# Advanced materials and Reactors for Energy storage tHrough Ammonia

# ARENHA

areNH3a

https://arenha.eu/

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*Duration: Four and a half years. Starting date: 01 April 2020*

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# Index

# 1. Introduction

Nowadays, mankind is facing two of the most difficult challenges in its life:

- global warming and associated climate changes

- local pollution of urban areas.

# 1. Introduction

## Energy production 21st Century

- Majority from fossil fuel derivatives (carbon based): Currently, more than 80% of global primary energy use is fossil based. Over the last decade, 85% of the increase in global use of energy was fossil based.
- $CO_2$ production

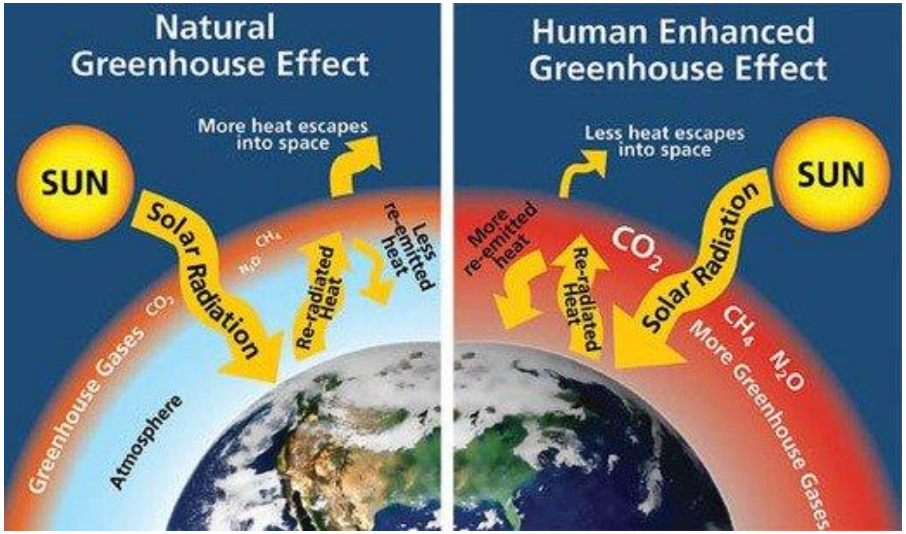
## Greenhouse gasses

- **Effect**

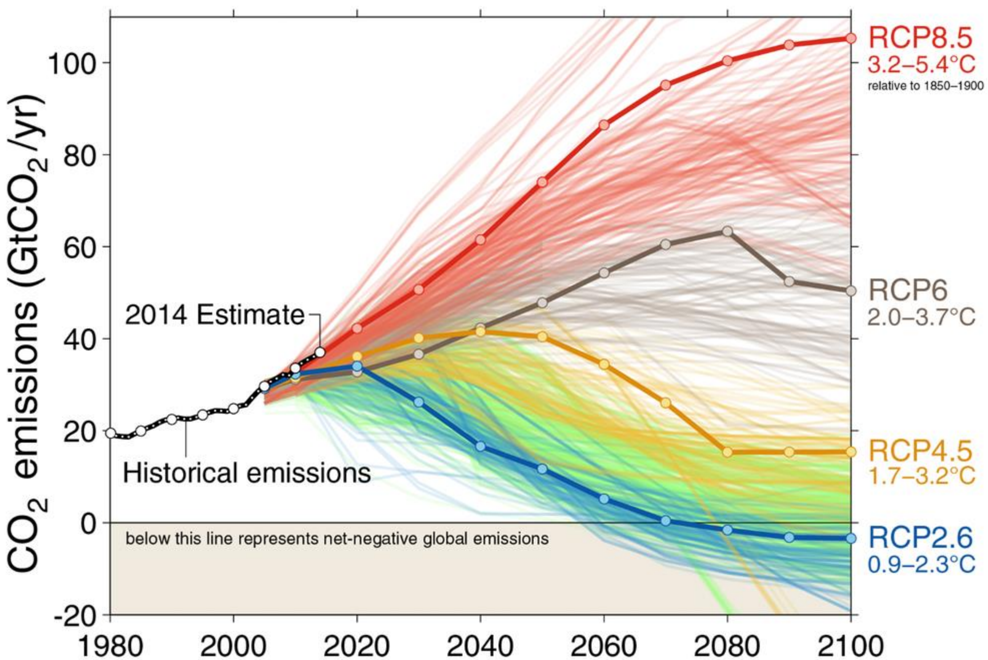
  Trap IR-radiation (heat)

- **Emission $CO_2$**

  Natural & human activity



# 1. Introduction




Global carbon dioxide emissions from human activity, compared to four different possible futures as depicted in IPCC scenarios. Fuss et al. 2014

The EU Commission's Low Carbon Roadmap (and the world climate contract) suggest a reduction of >80% of $CO_2$ emissions by 2050 compared to levels at the beginning of the 21st century.

**2018: 37,1 $GtCO_2$**
**(www.globalcarbonproject.org)**

Transition process requires a new energy system without C at the end with radical technical solutions and infrastructure investments.

13 CLIMATE ACTION

Climate Action in the UN's Sustainable Development Goals (SDGs): Limiting global warming to 1.5°C (https://www.ipcc.ch/sr15/)

# 1. Introduction

**Greenhouse gases. Reduce emissions to environment.**

- Increasing Energy efficiency;
- Carbon Capture, Utilizations and Storage
- Low carbon processes
- Net-negative global emission
- Search for renewable energy carrier: Hydrogen,……
- …..

