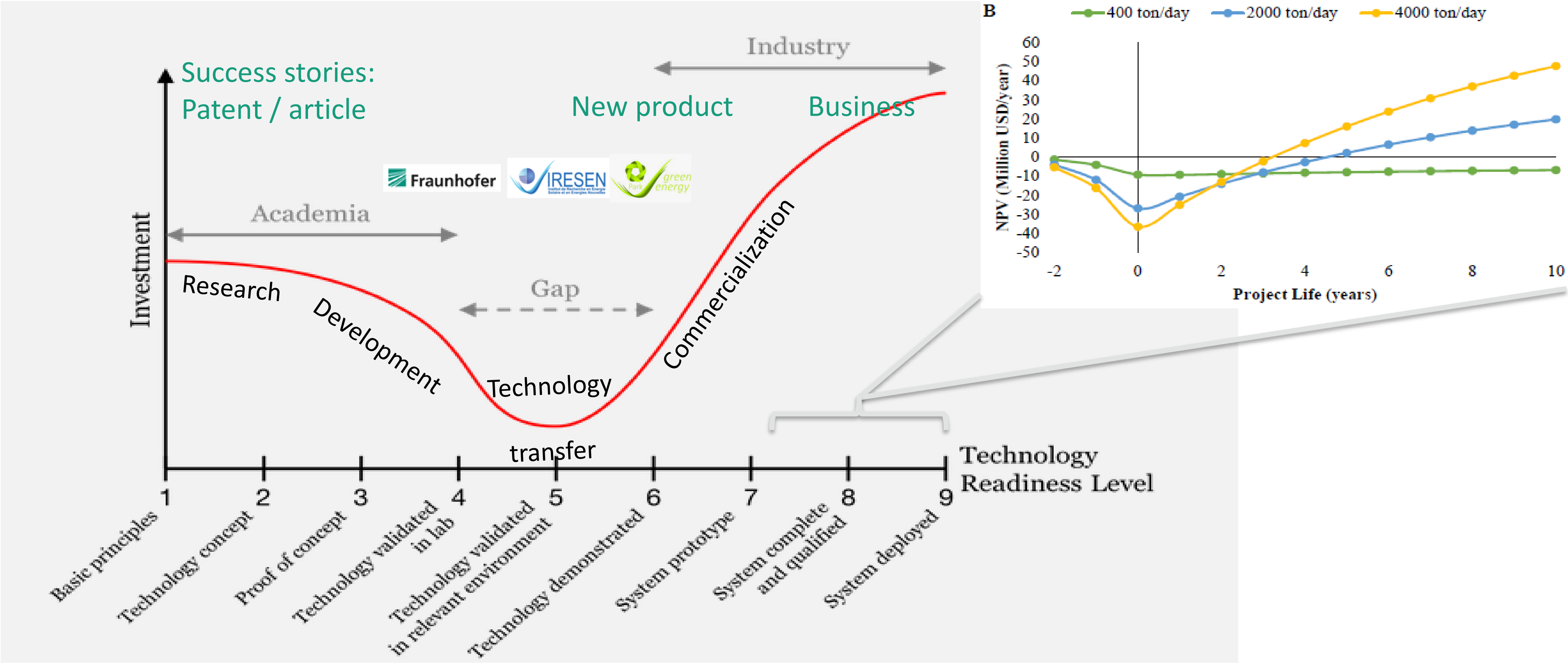
The long way from lab experiments to successful business case

