Unlocking the potential of ammonia as energy vector in energy transition: Market Trends and techno-economic assessment of ARENHA solutions

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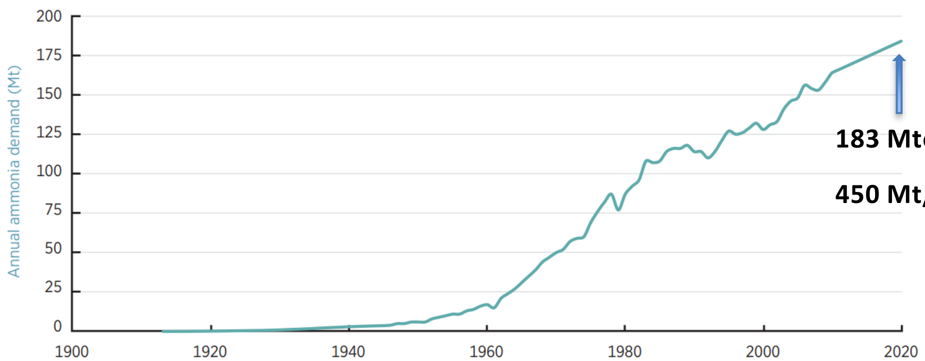
Ammonia Market Overview and Trends

Ammonia Demand and Applications



183 Mton

450 Mt/y CO_2

Global Ammonia demand (1900-2020) Source: Innovation Outlook, Renewable ammonia; IRENA 2024

Hydrogen sourcing for NH_3 synthesis reaction:

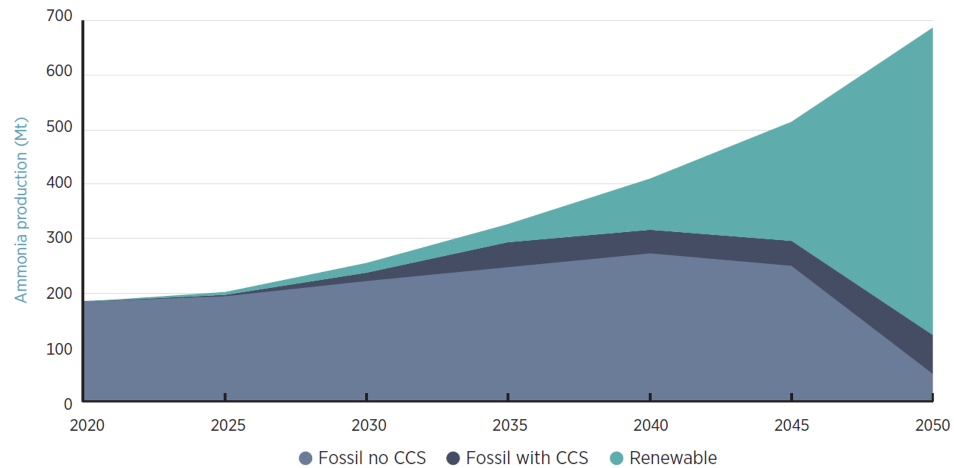
- Gas Reforming
- Coal Gasification

1.8-3.2 ton_{CO_2}/ton_{NH_3} CO2

- Gas Reforming with CCS
- Water Electrolysis

Low-Carbon Ammonia

➢ NH_3 demand could reach more than three times 2020 demand by 2050



Innovation Outlook, Renewable ammonia; IRENA 2024

Existing uses:


Fertilizers (~80%)


Plastics

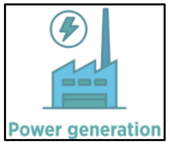

Textiles


Explosives


Refrigeration

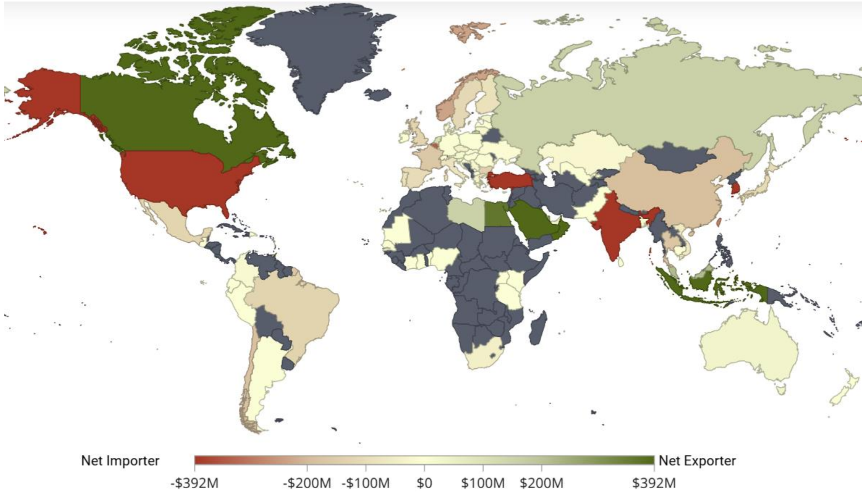
- The industry's current path is incompatible with climate neutrality goals.
- **Low-Carbon ammonia** could play a broader role in the energy transition, contributing to the **decarbonization** of the **chemical industry**, **transportation** and **power generation** sectors.

New Emerging uses:



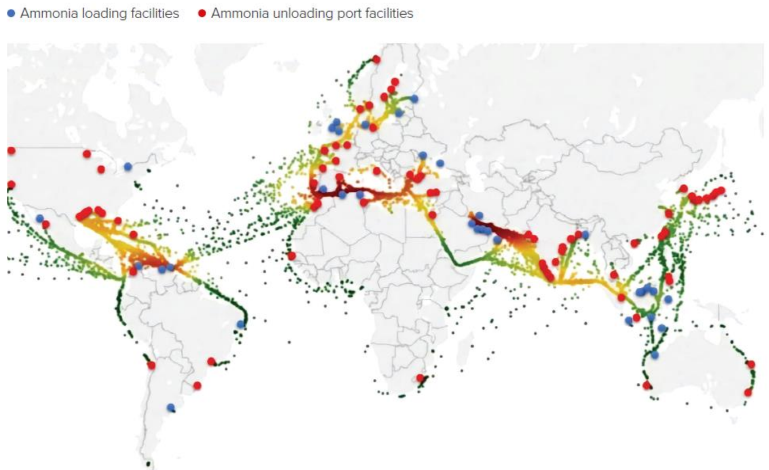
Ammonia Market Overview and Trends

Ammonia Market Trade



Anhydrous ammonia Product trade, Exporters and Importers in 2023 | Source: Observatory of Economic Complexity

➢ In 2023 **15 Mton** of NH3 were traded worldwide, for a total market value of **9 Bn$**



Ammonia shipping infrastructure in 2017 , including a heat map of liquid ammonia carriers and existing ammonia port facilities. | Source: The Royal Society

Main Exporters:

- Trinidad and Tobago (18.6%), Saudi Arabia (15.3%), Indonesia (10%) and Canada (8.85%)

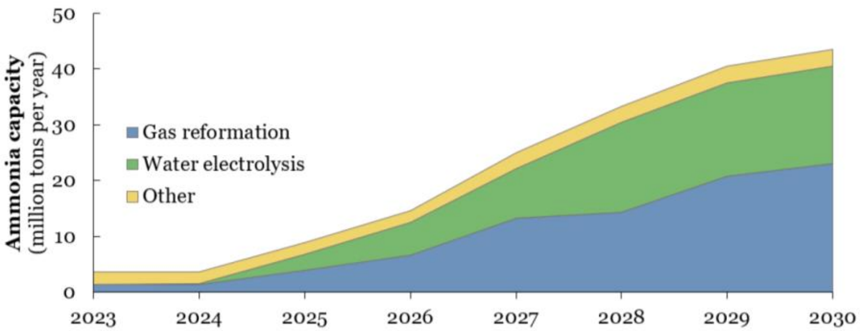
Main Importers:

- US (15.2%), India (13.6%), Morocco (9.75%), Turkey (4.81%) and Cina (3.51%)

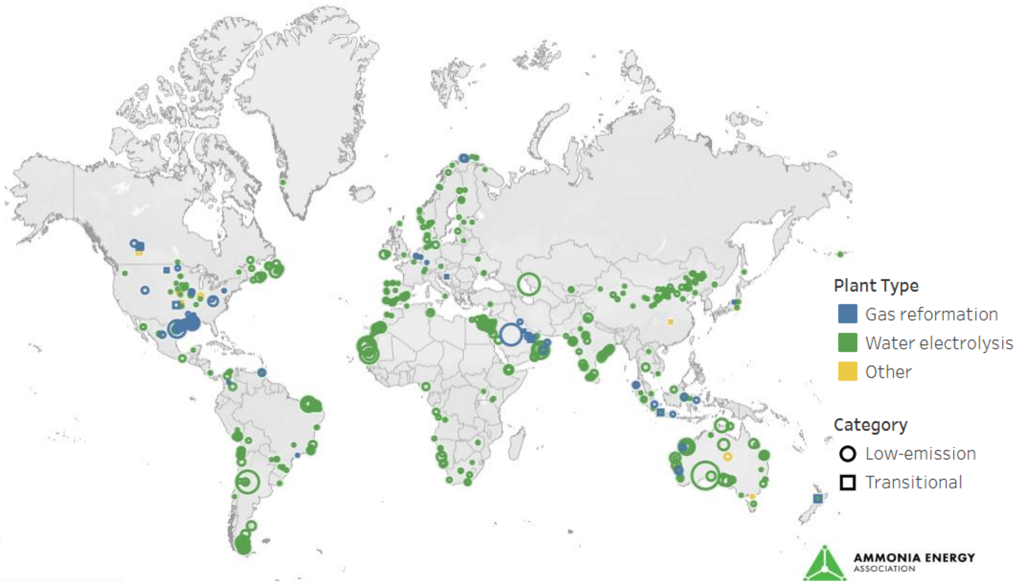
Existing ammonia trading infrastructure can support low-carbon ammonia exports

Low-Carbon Ammonia Supply

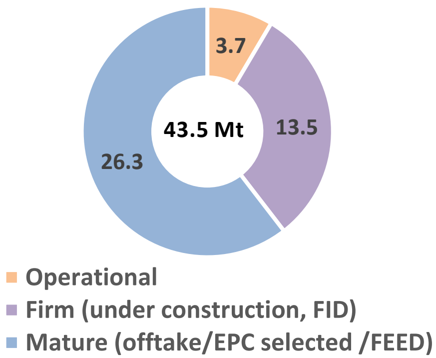
- **485** Ammonia projects (Feb. 2025) from 102 (Dec. 2022) for a total **451.2** millions tons (Mt)
- 43.5 Mt ammonia capacity could be operational by 2030, **37.7 Mt** low-carbon (~90%)



Operational, firm and mature Low-carbon ammonia projects. | Source: Ammonia Energy Association



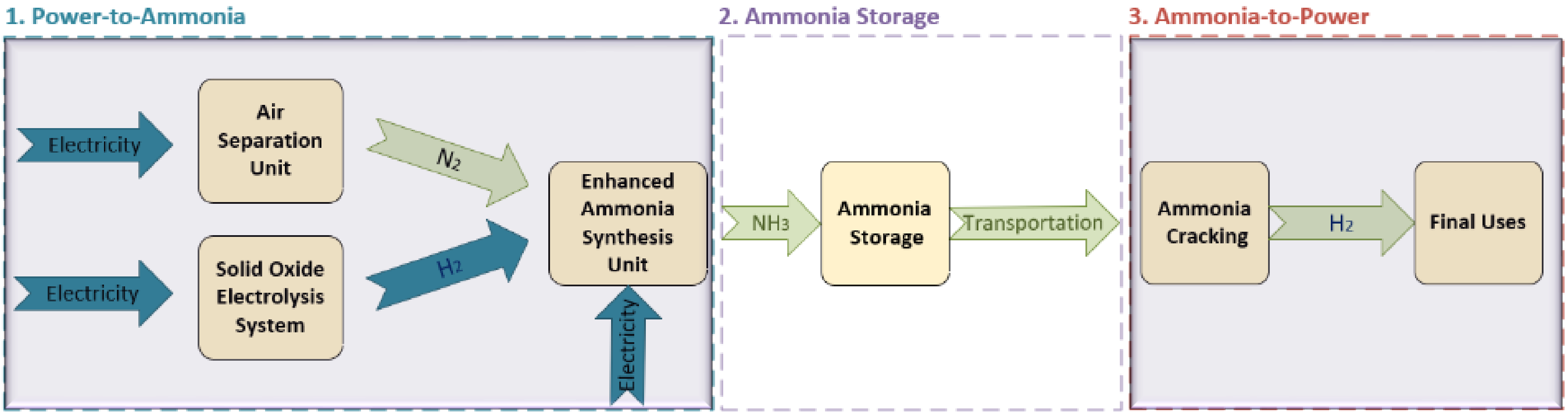
Announced ammonia projects. | Source: Ammonia Energy Association



- Low-carbon ammonia project based on natural gas (blue) set to lead near term supply compared to electrolysis based (green) ammonia projects
  - High financing cost and low offtackers willingness to pay is a barrier for green ammonia project develoments

Need of **affordable** and **cost effective** green ammonia production technologies to move more projects towards Final Investiment Decision (FID)

ARENHA Techno-economic Assessment



Objectives:

- Technology benchmarking;
- Optimize system design and evaluate economic feasibility;
- Gain valuable technical insights to help make investment decision;

Solutions modelled:

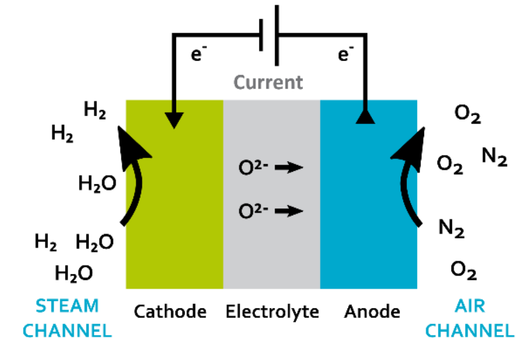
- Power-to-Ammonia
- Ammonia Solid Storage
- Ammonia-to-Hydrogen

Why Solid Oxide Electrolyis Cells (SOECs)?