**European Green Deal:** Set of policy initiatives by the European Commission with the overarching aim of making Europe climate neutral in 2050.

- Maximise the deployment of renewables and the use of electricity to fully decarbonize Europe’s energy supply.
- Increase renewable energy to at least 32% of the EU's final energy consumption by 2030
- By 2050, more than 80% of electricity will be coming from renewable energy sources.

# 1. Introduction

- Renewable energy is playing an important role in addressing some of the key challenges facing today's global society, such as the cost of energy, energy security and climate change.
- Energy storage is crucial for overcoming the inherent intermittency of renewable resources and increasing their share of generation capacity.
- Sustainable energy production can only work well when the specific different energy storage challenges are solved: provide the required capacity for grid-scale energy storage.
- Batteries may not be the best solution to face all energy storage needs, due to cost, safety and environmental issues.
- Pumped hydro and methods such as compressed gas energy storage suffer from geological constraints to their deployment.

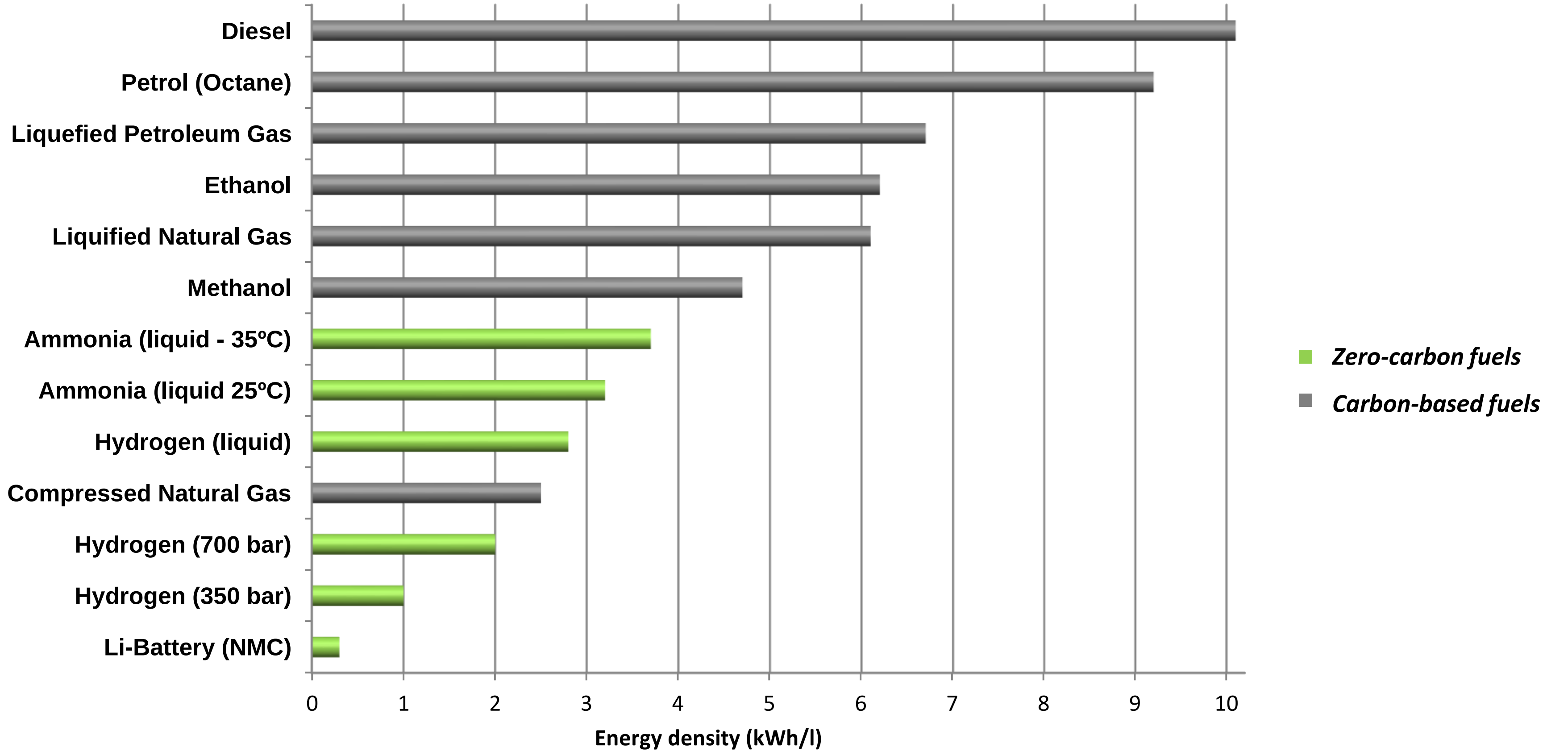
# 1. Introduction

- Non battery-based storage technology, such as Power-to-X technologies (Power-to-Gas, Power-to-Chemicals, Power-to-Liquids) that allows transforming renewable electricity into synthetic gases (hydrogen, methane or other gases) and chemicals/liquids, can be suitable solutions for different energy storage needs.

- The only sufficiently flexible mechanism allowing large quantities of energy to be stored over long time periods at any location is chemical energy storage: via hydrogen or carbon-neutral derivatives

# 1. Introduction

The volumetric energy density of a range of fuel options.



# 2. Objective

- The ARENHA project aims at using ammonia as a green hydrogen carrier and for that purpose it develops its main activities around the green hydrogen production, ammonia synthesis, ammonia storage and ammonia dehydrogenation.