Technology readiness levels (TRL), investments and ROI



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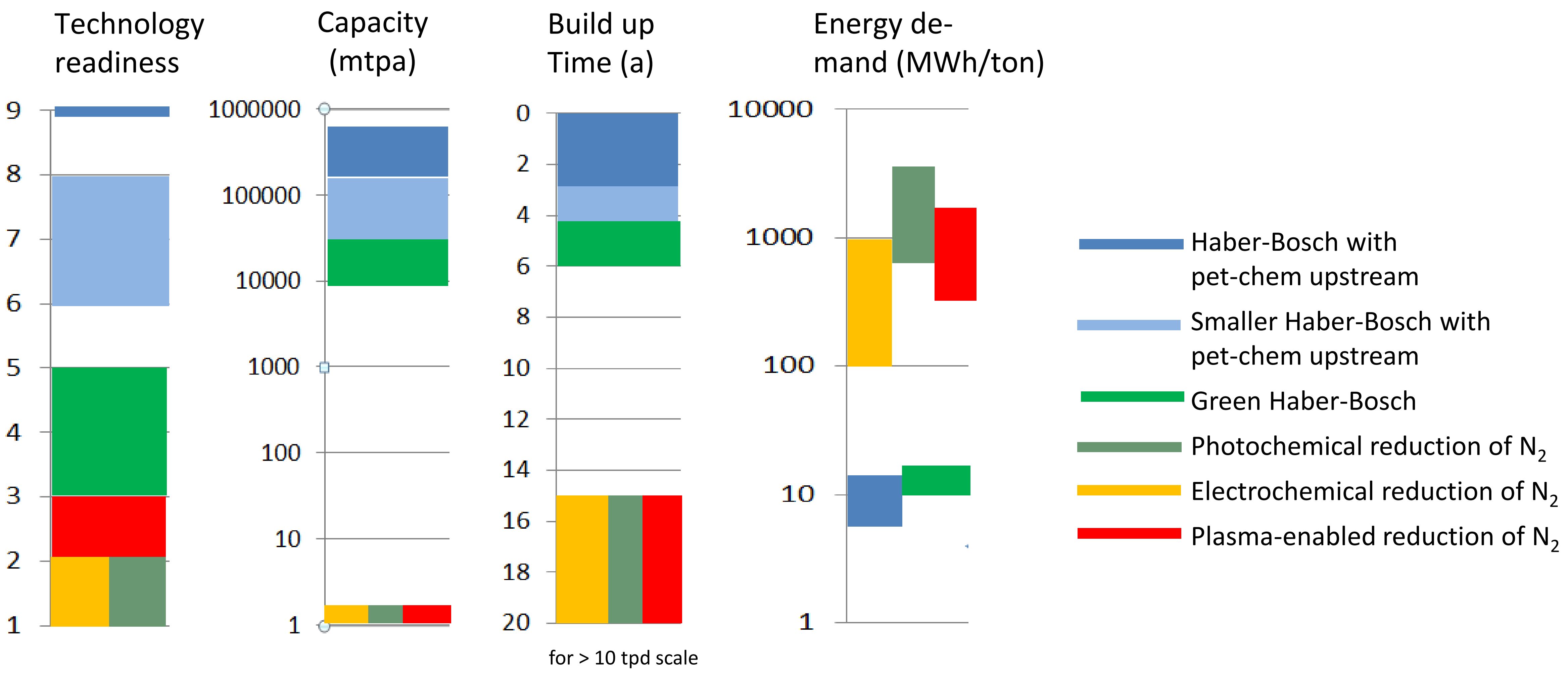
Ranking of the technologies



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Catalysts for Haber-Bosch process

Haldor-Topsoe

- KM-1: the magnetite based „industry benchmark“ with long lifetime, over 1200 charges delivered
- KM111: more performant than KM1, better energy efficiency
- KM1R and KMR111: faster plant start-up than with KM1 and KM111