Cathode semi-reaction: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$

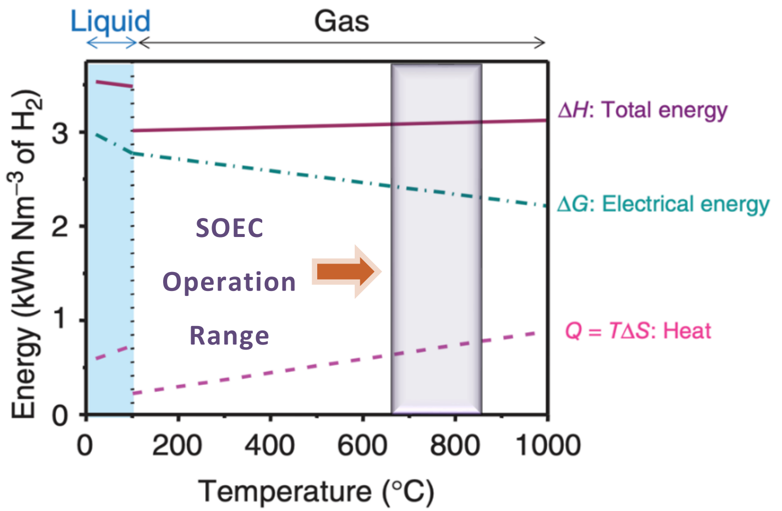
Anode semi-reaction: $O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$

Overall Reaction: $H_2O \rightarrow \frac{1}{2}O_2 + \mathrm{H}_2$



Key Advantages of high temperature operation :

- Lower total and electrical energy expenditure → Higher efficiency (Lower OPEX)
- No need for Platinum-Group Metals (PGMs) → More robust supply chain
- Heat integration possibility (e.g. Power-to-X applications)

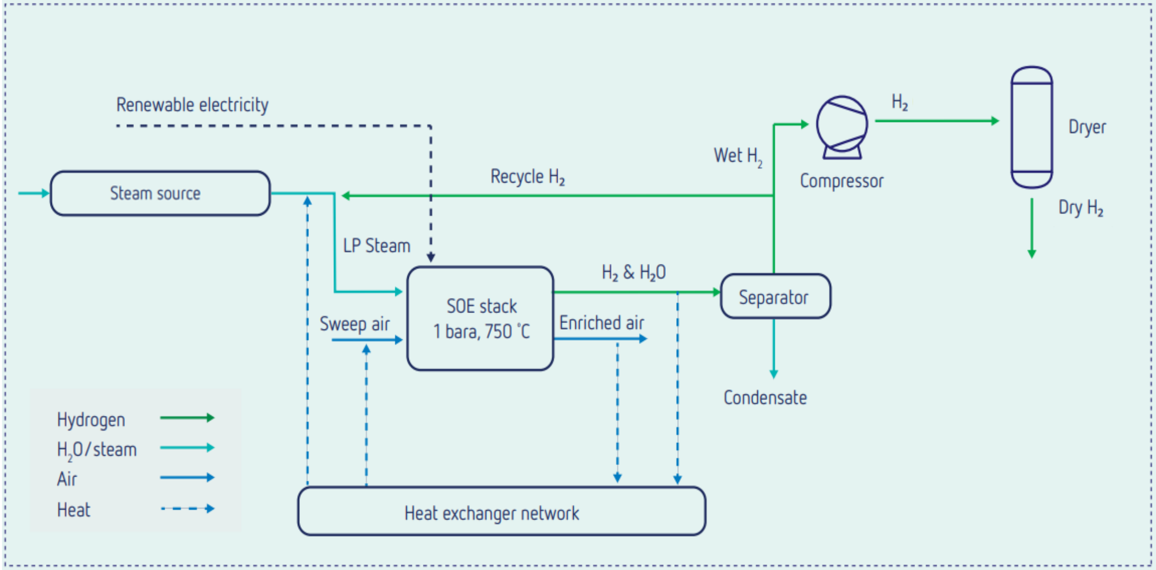


Energy need for the water electrolysis reaction, as function of temperature, enthalpy (ΔH), Gibbs free energy (ΔG) and entropy (TΔS) (Source: G. Jopek, "Hydrogen Production by Electrolysis ", 2018)

Solid Oxide Electrolysis Process Overview

High-temperature electrolysis process steps:

1. Steam Generation
2. Cathodic/anodic streams pre-heating
3. Electrolysis
4. Water Separation
5. H2 Compression & Drying



Green Hydrogen Production Process Based on SOEC (Source: ISPT, "Next Level Solid Oxide Electrolysis", 2023)

~5 kW ARENHA pilot! How to scale-up system for industrial application?

- Cell/stack development and scale-up
- Modular system approach

ARENHA Techno-economic assessment

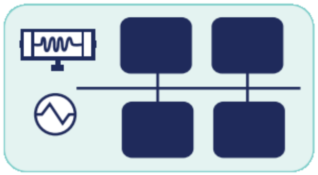
Power-to-Ammonia

Solid Oxide Electrolysis Process: Modularity

1. SOEC Cell (~W)

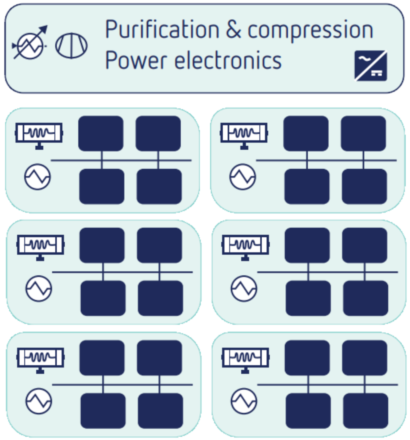
2. SOEC Stack (~kW)

3. SOE Stack Module (Hot-box) (~kW to MW)

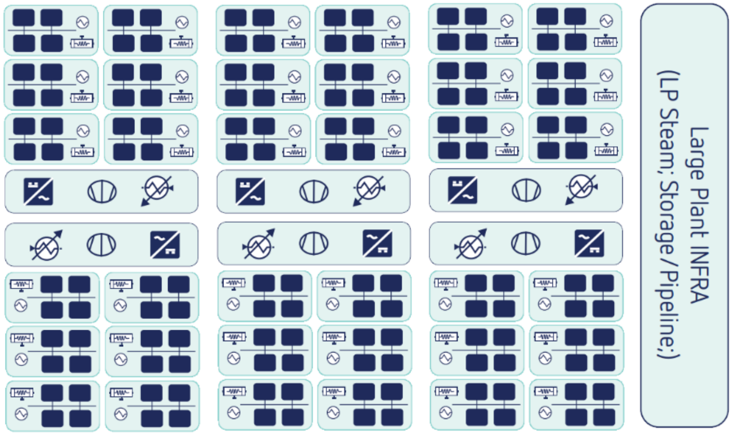


4. SOE System

Repeating Block (~MW)



5. Complete SOE Plant (~MW)



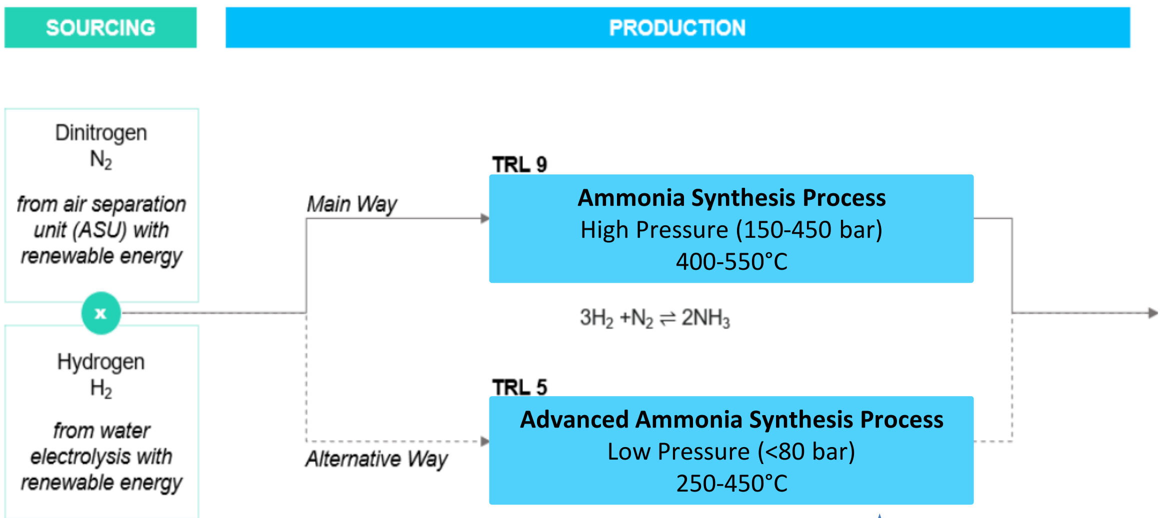
World biggest SOE project:

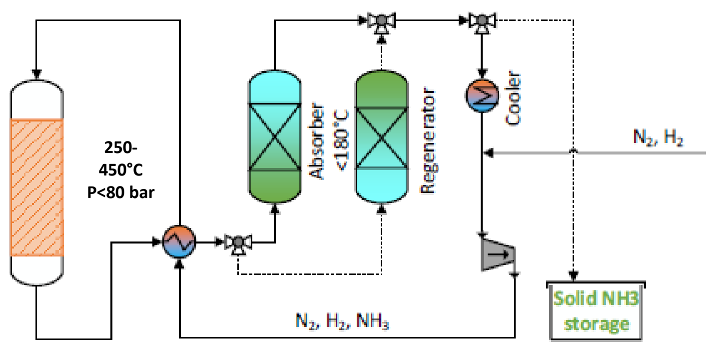
Mountain view NASA Facility (Bloom Energy):

4 MW_{DC} (~2.4 tH2/d)

ARENHA Ammonia Synthesis Process

➢ **Advanced ammonia synthesis process** developed in ARENHA consists of **ammonia separation** using **absorption** process allowing for **milder operating conditions**





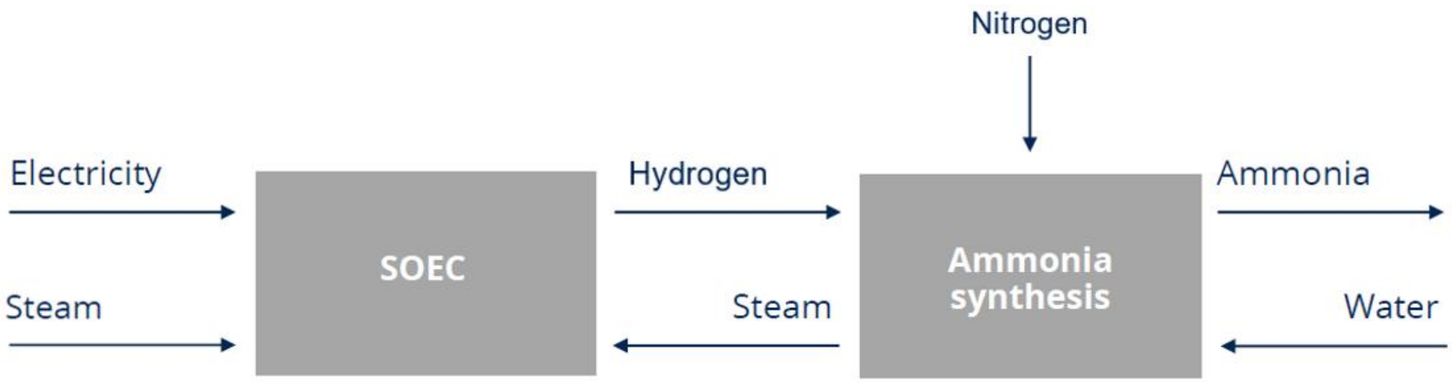
Advantages of ARENHA advanced ammonia synthesis technology:

- **Lower equipment cost (15-20%)**
- **Energy consumption comparable** to traditional small scale green ammonia synthesis technologies;
- **No CO2 emissions;**
- **High system flexibility** enhanced by milder operating conditions.