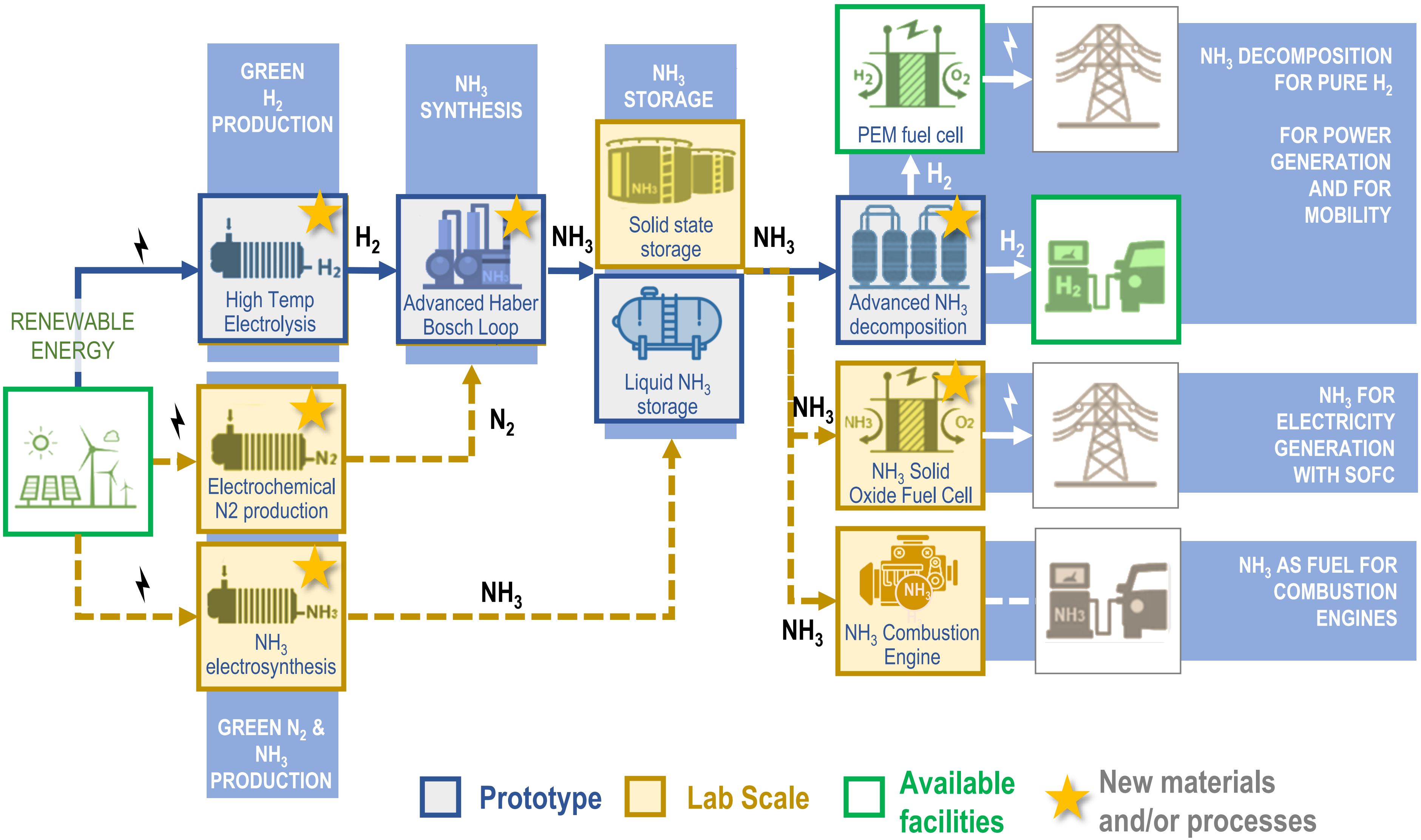
Duration: 4 years
H2020 funding 5,7 M€ approx.

- ARENHA main goal is to develop, integrate and demonstrate key material solutions enabling the flexible, secure and profitable storage and utilization of energy under form of green ammonia.

- ARENHA will demonstrate the full power-to-ammonia-to-usage value chain at TRL 5 and the outstanding potential of green ammonia to address the issue of large-scale energy storage.