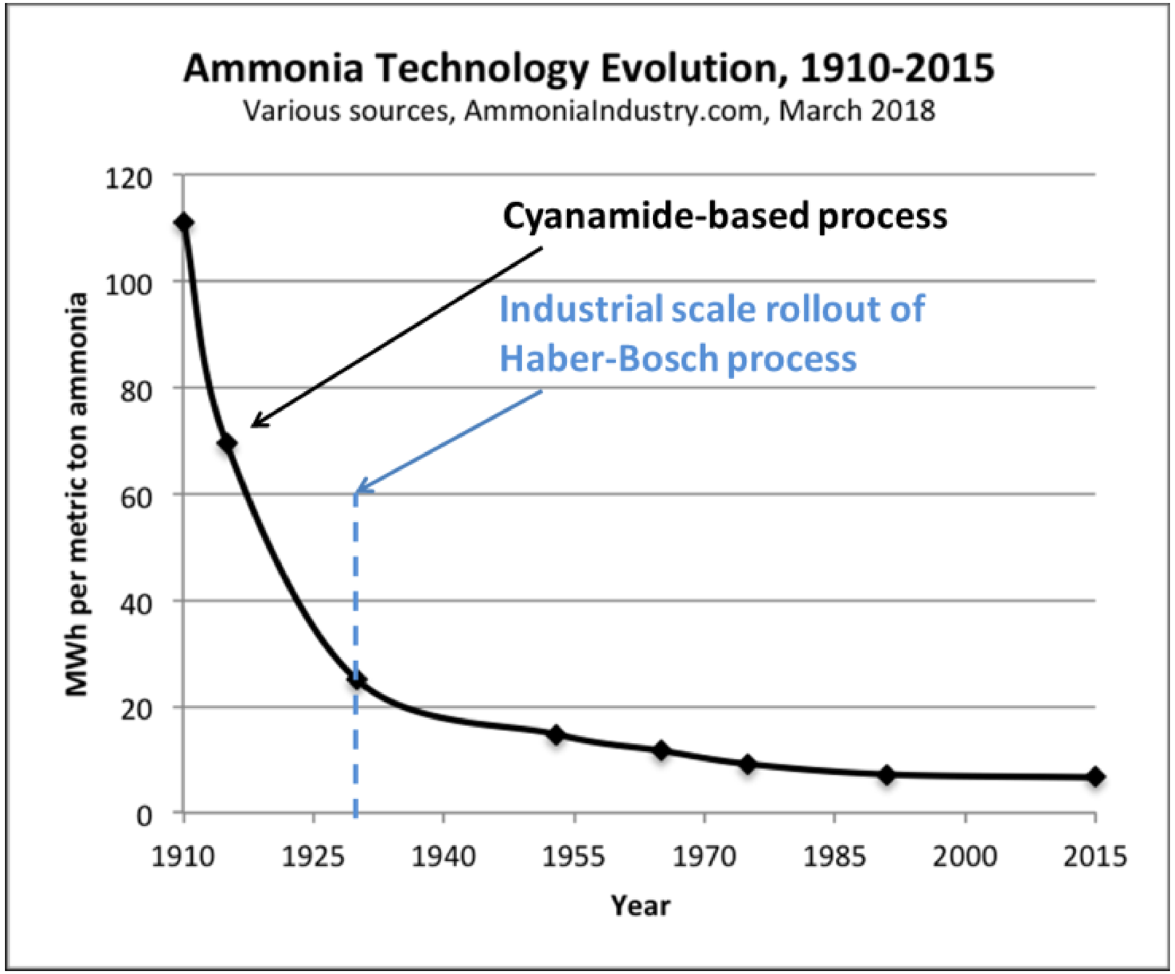
Clariant

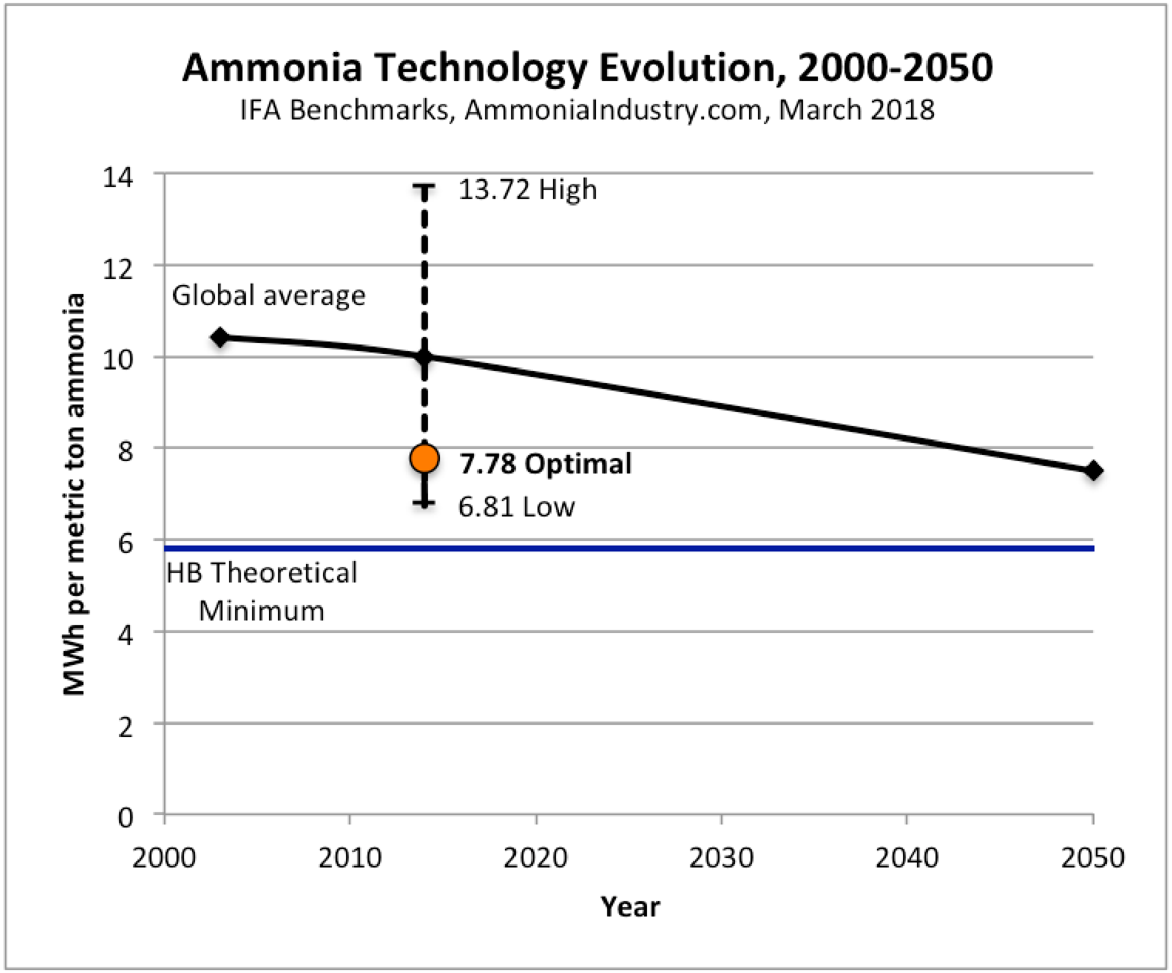
- AmoMax10: increased activity compared to magnetite-based catalysts

Johnson Matthey

- Katalco35: long lifetime, high activity
- Katalco74 superior activity in particular between 80 and 120 bar

Energy demand evolution of the Haber-Bosch process





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Plant size and economics