★ **Patented** solution

ARENHA Power-to-Ammonia

Synergy between Solid Oxide Electrolysis and Ammonia synthesis processes



- **Solid Oxide Electrolyser (SOE)**
  - Lower energy consumption for H_2 production (47-50 kWh/kg_{H2}) compared to low temperature electrolysis solutions;
  - High energy demand for steam vaporization (~ 20 % of total electrolyser electricity consumption):

- **Ammonia Synthesis Loop**
  - High quality heat availability (T > 400°C) from ammonia synthesis reaction which can be used for steam production.

The **integration** of steam produced in ammonia synthesis loop in Solid Oxide Electrolyzer enables for superior efficiency, offering **greater performances** and **cost reduction potential** compared to low-temperature electrolysis-based Power-to-Ammonia solutions.

ARENHA Techno-economic assessment

Power-to-Ammonia

Techno-economic Assessment Methodology

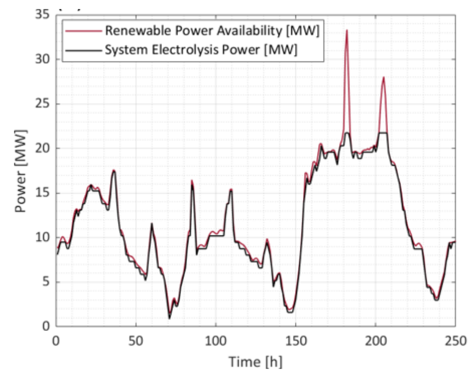
Development of a 0D lumped parameter dynamic model of Power-to-Ammonia chain, validated with experimental data from project partners.

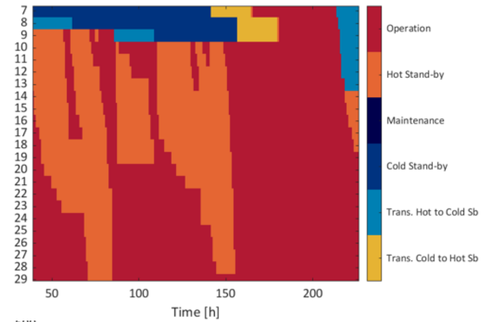
Renewable Power Input

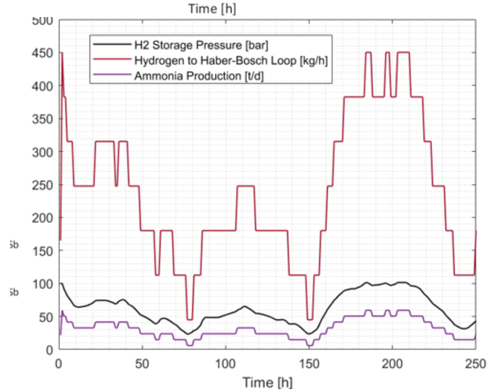
Process Modelling: Sub-system KPI and Cost

Power-to-Ammonia system operation:
- SOE Multi-Module operation
- H_2 Storage
- NH_3 Loop operation

System Modular Configuration







- OPEX
- CAPEX
- H_2 Prod.
- NH_3 Prod.

Economic Assessment (Discounted Cashflow)

LCOH [€/kg]

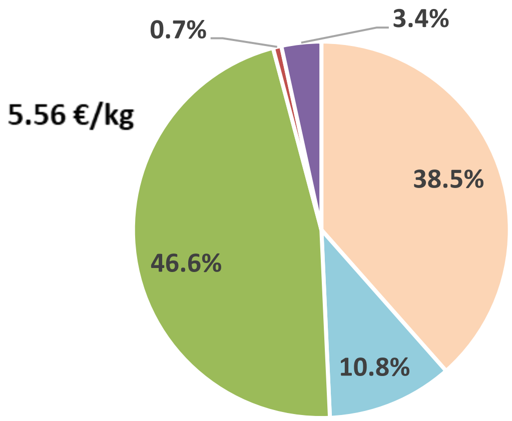
LCOA [€/ton]

Acronyms:
- **LCOH**: Levelized Cost of Hydrogen
- **LCOA:** Levelized Cost of Ammonia
- **OPEX**: Operational Expenditure
- **CAPEX:** Capital Expenditure

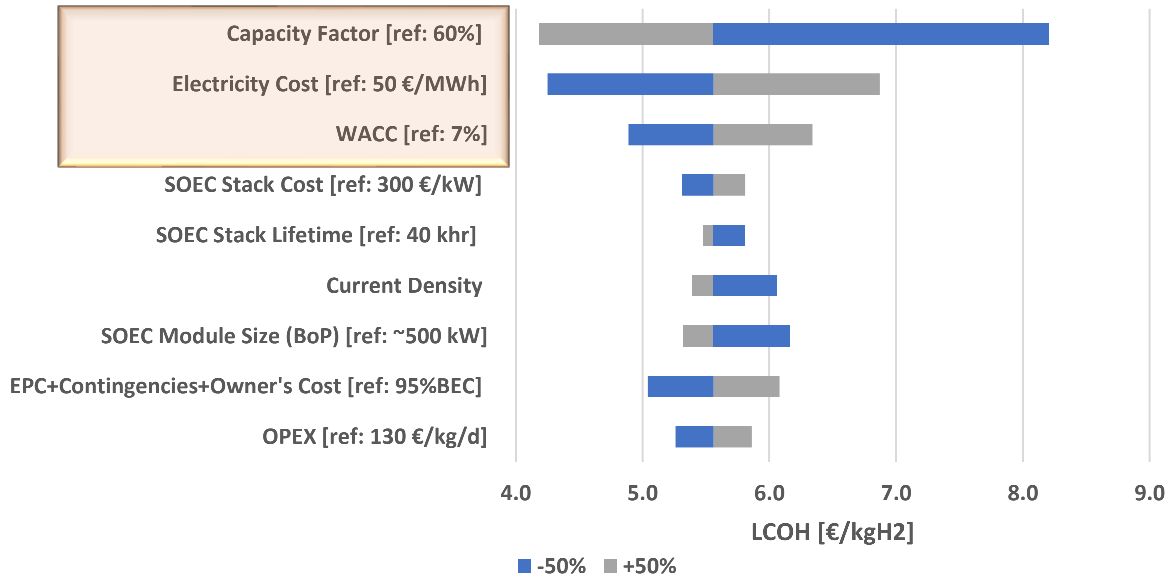
Results: Solid Oxide Electrolysis

~16 MW electrolysis power system (11.15 t/d H_2) fed by PV/Wind hybrid system

Reference Case:
System CAPEX: **4020 €/kW**
LCOH: **5.56 €/kg**



60% system availability. 30 Year plant operation, 50€/MWh electricity cost, 7% discount rate. Hydrogen output : 30 bar.



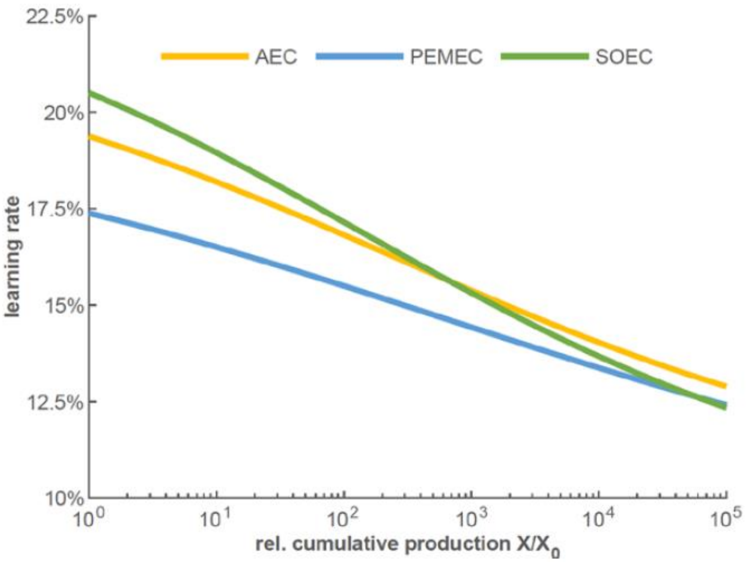
Acronyms:
LCOH: levelized Cost of Hydrogen | **BEC**: Bare Erected Cost | **BoP**: Balance of plant |
WACC: Weighted average cost of capital | **EPC**: Engineering Procurement and construction

OPEX and CAPEX driven process. Main cost affecting parameters:

- Renewable energy availability (Capacity Factor);
- Electricity Cost;
- Project financing cost;

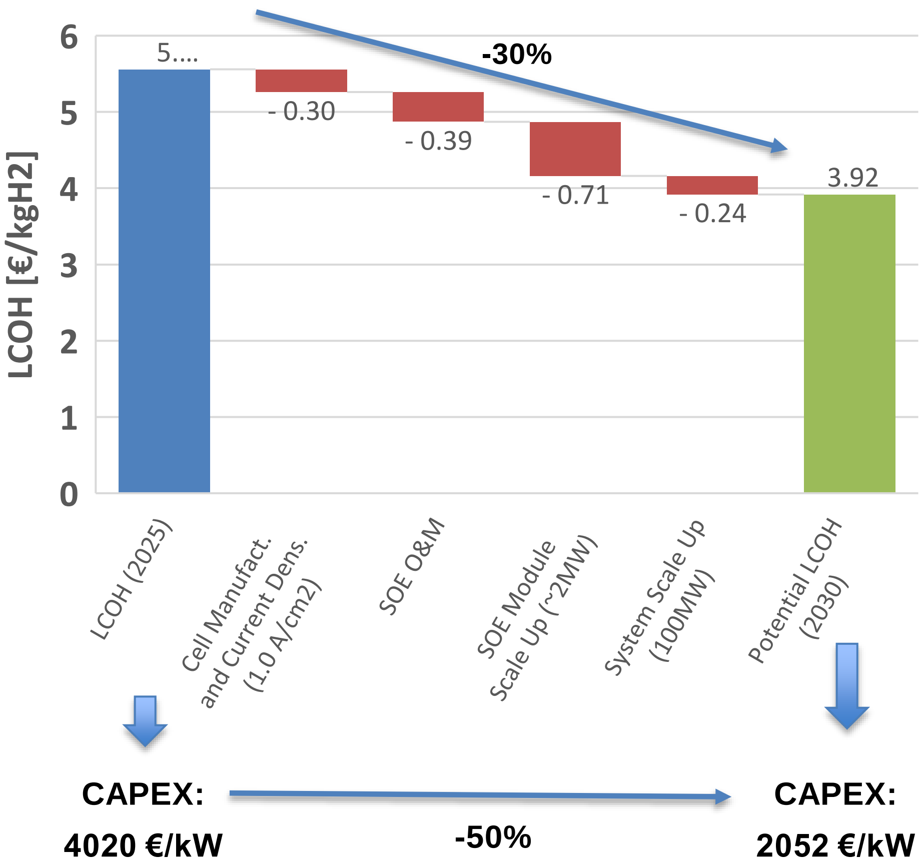
Results: Solid Oxide Electrolysis

Potential LCOH reduction driven technology improvement and CAPEX reduction



Estimated Learning rate of main electrolysis technologies. (Source: IRENA)

- Solid Oxide Electrolysis benefit of a higher cost potential reduction (learning rate) compared to low temperature electrolysis technologies