# 2. Objective

Power-to-ammonia-to-usage value chain in ARENHA



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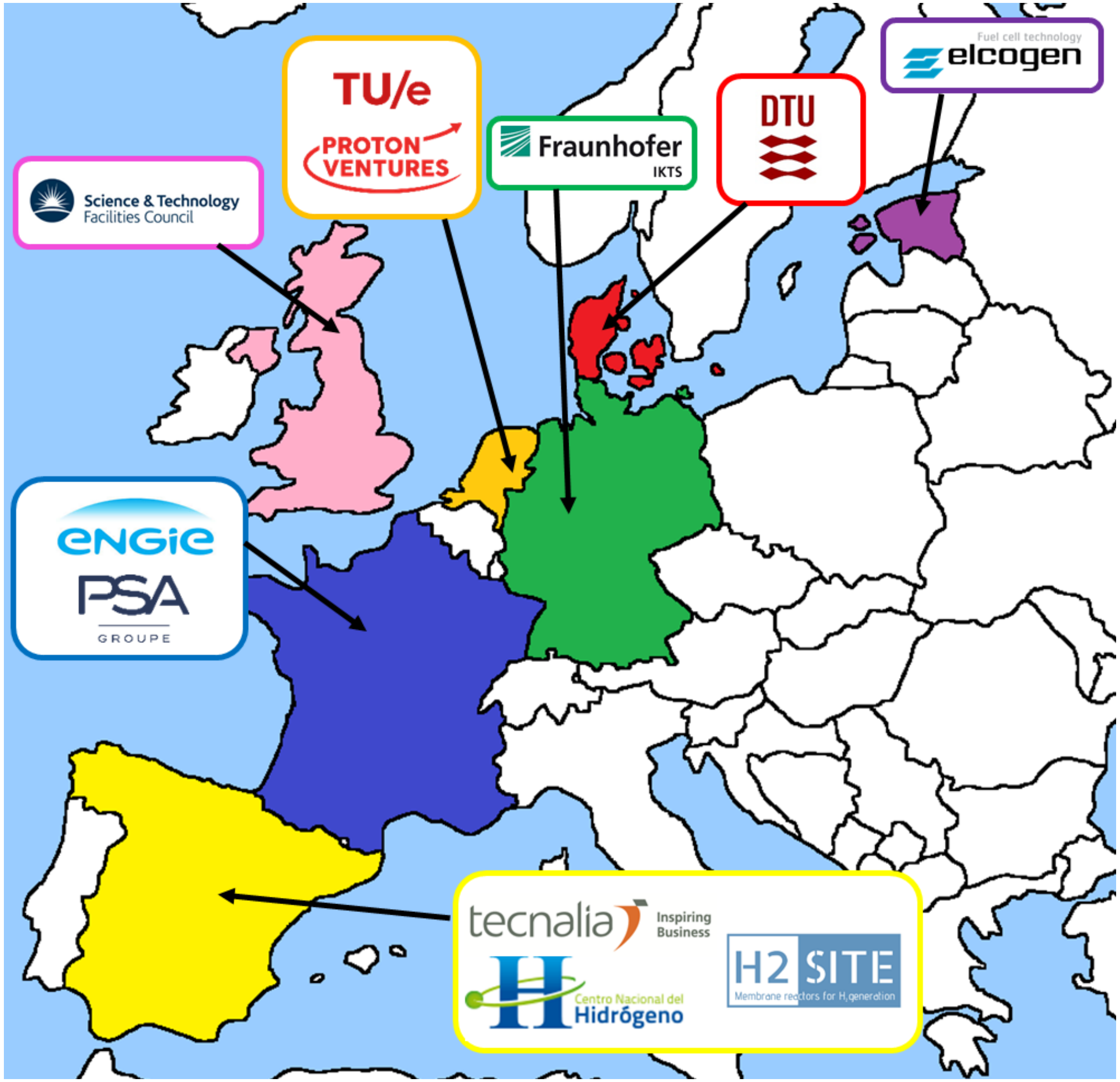
# 3. Partnership




- Multidisciplinary and complementary team.
- 11 partners in 7 countries.
- Industrial oriented (45%):

  5 SME/IND + 6 RTO/HES
- 3 SMEs & 2 IND

# 3. Partnership

Coordinator

tecnalia Inspiring Business

Universities

TU/e

DTU

Research institutions

tecnalia Inspiring Business

Centro Nacional del Hidrógeno

Fraunhofer IKTS

Science & Technology Facilities Council

Industries

PROTON VENTURES

Fuel cell technology elcogen

H2 SITE Membrane reactors for $H_2$ generation

PSA GROUPE

ENGIE

# 4. Overall approach

## GREEN HYDROGEN PRODUCTION

### Material development and scale up

**SOEC cells and stacks**

Fraunhofer IKTS; elcogen (Fuel cell technology)