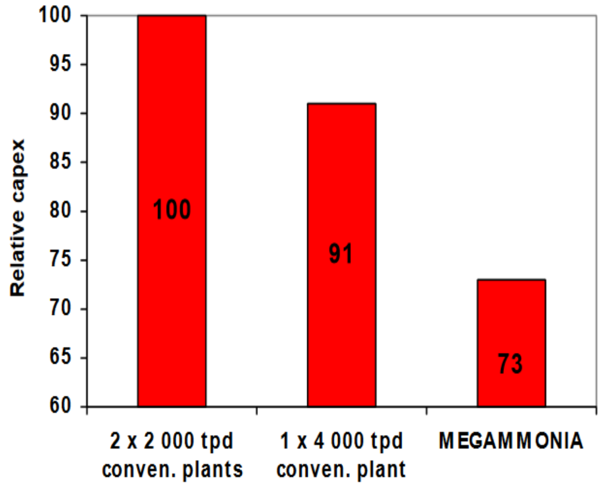
Company	Capacity (mtpa)	CAPEX (US$)	CAPEX/t_{NH3}/day ($/t/day)	Type
Ammoni	715000	1,4 b	1958	Pet-Chem, greenfield
JV Yara&BASF	750000	600 m	800	H_2 from other process
J.R. Simplot	Ca. 200000	350 m	1765	brownfield
Fortigen	Ca. 33000	75 m	2275	greenfield

Assuming 10 years payback time on the plant, the specific CAPEX is in the interval between 80 and 227 $/ton NH3

Modularity:

CAPEX comparison

2x2000 vs 1x4000 tpd

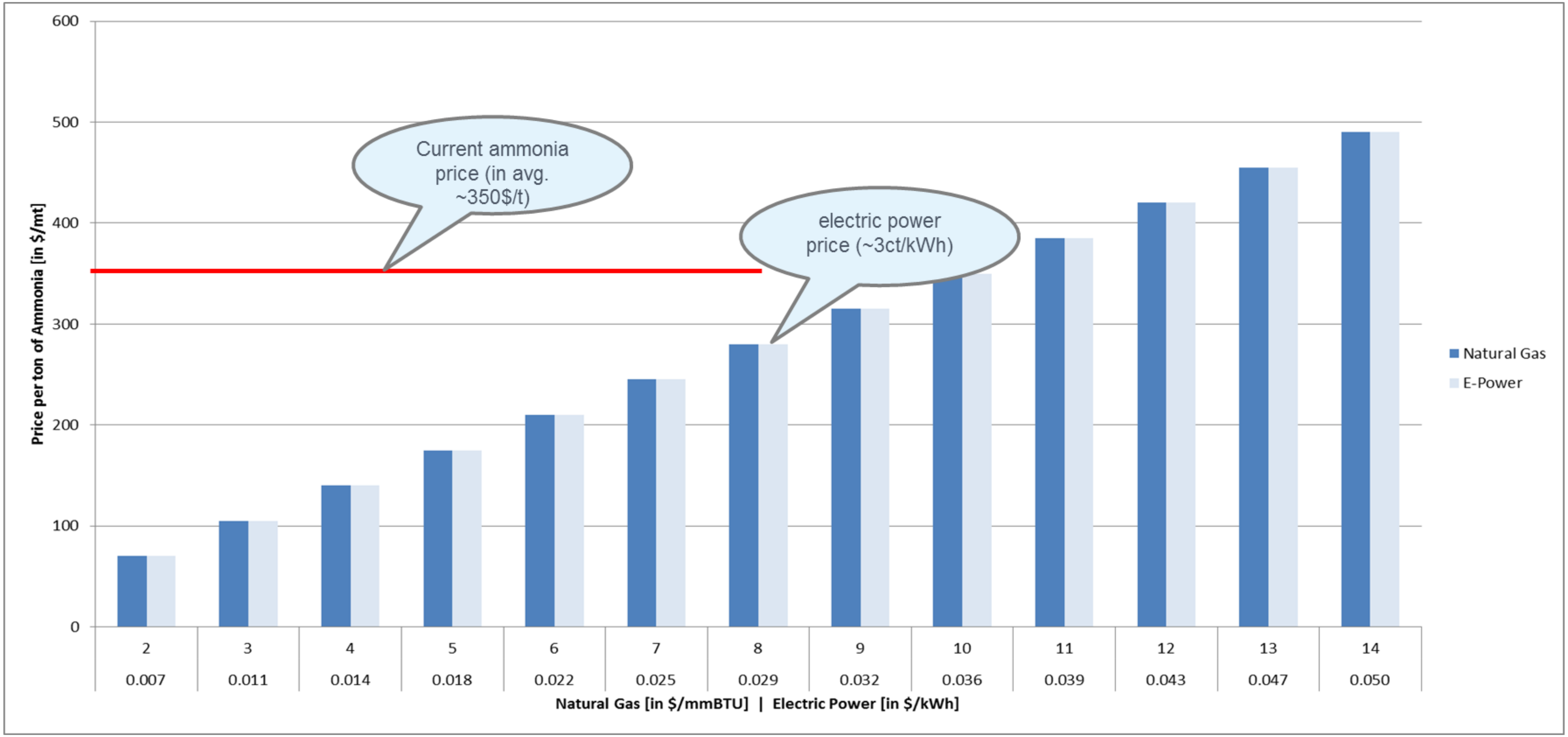


CAPEX Structure

MEGAMMONIA (Casale)

Process Plant	61 %
Utilities (including cooling tower)	15 %
Tank farm (40 000 t NH_3)	7 %
Air Separation Unit	17 %
TOTAL	**100 %**

OPEX estimation (energy price)