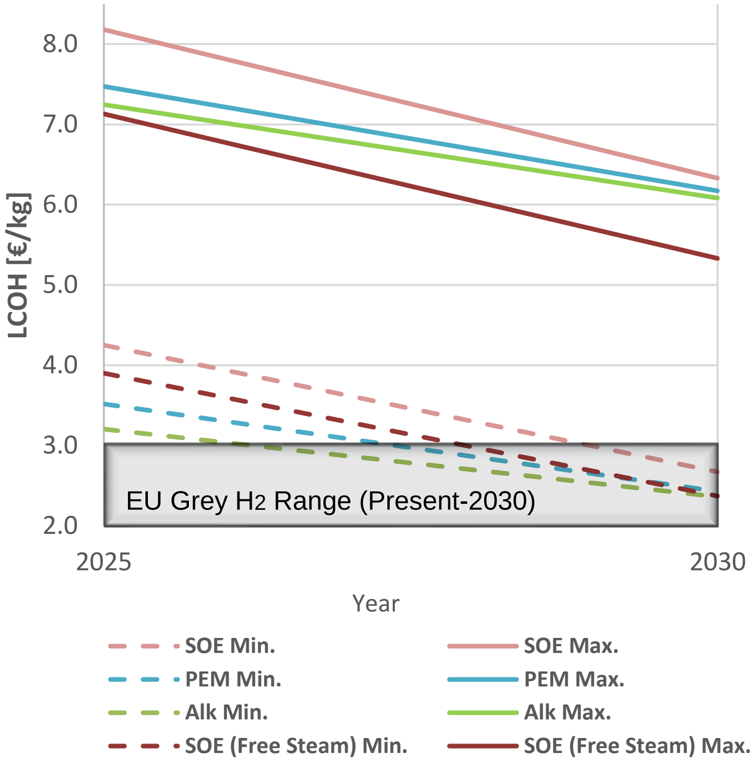


Technology improvement, higher manufacturing rate and system scale up are crucial for CAPEX and LCOH reduction in SOE systems

ARENHA Techno-economic assessment

Power-to-Ammonia

Results: Solid Oxide Electrolysis vs Low-T Electrolysis Technologies



Scenario	2025				2030			
Electrolysis Technology	**Alk**	**PEM**	**SOE**	**SOE (free steam)**	**Alk**	**PEM**	**SOE**	**SOE (free steam)**
Installed Electrolysis Power [MW]	24.2	23.7	15.9	15.9	140	140	100	100
Hydrogen Production [t/d]	11.15				70.00			
Tot. CAPEX* [€/kW] [2]	2000	2450	4020	3921	1250	1400	2052	1980
System Energy Consumption [kWh/kg$_{H2}$]	**52**	**51**	**49.85**	**41.10**	**48**	**48**	**47.85**	**39.10**

*CAPEX is calculated per kW of installed electrolysis power.
O&M: Operation and Maintenance | **Alk:** Alkaline electrolyser **|** **PEM:** Proton exchange membrane electrolyzer | **SOE**: Solid Oxide Electrolyzer

Electrolyzers operated with 60% year average capacity factor. Min and Max. refer respectively to 25 and 100 €/MWh electricity cost scenario. 30 years plant lifetime and 7% discount rate assumed. PEM and Alk. CAPEX and stack cost from STEPS scenario in [2]. 2025 PEM system energy consumption from [3], 2025 Alkaline system energy consumption from [4]. 2030 System energy consumption scenarios from [1].

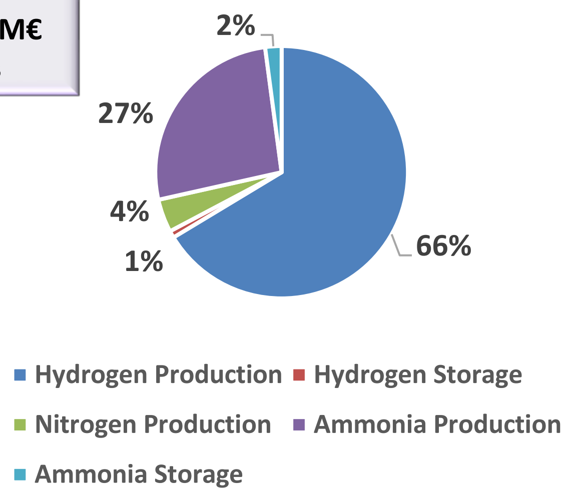
Despite higher cost greater efficiency makes SOE potentially competitive with low-T electrolysis technologies, especially for high electricity cost and free steam to electrolyzer scenarios

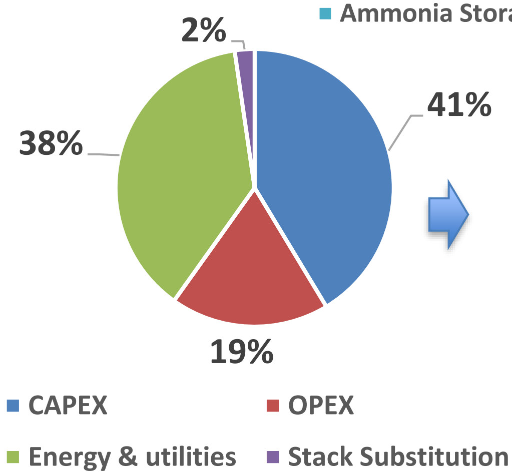
[1]. Clean Hydrogen JU - SRIA Key Performance Indicators (KPIs) - Clean Hydrogen Partnership
[2]. IEA, Global Hydrogen Review, 2024
[3]. Cummins Hylizer specsheet, 2021
[4]. Sunfire-Hylink Alkaline specsheet, 2025

Results: Power-to-Ammonia

Power-to-Ammonia system based on SOE - ~16MW electrolysis power (~60t/d$_{NH3}$):

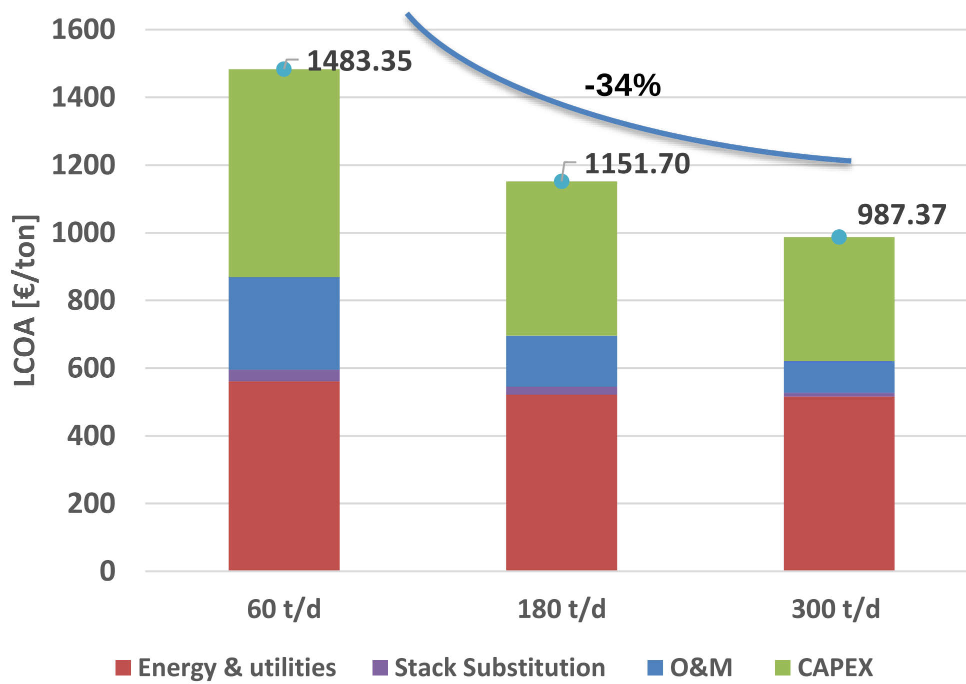
Reference Case:
System CAPEX: **~100 M€**
LCOA: **1483 €/ton$_{NH3}$**





System economic is challenged at 60 t/d scale with CAPEX and O&M representing two third of total LCOA

Improving economics with system scale:

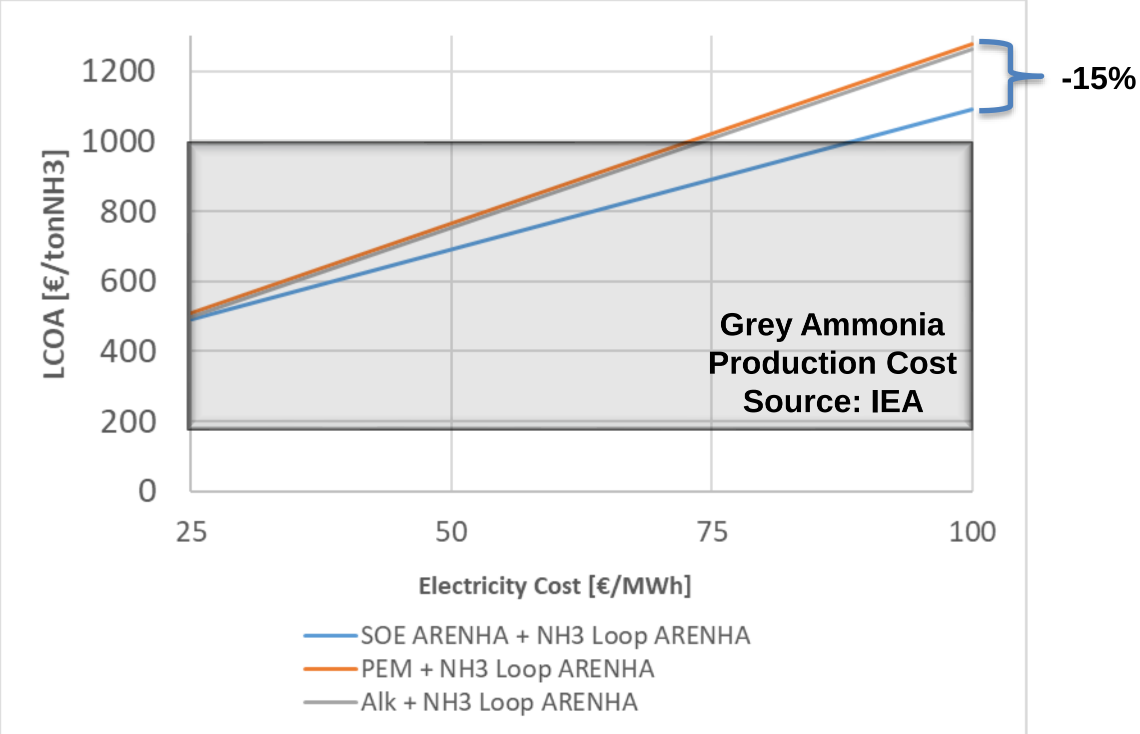


System operated with 60% year average capacity factor. 50€/MWh electricity cost, 30 years plant lifetime and 7% WACC assumed. A 100 bar H2 storage, 30 days ammonia storage and Nitrogen production were included in the study.

Increasing system scale could allow for economic competitiveness with traditional production pathways

Results: Power-to-Ammonia

Comparison with low-temperature based PtA system



Analysis carried out for ~300 t_{NH3}/d Power-to-Ammonia based on SOE, Alkaline and PEM electrolysis technologies, 90% system availability, 30 years plant lifetime and 7% discount rate.

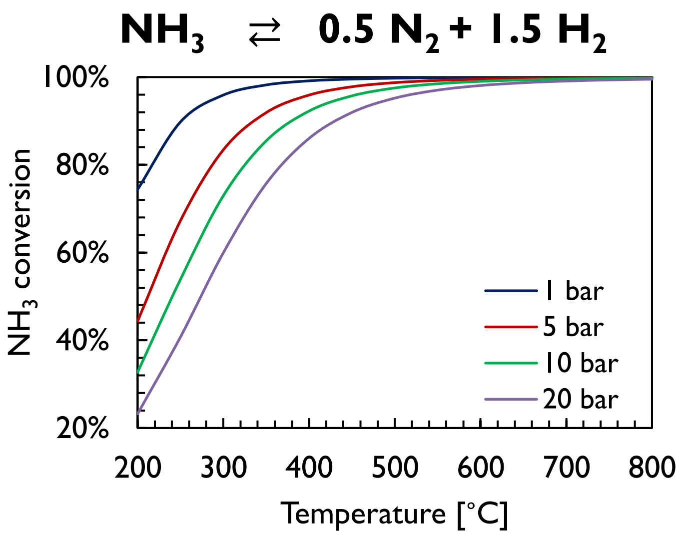
ARENHA Power-to-Ammonia solution based on SOE could be competitive with Power-to-Ammonia solutions based on low temperature electrolysis technologies and with traditional production (in case favourable electricity market conditions)