### Prototype manufacturing

**SOEC stack modules and BoP**

Fraunhofer IKTS; elcogen (Fuel cell technology); Centro Nacional del Hidrógeno

### Process, Quality Control & Recyclability

**Process Control:**

- **Flexibility**
- **H2 productivity and purity**
- **Efficiency**
- **Safety**

**Product Control & Reciclability:**

- **Cell materials**
- **Stacks & stack modules**

Fraunhofer IKTS; elcogen (Fuel cell technology); Centro Nacional del Hidrógeno

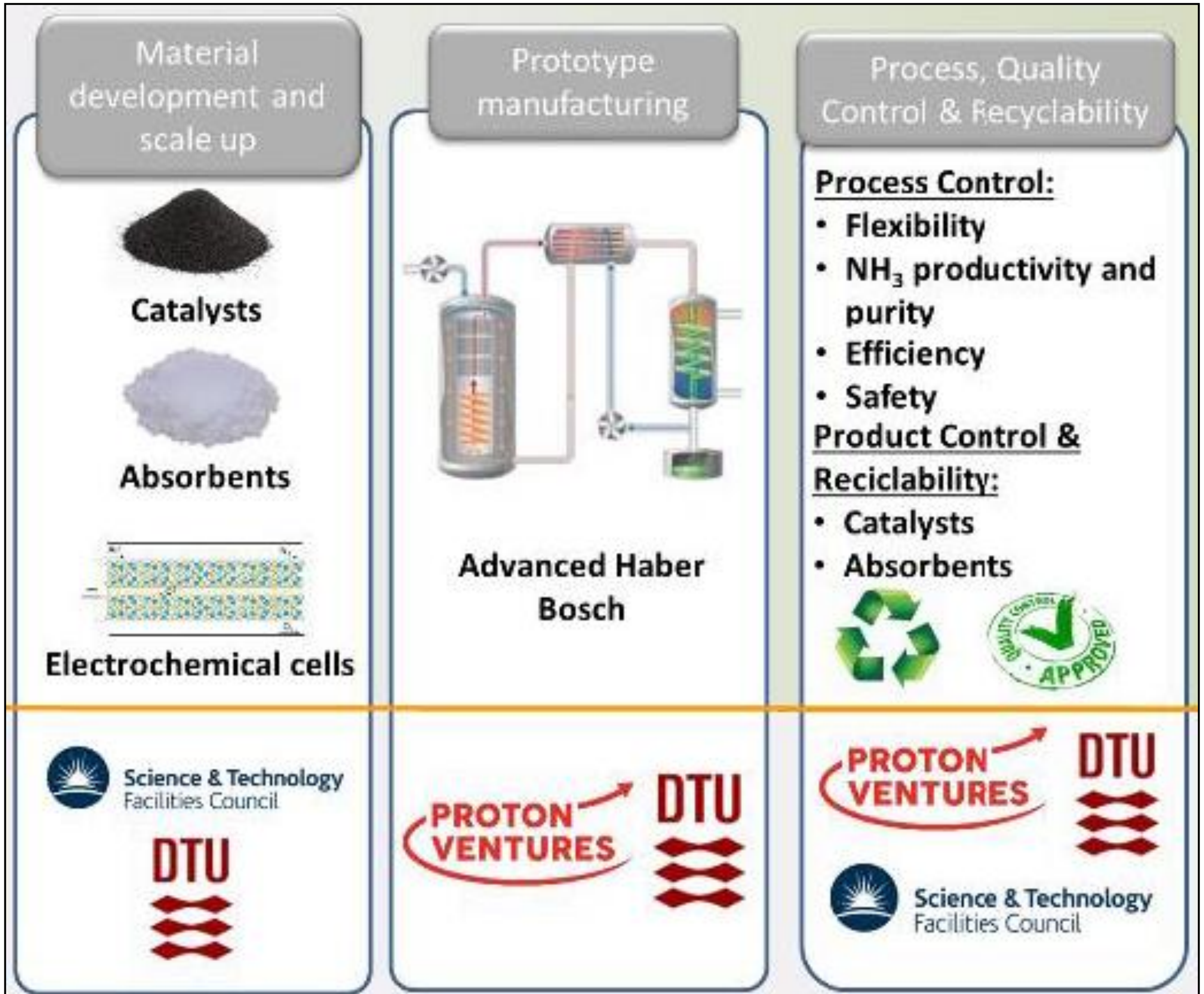
### Benchmarking of novel technologies

**Battolyzer**

PROTON VENTURES

# 4. Overall approach

AMMONIA SYNTHESIS

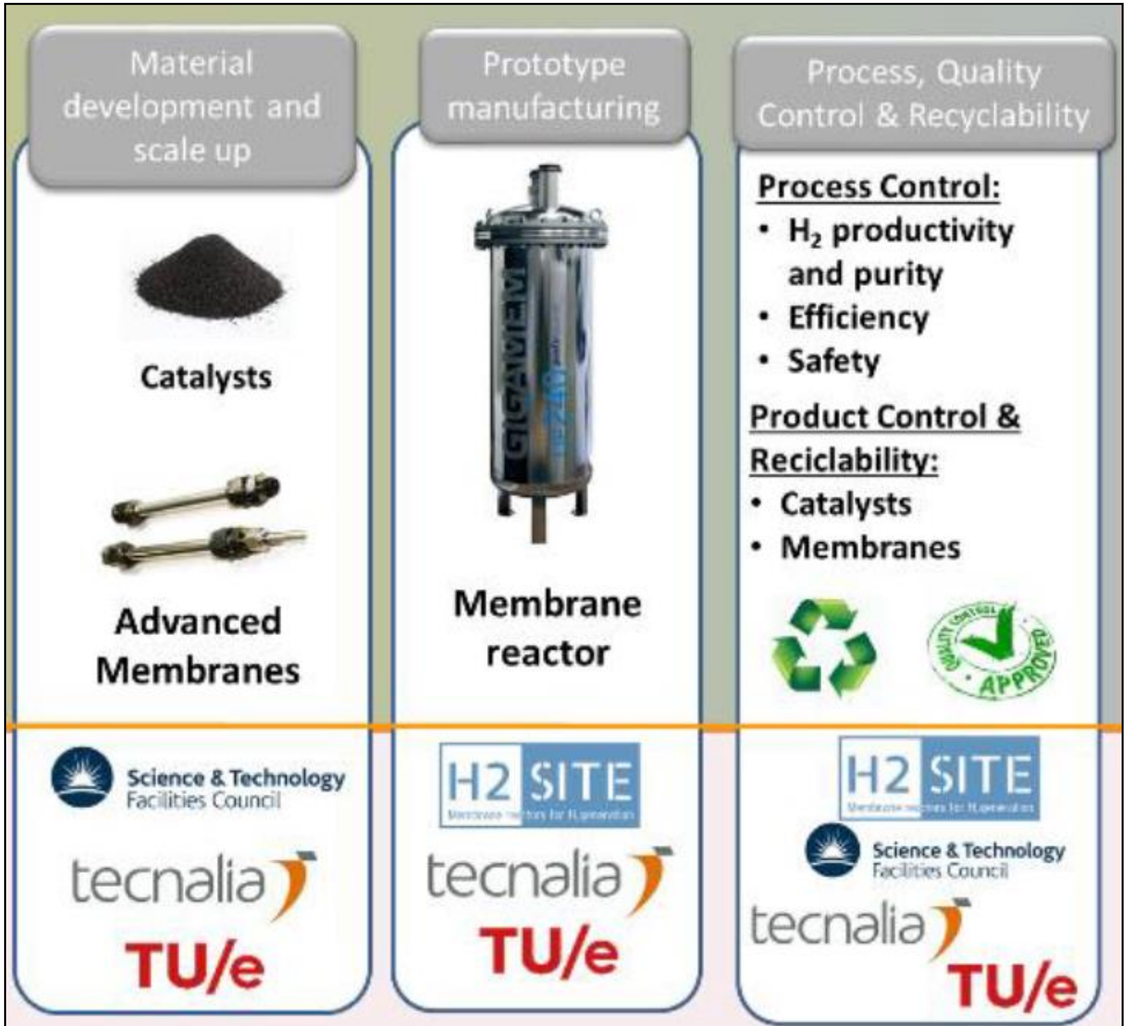


# 4. Overall approach

## AMMONIA STORAGE

# 4. Overall approach

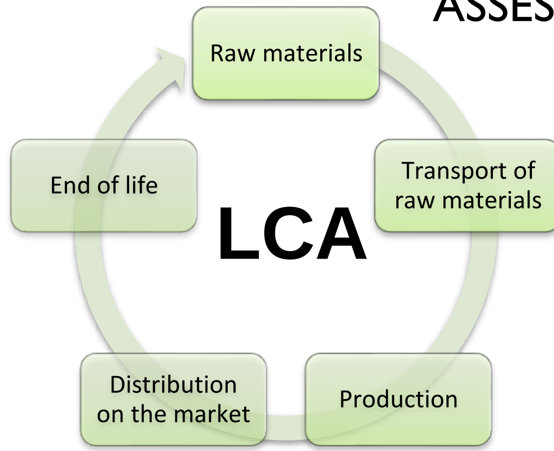