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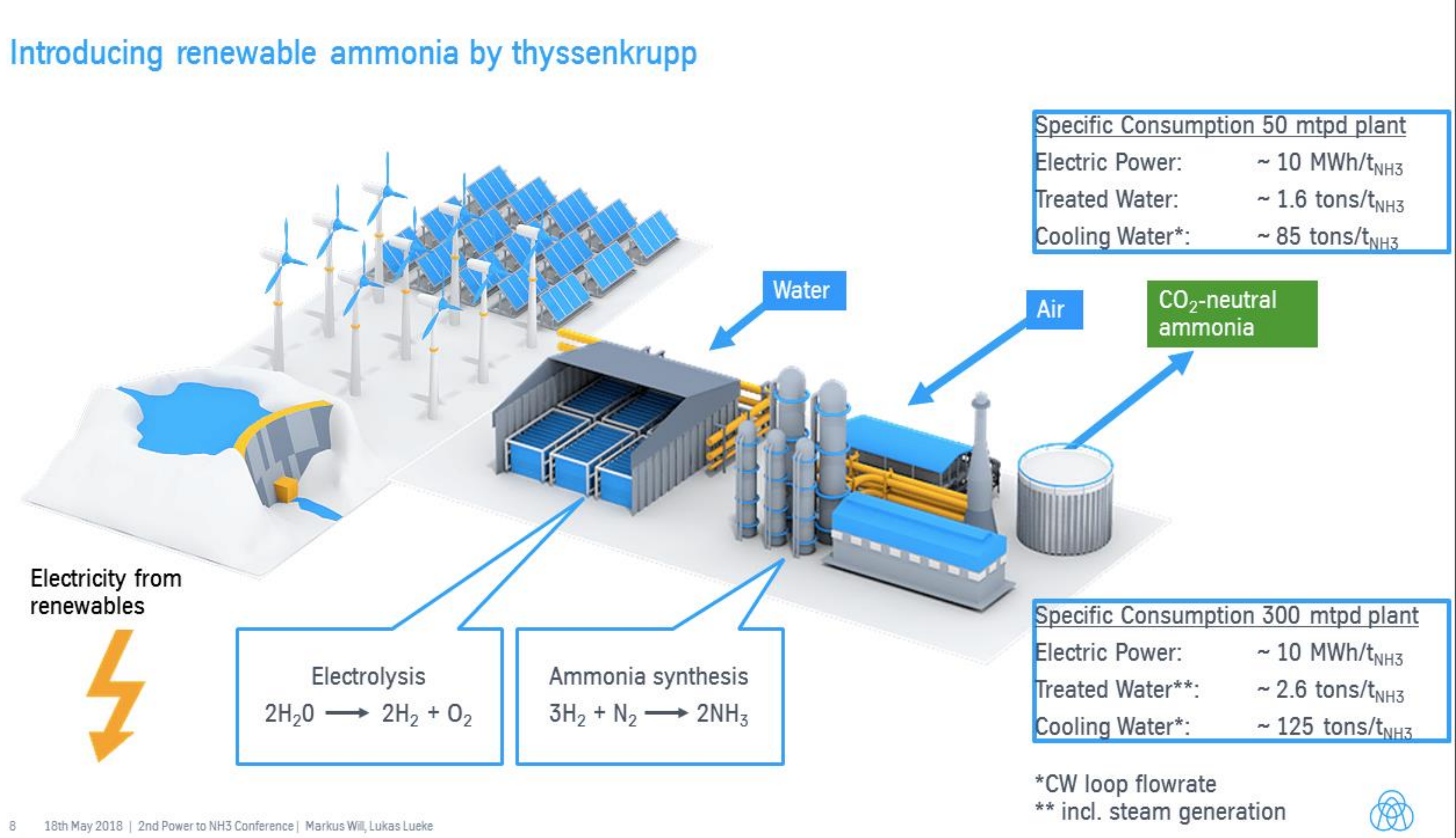
Green Ammonia plant by Thyssen-Krupp



Location: Port Lincoln, AU

CAPEX: 90 m $

CAPEX/t/day: 4931 *Aus*$/t/d

Target energy demand:

10 MWh/ton NH_3

"one of the first ever commercial plants to produce CO_2-free 'green' ammonia from intermittent renewable resources."