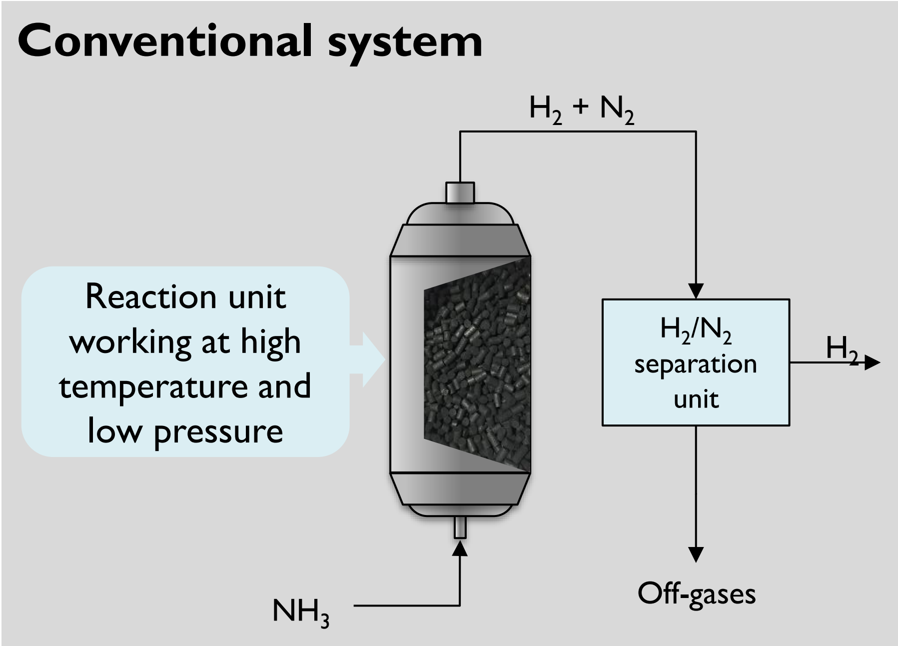
<u>What is required</u>

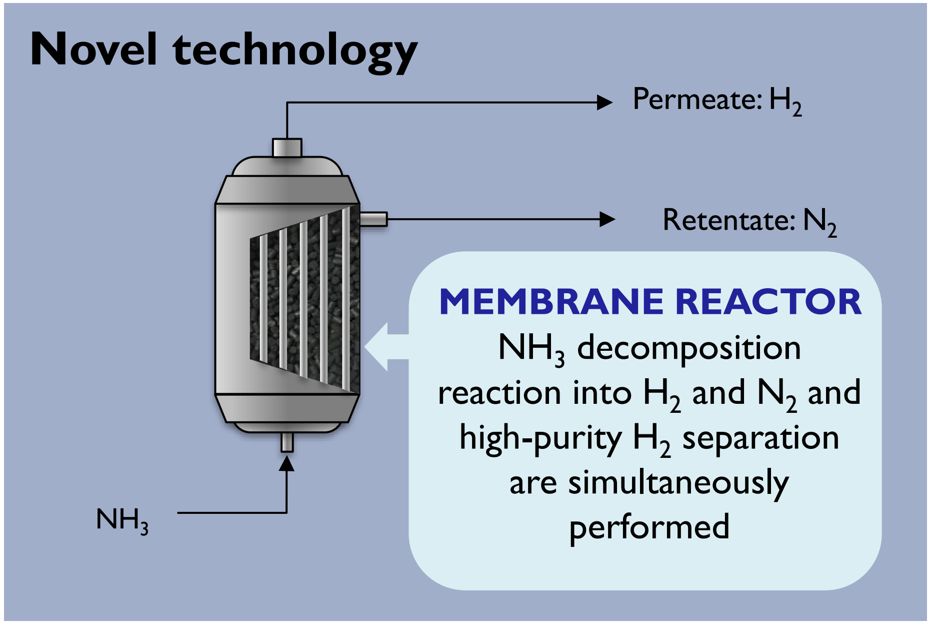
- Continue R&D activities on SOE and enhanced NH_3 Synthesis
- Effort in scaling up (e.g. SOE stacks and modules)
- High energy utilisation and low electricity cost from renewable energy assets

ARENHA Techno-economic assessment

Ammonia-to-Hydrogen

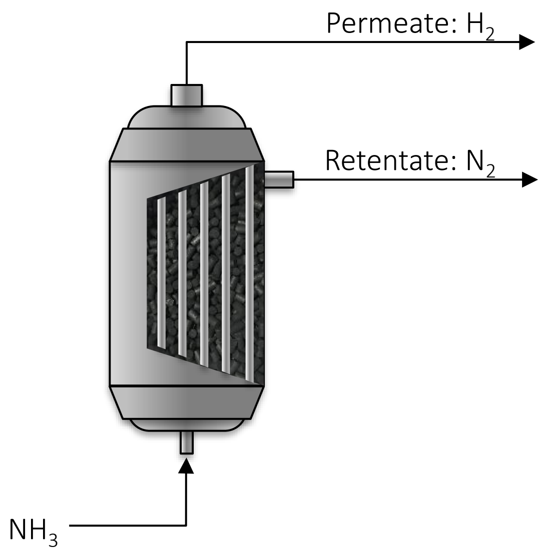


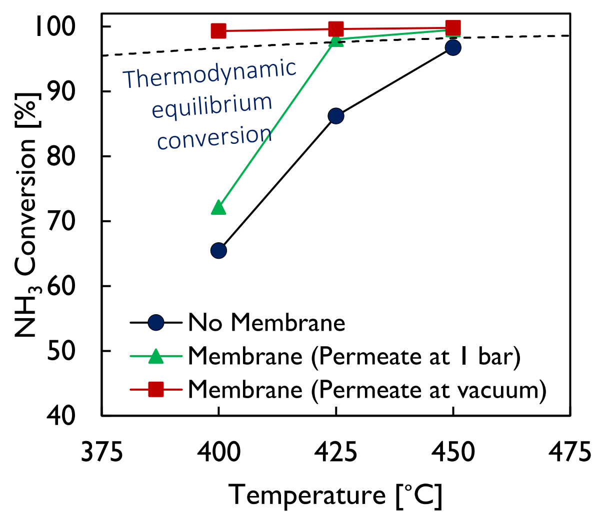


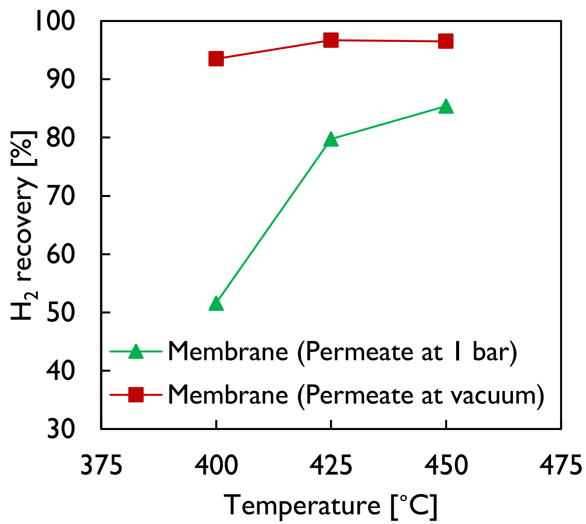


ARENHA Techno-economic assessment

Ammonia-to-Hydrogen







Experimental conditions	
ΔP [bar]	3
Permeate pressure [bar]	0.01-1
Feed flow rate [L_N/min]	0.5
Membrane	Double-skinned Pd-Ag
Thickness selective layer [µm]	~4.61

Compared to conventional systems, in a membrane reactor:

- ❑ Comparable or higher NH_3 conversion can be achieved at lower temperature (higher efficiencies)
- ❑ High-purity H_2 is recovered

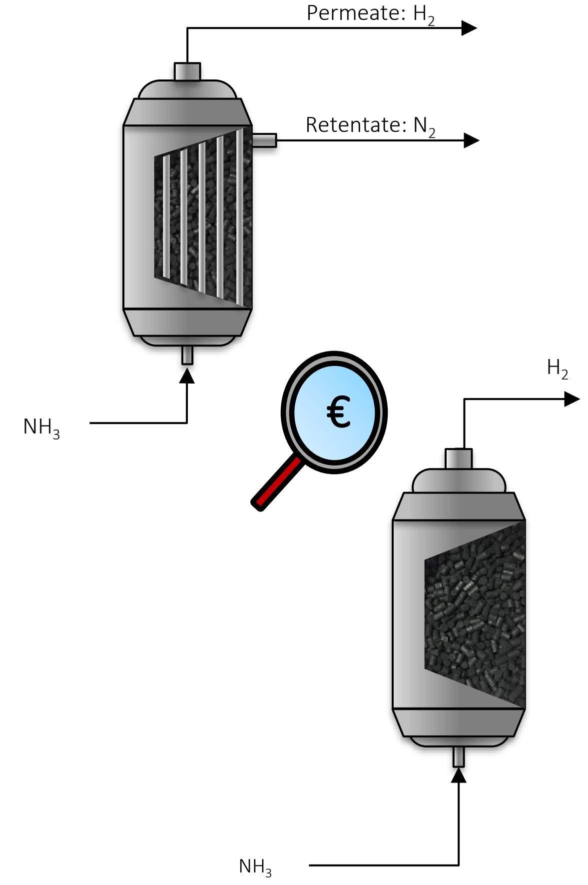
Cechetto, V.; Di Felice, L.; Medrano, J.A.; Makhloufi, C.; Zuniga, J.; Gallucci, F. H_2 production via ammonia decomposition in a catalytic membrane reactor, *Fuel Processing Technology*, **2021,** Volume 216, 106772, https://doi.org/10.1016/j.fuproc.2021.106772.

ARENHA Techno-economic assessment

Ammonia-to-Hydrogen

Is the membrane reactor-based system economically competitive compared to a conventional system?

➢ Studies available in literature calculated the costs of hydrogen production, but a comparative study addressing a techno-economic assessment at different plant capacities and system configurations is not available.



Techno-economic assessment of a decentralized plant for hydrogen production from ammonia decomposition

➢ H_2 for direct use in PEM fuel cells

➢ Applications: stationary applications (a), on-board vehicle applications (b), and refuelling stations (c)

ARENHA Techno-economic assessment

Ammonia-to-Hydrogen

Design of conventional system for green NH_3-derived hydrogen production

- H_2 production: 500 kg/day
- Final H_2 application:

1) Stationary applications (SA)
2) On-board vehicle applications (O-VA)
3) Refueling stations for vehicle applications (R-VA)

Optimization of the conventional system design

- Evaluation of operating conditions allowing for minimization of cost of hydrogen (COH)
- Evaluated reactor operating conditions: T=450-550°

Design of the MR-based system

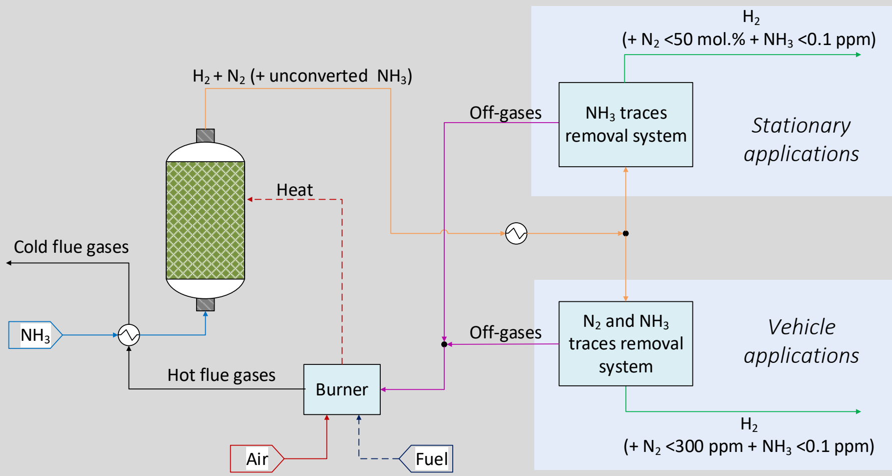
- Reactor operating conditions: $T_{MR}=T_{CR}-50°\ C$ $P_{MR}=P_{CR}$

Optimization of the MR-based system design

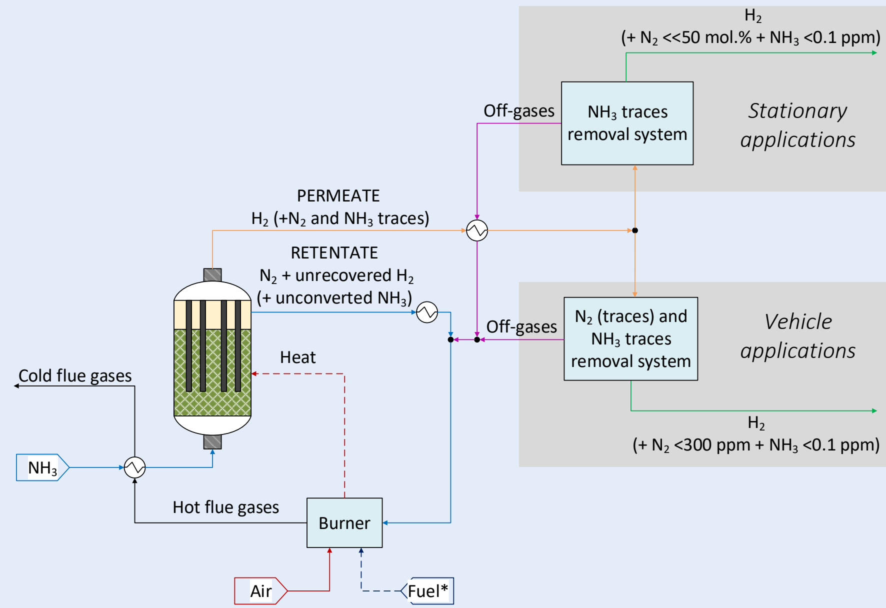
- Investigation of process parameters that optimize the COH