## AMMONIA DECOMPOSITION



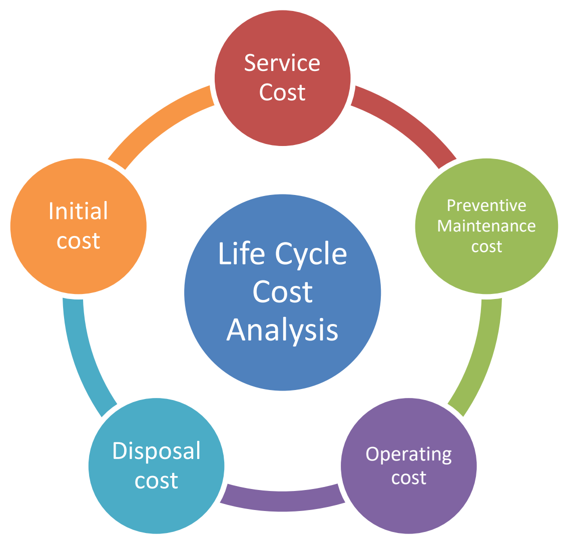
# 4. Overall approach

## AMMONIA USAGE


## ENVIRONMENTAL LCA, ECONOMY AND SAFETY ASSESSMENT

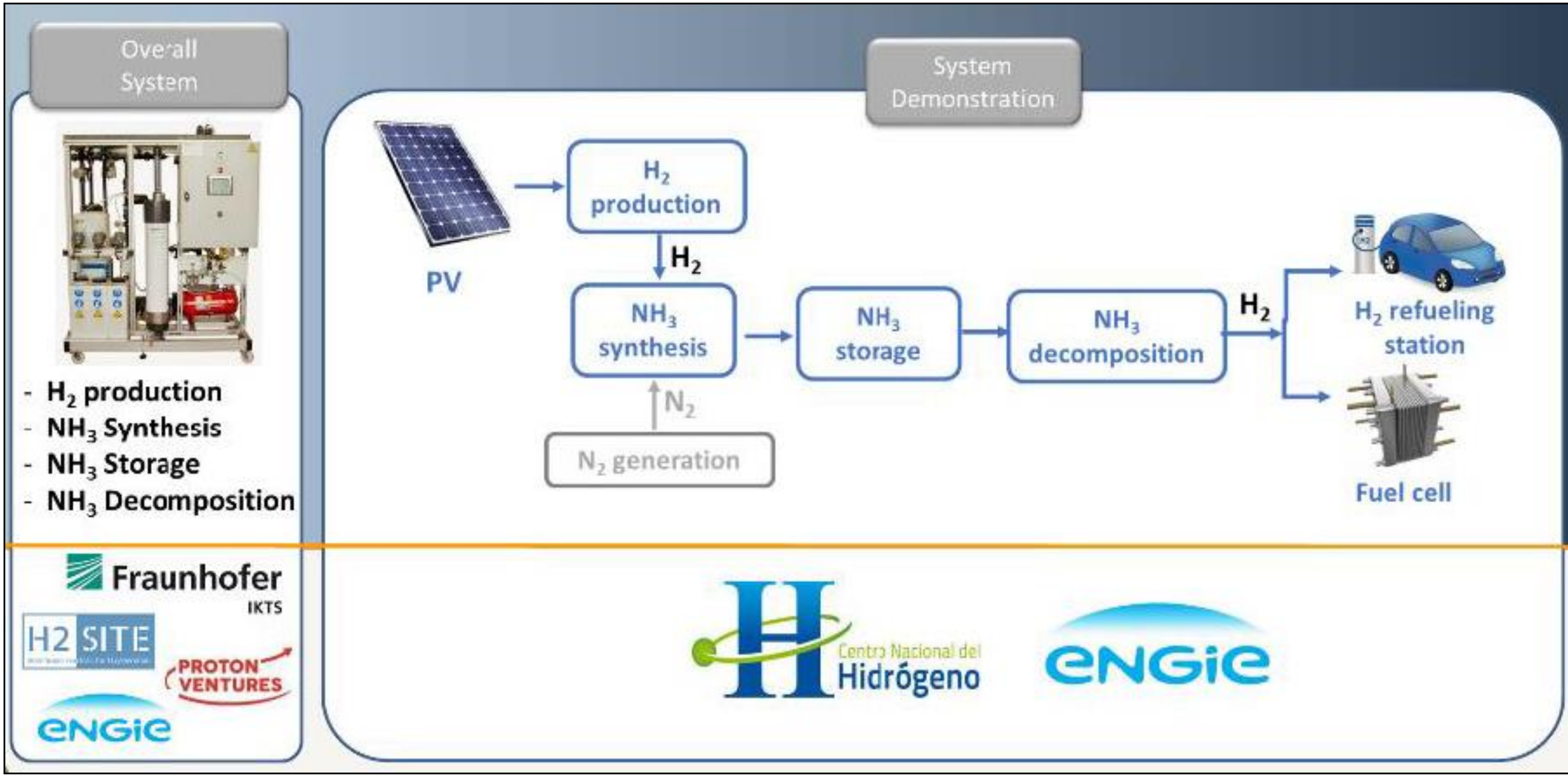






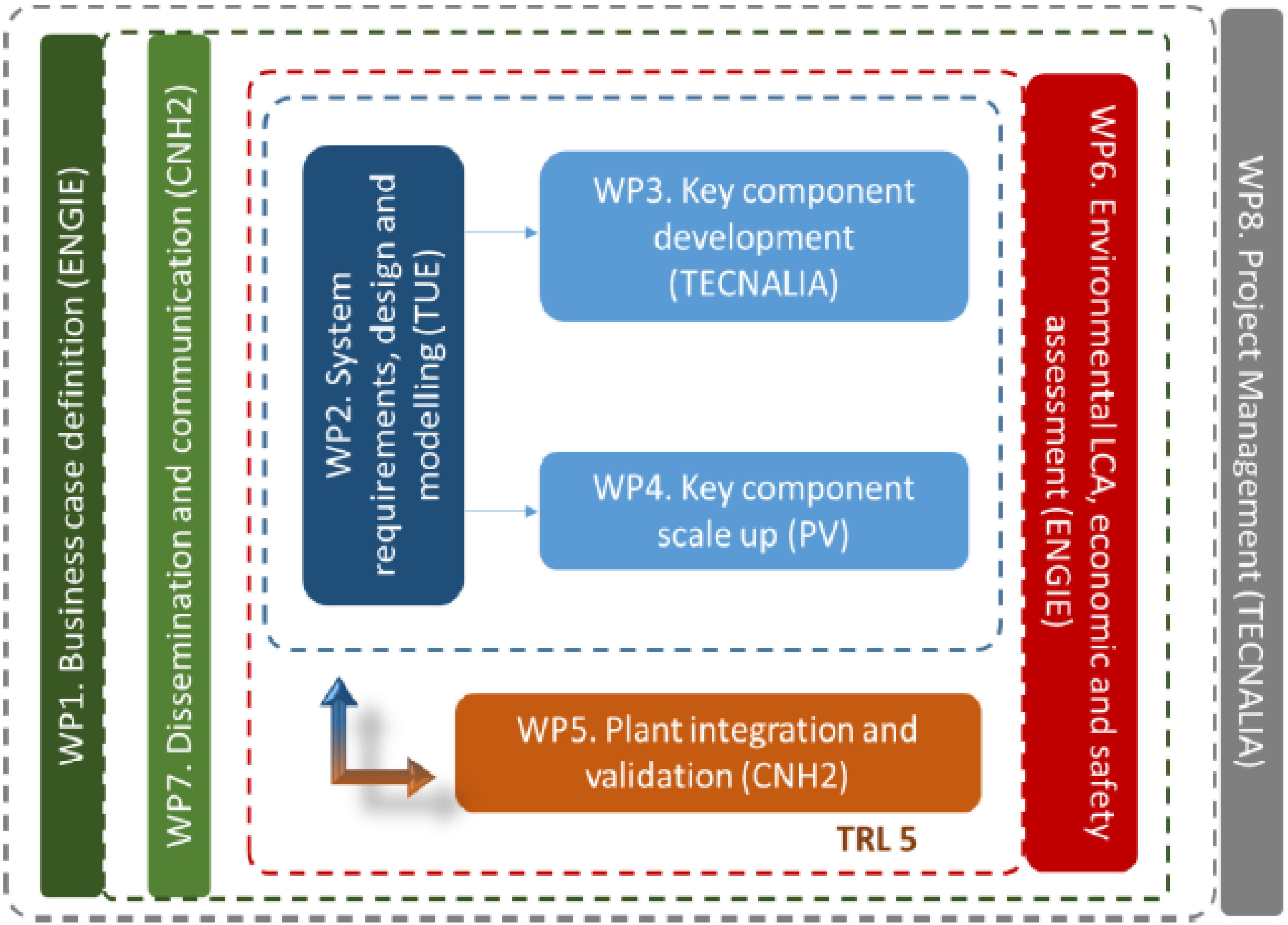
# 4. Overall approach

## SYSTEM INTEGRATION AND DEMONSTRATION




Demonstrate the full power-to-ammonia-to-usage value chain at TRL 5.