Intermittent operation of lone standing technologies

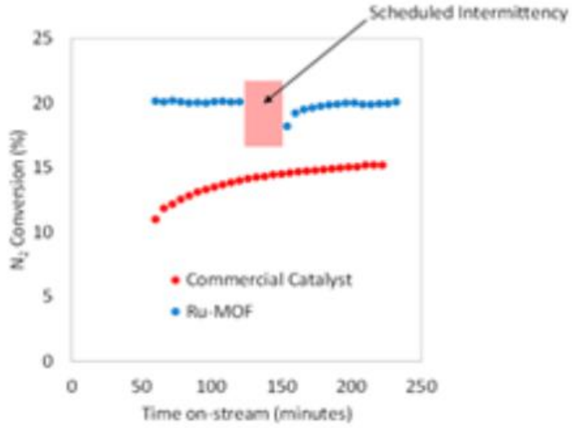
PV,
Wind mill → Electrolysis → H_2 Pet-chem upstream → Haber-Bosch Synth. → NH_3

Electrolysis

0-100% in
10 s-50 min
Role:
valorizes peak
energy

Pet-chem upstream / Haber-Bosch Synth.

x±1-10% in
24 h -1 week
Role:
damps fluctuation
in the demand
Open question:
0%-100%-0%
cycles not proven



Lab-scale intermittency

Addressing coupled intermittent operation on large scale

Scenario 1: Direct coupling of the electrolyzer and PSA with Haber-Bosch

Condition: The Haber-Bosch reactor has to follow quasi real time the intermittency of the electrolyzer.

PV, Wind mill → PSA Electrolysis → N_2 / H_2 → Haber-Bosch Synth. → NH_3

PSA Electrolysis:

0-100% in 10 s-10 min

Intermittency proven

Haber-Bosch Synth.:

0%-100%-0% cycle operation

Fast ramp up/ramp down

Open questions:

0%-100%-0% cycles not proven

Catalyst stability to be determined

Energy losses due to cooling down

- Addressing the open questions in pilot plant
- Relatively high CAPEX
- Higher energy demand

Addressing coupled intermittent operation on large scale

Scenario 2: Indirect coupling of the electrolyzer and PSA with Haber-Bosch

Condition: The Haber-Bosch reactor may be operated with loads >0 %.

PV, Wind mill → PSA Electrolysis → (N_2, H_2) → Haber-Bosch Synth. → NH_3

PSA Electrolysis: 0-100% in 10 s-10 min

Intermittency proven

Haber-Bosch Synth.: x±1-10% in 24 h -1 week

Small ramps proven

Exothermic heat valorization to power the electrolyzer

Advantages vs. Scenario 1

- Possible to build larger plant
- Significantly less R&D needed
- Better energy efficiency
- Maintaining >0% load factor of electrolyzer by feeding it with electricity from exothermal energy from the Haber-Bosch

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Thank you for your attention!

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Fraunhofer IMWS

sources of information / literature

[1] Study IndWEDe, Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme, BMWi Germany 2018, Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie – NOW GmbH, Fasanenstraße 5, 10623 Berlin

[2] Frontier economics, from World energy council 2018 (INTERNATIONAL ASPECTS OF A POWER-TO-X ROADMAP, A report prepared for the World Energy Council Germany

[3] Hydrogen Council, McKinsey – Investor Day Presentation, 24.06.2018

[4] Tsotridis, G., & Pilenga, A. (2018). EU harmonised terminology for low temperature water electrolysis for energy storage applications.

[5] Smolinka, T., Water Electrolysis: Status and Potential for Development, Fraunhofer-institute for solar energy systems ISE, Water Electrolysis Day Brussels (BE), April 03, 2014

[6] Cost break down and cost reduction strategies for PEM water electrolysis systems, Presentation held at 6th European PEFC & Electolyser Forum, Lucern, Switzerland, July 5, 2017, Author(s): Smolinka, T.; Wiebe, N.; Thomassen, M.

[7] Study by AGORA Germany Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The Future Cost of Electricity-Based Synthetic Fuels., https://www.agora-energiewende.de/

[8] http://re.jrc.ec.europa.eu/PVg_tools/en/tools.html#PVP