H_2 production from NH_3: the conventional and the MR-based systems

Conventional system



Membrane reactor-based system



Target:	*Design choices:*
➢ 500 kg/day of H_2	➢ Catalyst: Ru/Al_2O_3
➢ H_2 purity = 99.97%	➢ NH_3 removal unit: TSA (2 beds configuration)
➢ Max NH_3 concentration in H_2 stream = 0.1 ppm	➢ N_2 removal unit: PSA (4 beds configuration)

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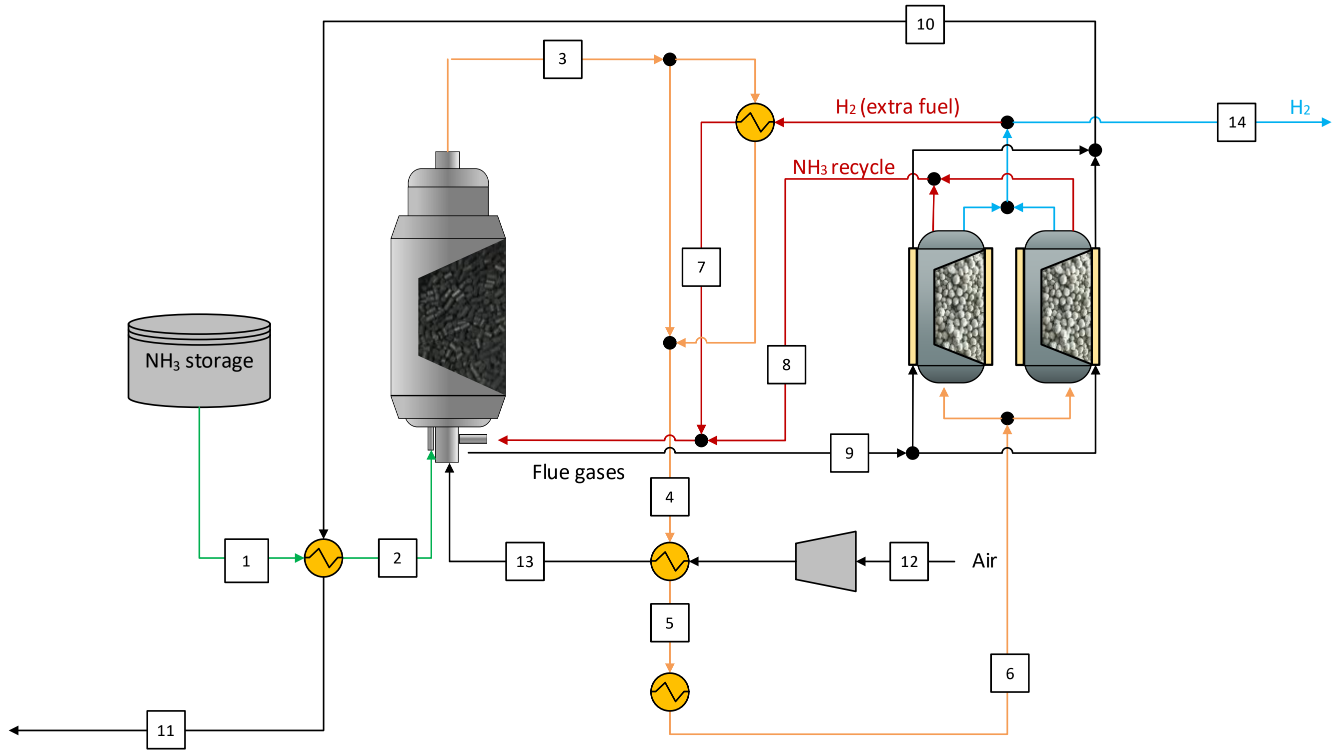
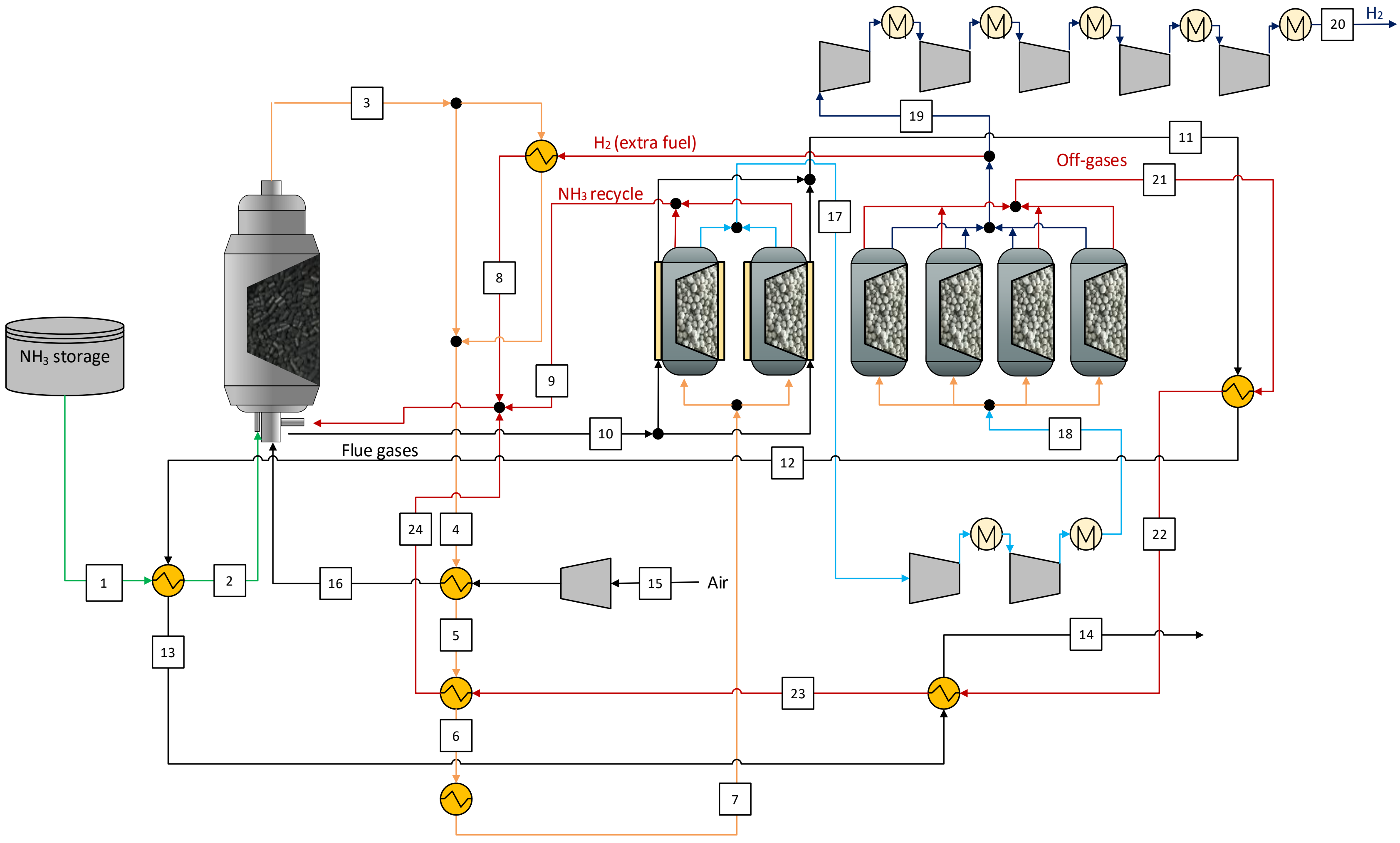
Design of the conventional process for SA

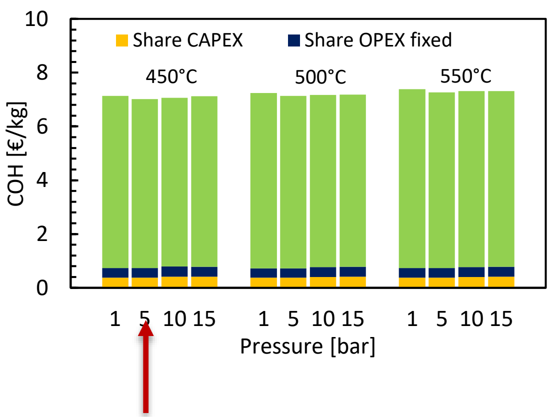


Design of the conventional process for VA

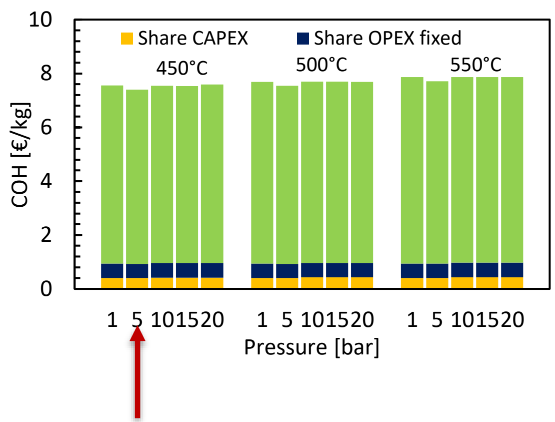


Optimization of the conventional system

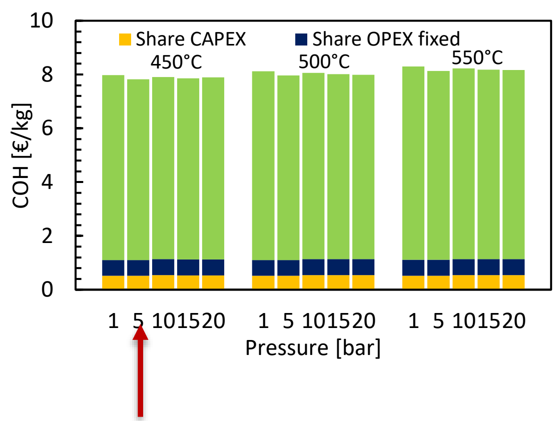
Stationary applications (SA)



On-board vehicle applications (O-VA)

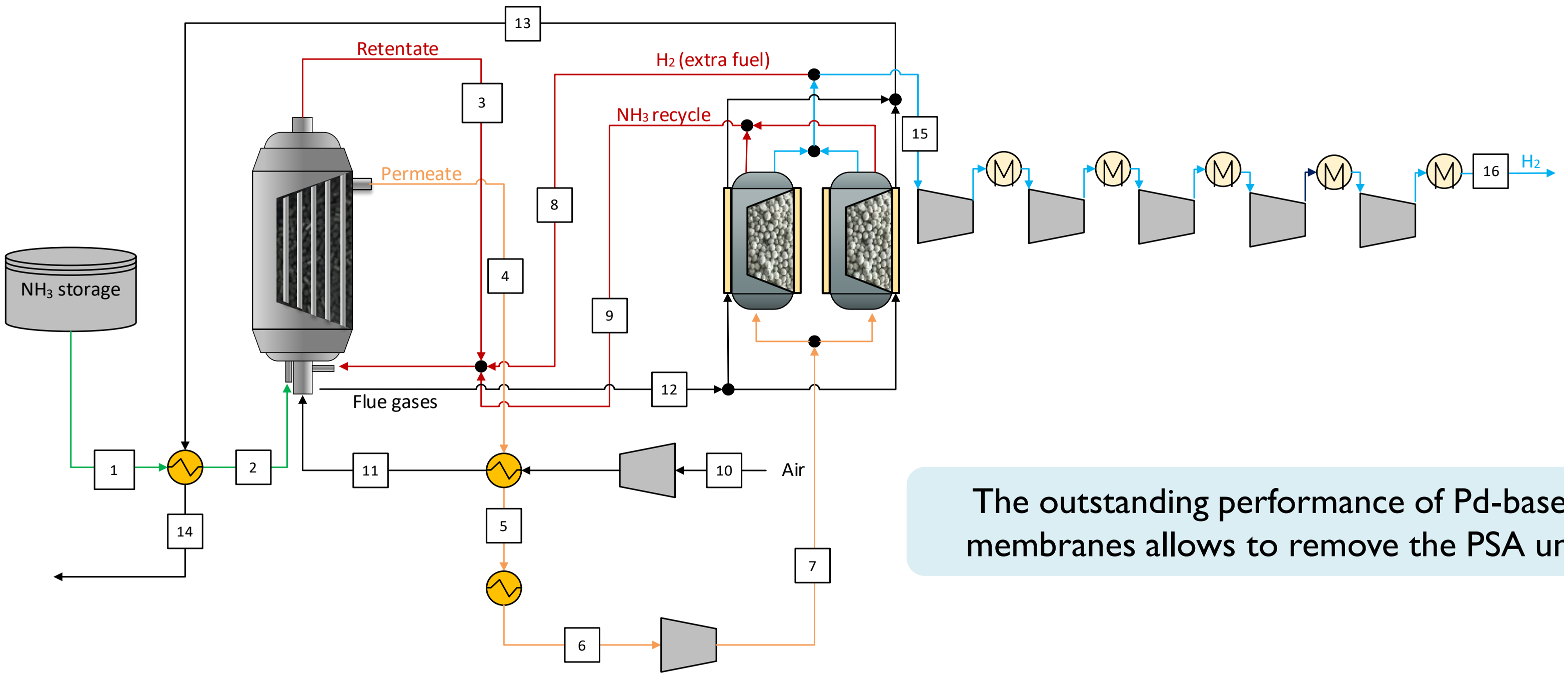


Refueling stations for vehicle applications (R-VA)



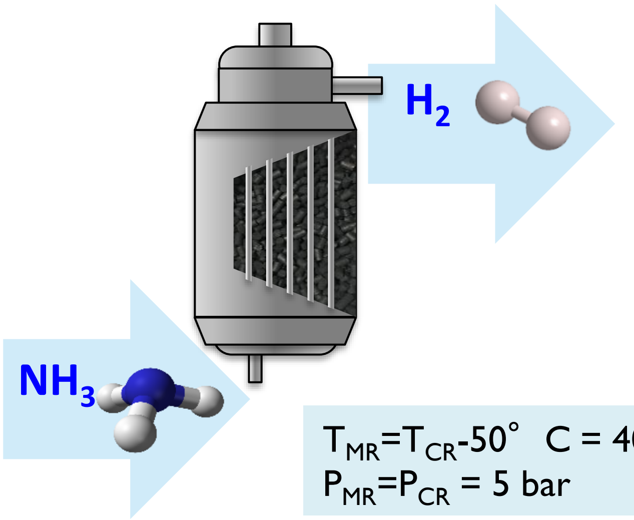
- COH in the conventional system is minimized with the reactor operated at T=450 °C and 5 bar
- The process is OPEX-intensive with the cost of the NH_3 feedstock being the main contributor to COH

Design of the MR-assisted process for SA/VA

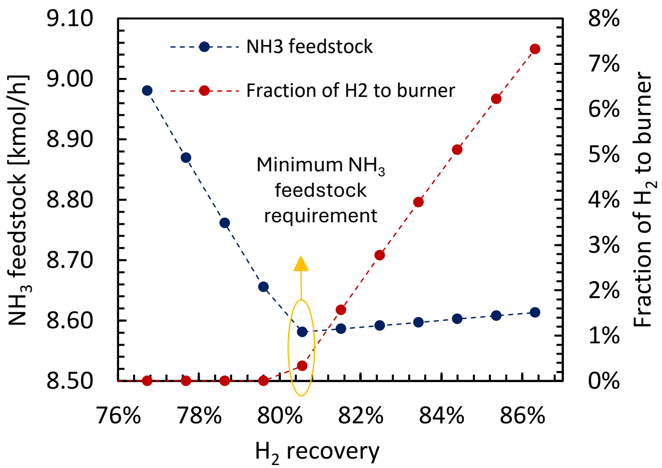


The outstanding performance of Pd-based membranes allows to remove the PSA unit

Optimization of MR-based system



$T_{MR}=T_{CR}$-50° C = 400 ° C
$P_{MR}=P_{CR}$ = 5 bar



Reactor optimization ≠ Process optimization

The cost of NH_3 feedstock is the main contributor to COH

Objective
Minimization of the NH_3 feedstock

A higher recovery reduces the available heat from the combustion of the retentate, which leads to an increased quantity of fuel that must be burned to sustain the NH_3 decomposition reaction and that, in turn, implies a greater flow rate of NH_3 to be processed.

Technical assessment

Process	Conventional			MR-assisted	
Application	**Stationary**	**Vehicle on-board**	**Vehicle refueling stations**	**Stationary and vehicle on-board**	**Vehicle refueling stations**
Feedstock					
NH_3 [kg/h]	151.03	153.46	153.46	146.15	146.15
Thermal input [kW_{LHV}]	780.50	793.09	793.09	755.27	755.27
Chemical products					
H_2 [kg/h]	20.83	20.83	20.83	20.83	20.83
Thermal output [kW_{LHV}]	693.92	693.92	693.92	693.92	693.92
Cold Gas Efficiency (CGE)	**88.91%**	**87.50%**	**87.50%**	**91.88%**	**91.88%**
Electricity					
Air blower [kW_{el}]	1.95	2.29	2.29	1.87	1.87
Hydrogen booster [kW_{el}]	-	-	28.33	19.33	37.09
Hydrogen compressor [kW_{el}]	-	-	46.04	-	45.85
Vacuum pump [kW_{el}]	-	-	-	29.69	29.69
Total electricity [kW_{el}]	1.95	2.29	76.74	50.89	114.50
Overall plant efficiency **(η_{tot})**	**88.69%**	**87.24%**	**79.78%**	**86.08%**	**79.78%**

$$CGE = \frac{\dot{m}_{H_2} LHV_{H_2}}{\dot{m}_{NH_3} LHV_{NH_3}}$$

$$\eta_{tot} = \frac{\dot{m}_{H_2} LHV_{H_2}}{\dot{m}_{NH_3} LHV_{NH_3} + \frac{Q_{el}}{\eta_{el,ref}}}$$

Economic assessment

Is the packed bed MR technology competitive compared to the packed bed conventional technology?

Scenario 1: stationary applications

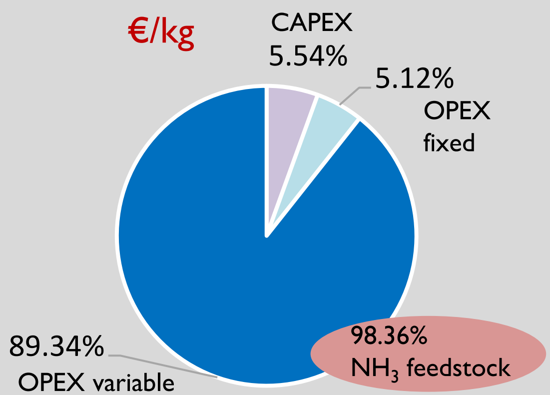
Both in the conventional and in the MR-based systems the COH is 6.95 €/kg

No economic advantage from utilization of the packed bed MR technology

Scenario 2.1: on-board vehicle applications

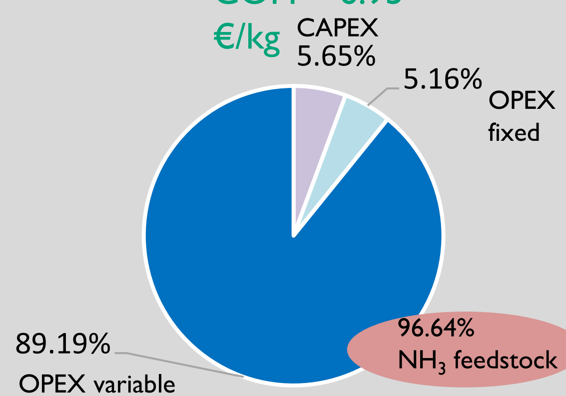
Conventional system

COH = 7.15 €/kg



MR-assisted system

COH = 6.95 €/kg

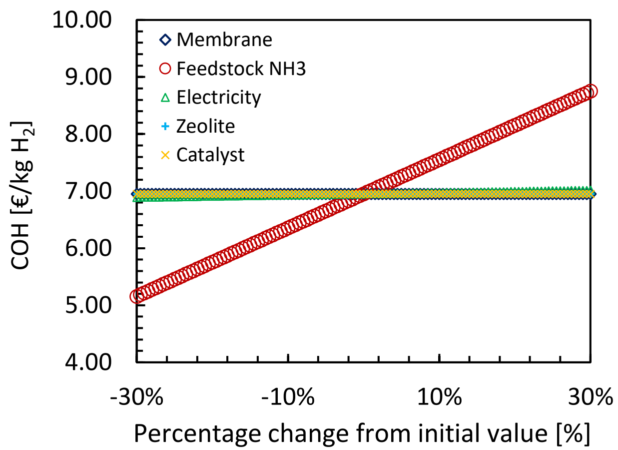


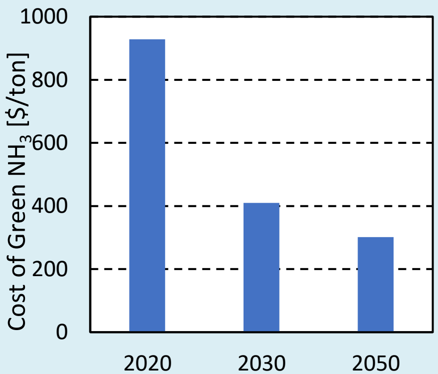
Scenario 2.2: refueling stations for vehicle applications

Similar conclusions to scenario 2.1 with $COH_{conventional}$=7.57 €/kg and $COH_{MR\text{-}assisted}$=7.38 €/kg

Economic assessment

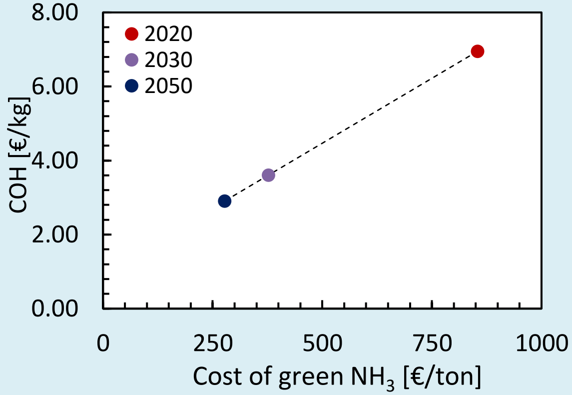
Sensitivity analysis and forecasting





https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary

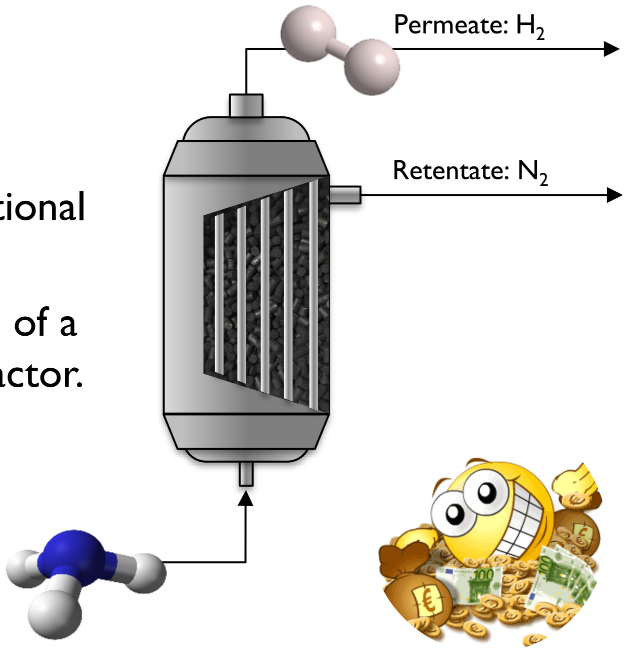
Year	Cost of NH_3 [€/ton]	COH [€/kg]
2020	853.92	6.95
2030	377.07	3.60
2050	277.30	2.90



Conclusions

In a membrane reactor for H_2 production from NH_3:

- Higher efficiency and compactness compared to a conventional system are achieved
- Fuel cell-grade H_2 production is possible with the addition of a relatively inexpensive sorption unit downstream of the reactor.



From an economic point of view, the recovery of H_2 from green NH_3 using MRs can be achieved at lower costs compared to the benchmark technology.

The MR technology holds significant potential in advancing the decarbonization of the current energy system.

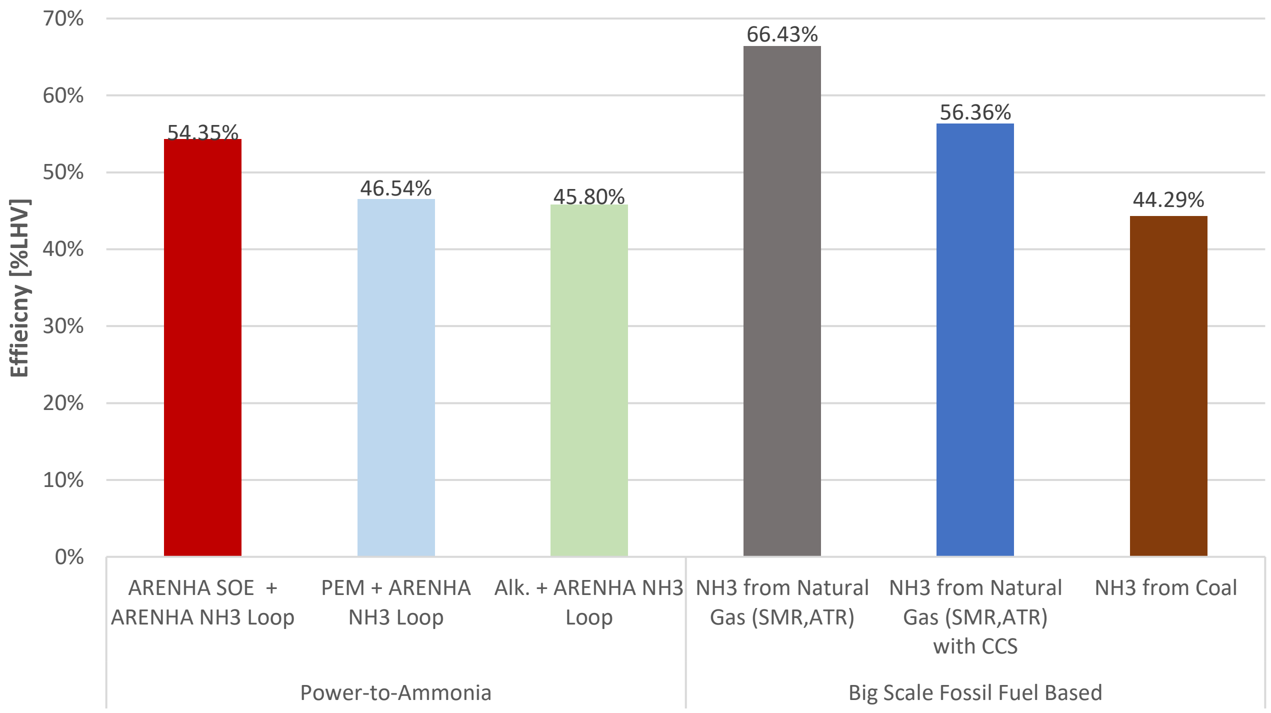
Advanced materials and Reactors for Energy storage tHrough Ammonia

areNH3a

Thank you for your attention

Website: arenha.eu/
LinkedIn: ARENHA Project
Twitter: @ARENHA_H2020

Backup Slide: Power-to-Ammonia System Efficiency



Economic assessment: Cost estimation methodology and reference operation parameters and economic assumptions

$$LCOH = \frac{(TASC_{SOE} \cdot CRF) + C_{O\&M,fixed,SOE} + C_{O\&M,variable,SOE}}{M_{H2,produced}}$$

$$LCOA = \frac{(TASC_{PtA} \cdot CRF) + C_{O\&M,fixed,SOE} + C_{O\&M,variable,PtA}}{M_{NH3,produced}}$$

Cost Estimation (AACE Class IV)	
Bare Erected Cost [k€]	
Equipment 1 Bare Erected Cost	A
Equipment 2 Bare Erected Cost	B
Equipment n Bare Erected Cost	N
Bare Erected Cost [BEC]	A+B+…+N
Direct Cost [k€]	
SOEC Stack Installation	10%BEC_SOEC
EPC	15%BEC
Contingencies and Owner's Cost [k€]	
Project Contingencies (PC)	15%BEC
Process Contingencies (PSC)	10%(BEC+EPC+PC)
Owner's Cost (OC)	20%(BEC+EPC+PC+PSC)
Total Plant Cost	
Total Plant Cost (TASC)	1.1*(BEC+EPC+PC+PSC+OC)

Economic Assumptions	
Plant Operation (n)	30 years
Discount rate	7%
SOEC Stack Cost [€/kW]	300 (IKTS) – 500 (Elcogen)
SOEC Stack Installation Factor [€/kW]	40

Cost Fixed O&M	
Maintenance (SOE) [€/kg/d]	130
Maintenance (Others)	3%TOC

Cost Variable OPEX	
Electricity	50 €/MWh
Absorbent Cost	0.9 €/kg
Catalyst Cost	30 €/kg
Utilities (Refrigerant 5°C)	3.57 €/GJ
Process Water	0.23 €/m3

Electrolyser Operation		
Cell Technology	**CSC (Elcogen)**	
Nominal Temperature [°C]	680	800
Cell Current Density [A/cm2]	0.50	0.6
Cell Voltage [V]	~1.32	~1.29
Reactant Utilisation	70%	75%
Module Size [kW]	~530	~520
Stack Lifetime [hours]	40000	40000

PSA Operation	
Energy Consumption	0.6 GJ/ton

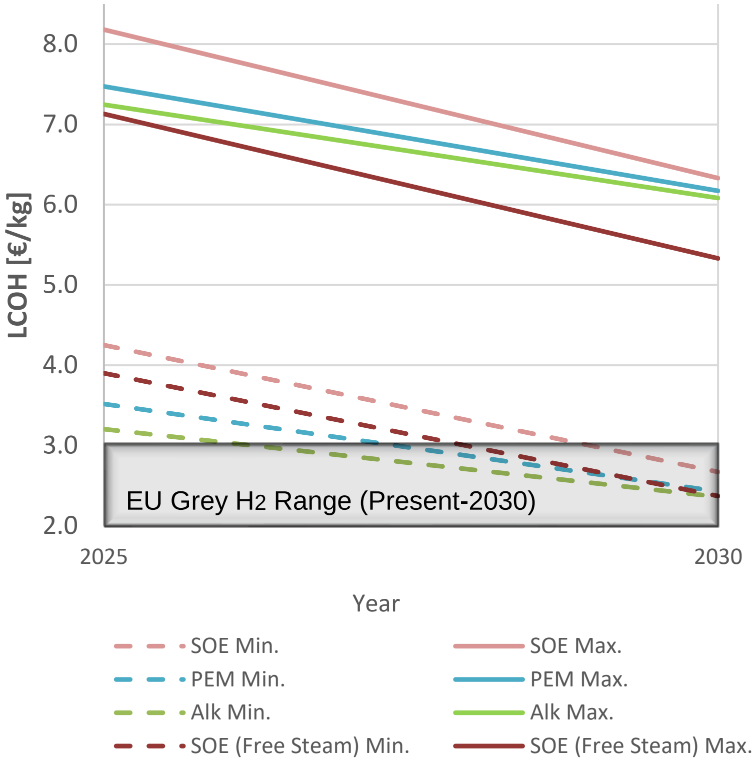
H2 Storage Operation	
Nominal Pressure	100 bar

Ammonia Synthesis Loop Operation	
Nominal Reactor Pressure	80 bar
Reactor Inlet Temperature	300 °C
Catalyst Type	Fe-Based (Wu)
Absorbent Type	36% $MnCl_2$ – 64% Silica Gel

NH3 Storage	
Storage Capacity	30 Days

ARENHA Techno-economic assessment

Backup Slide: Detailed assumption of electrolysis scenario analysis



Scenario	2025				2030			
Electrolysis Technology	**Alk**	**PEM**	**SOE**	**SOE (free steam)**	**Alk**	**PEM**	**SOE**	**SOE (free steam)**
Installed Electrolysis Power [MW]	24.2	23.7	15.9	15.9	140	140	100	100
Hydrogen Production [t/d]	11.15				70.00			
Tot. CAPEX* [€/kW] [2]	2000	2450	4020	3921	1250	1400	2052	1980
Stack Lifetime [khr]	80	50	40		80	80	40	
O&M [€/(kg/d*y)] [1]	43	30	130		35	21	45	
Stack Replacement Cost [€/kW]	195	255	300		130	170	100	
System Energy Consumption [kWh/kg$_{H2}$]	**52**	**51**	**49.85**	**41.10**	**48**	**48**	**47.85**	**39.10**

Electrolyzers operated with 60% year average capacity factor. Min and Max. refer respectively to 25 and 100 €/MWh electricity cost scenario. 30 years plant lifetime and 7% WACC assumed. PEM and Alk. stack degradation [1]. PEM Alk and SOEC O&M from [1]. PEM and Alk. CAPEX and stack cost from STEPS scenario in [2]. 2025 PEM system energy consumption from [3], 2025 Alkaline system energy consumption from [4]. 2030 System energy consumption scenarios from [1].

*CAPEX is calculated per kW of installed electrolysis power: Stack energy consumption for Alk. and PEM assumed close to total system energy consumption.
O&M: Operation and Maintenance | **Alk:** Alkaline electrolyser **| PEM:** Proton exchange membrane electrolyzer | **SOE**: Solid Oxide Electrolyzer

[1]. Clean Hydrogen JU - SRIA Key Performance Indicators (KPIs) - Clean Hydrogen Partnership
[2]. IEA, Global Hydrogen Review, 2024
[3]. Cummins Hylizer specsheet, 2021
[4]. Sunfire-Hylink Alkaline specsheet, 2025

Despite higher cost greater efficiency makes SOE potentially competitive with low-T electrolysis technologies (especially with high electricity prices!)

ARENHA Techno-economic assessment

Ammonia-to-Hydrogen

$$COH = \frac{(TOC \cdot CCF) + C_{O\&M,fixed} + C_{O\&M,variable}}{Capacity \cdot Plant\ availability}$$

Plant Component	Cost [k€]
Component W	A
Component X	B
Component Y	C
Component Z	D
Bare Erected Cost [BEC]	A+B+C+D
Direct costs as percentage of BEC	
Total Installation Costs [TIC]	80% BEC
Total Direct Plant Cost [TDPC]	BEC+TIC
Indirect Costs [IC]	14% TDPC
Engineering procurement and construction [EPC]	TDPC+IC
Contingencies and owner's costs	
Contingency	10% EPC
Owner's cost	5% EPC
Total contingencies & OC [C&OC]	15% EPC
Total Overnight Cost [TOC]	EPC+C&OC

$$C_i = C_0 \cdot \left(\frac{S_i}{S_0}\right)^n \cdot F_p \cdot F_m \cdot F_T \cdot \frac{CEPCI}{CEPCI_{reference\ year}}$$

Cost O&M fixed	
Maintenance	2.5% TOC
Insurance	2% TOC
Labor	27991 €/year/pp [1]

COST O&M variable	
Green NH_3	853.92 €/ton [2]
Electricity	0.085 €/kWh [3]
Catalyst	143 €/kg [3]
Zeolite 13X	43.7 €/kg [4]
Membrane	6000 €/m [3]

Assumptions	
Plant availability	90%
Plant lifetime (n)	25 years [3]
Catalyst lifetime	5 years [3]
Lifetime Zeolite 13X	5 years
Membrane lifetime	5 years
Discount factor (i)	8% [3]

$$CCF = \frac{(i+1)^n}{((i+1)^n - 1)}$$

[1] https://www.payscale.com/research/NL/Job=Chemical_Process_Operator/Salary
[2] https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary
[3] S. Richard, A. Ramirez Santos, and F. Gallucci, "PEM genset using membrane reactors technologies An economic comparison among different e-fuels", International Journal of Hydrogen Energy
[4] https://www.msesupplies.com/products/1kg-molecular-sieves-13x-pellets-spheres?variant=31758805205050

Technical assessment

	Conventional process Stationary applications	Conventional process Vehicle applications	MR-assisted process Stationary and vehicle applications
Reactor operating conditions			
Reaction temperature [°C]	450	450	400
Reaction pressure [bar]	5	5	5
Permeate pressure [bar]	-	-	0.1
Feedstock			
NH_3 flow rate at reactor inlet	151.03 kg/h 8.87 kmol/h	153.46 kg/h 9.01 kmol/h	146.15 kg/h 8.58 kmol/h
Energy requirement			
Thermal input [kW]	127.51	129.58	123.72
KPI			
NH_3 conversion	97.8%	97.8%	99.1%
H_2 recovery	-	-	80.6%
Reactor efficiency ($\eta_{reactor}$)	96.2%	96.2%	79.2%* (97.4%**)
$\eta_{NH_3\ to\ H_2}$	5.8 kg/kg	5.8 kg/kg	7.0 kg/kg* (5.7 kg/kg**)

* Calculated considering as valuable reaction product only hydrogen available at the reactor's permeate side

** Calculated considering as valuable reaction product both the hydrogen available at the reactor's permeate and retentate sides

$$\eta_{reactor} = \frac{\dot{m}_{H_2} LHV_{H_2}}{\dot{m}_{NH_3} LHV_{NH_3} + W_{in}}$$