# 5. Project Structure and planning



# 6. Progress: WP1

## Business case definition

- Market and stakeholder analysis assessed
- Preliminary business model identified
- Preliminary commercialization & market strategy ongoing
- IPR protection and agreements ongoing

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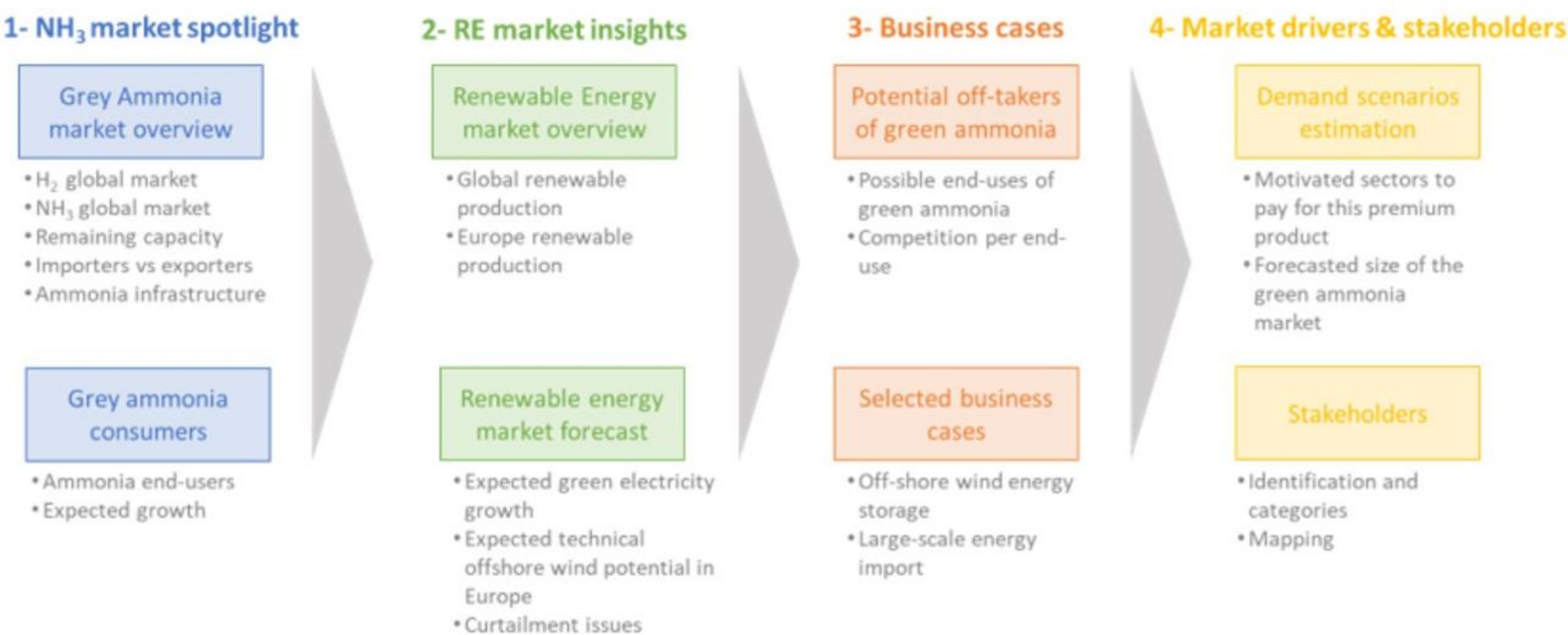
# 6. Progress: WP1

## Business case definition

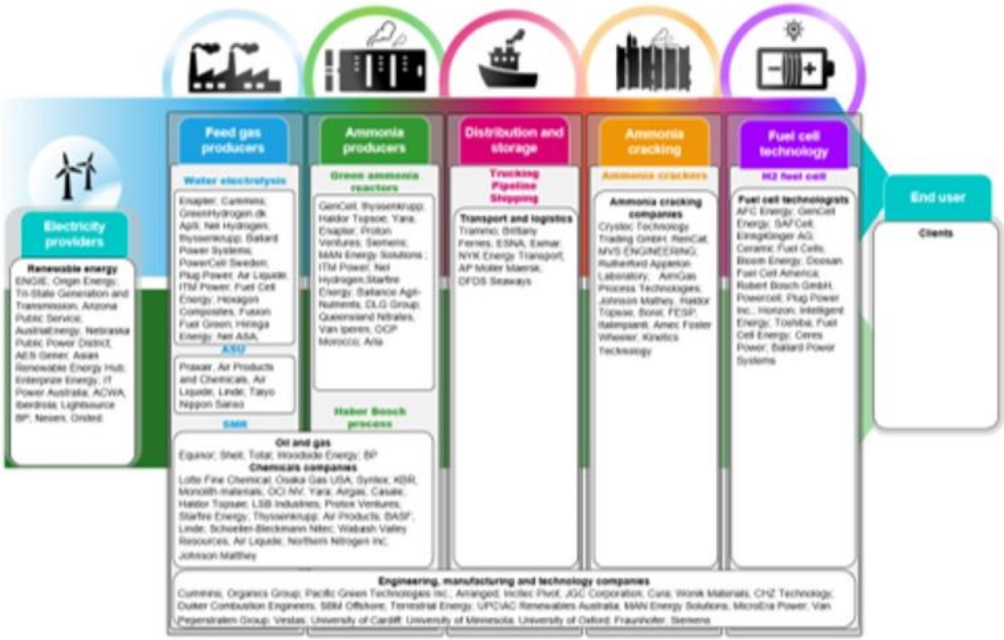
- Market and stakeholder analysis focused on the present and expected markets considering ammonia production, transport and storage.



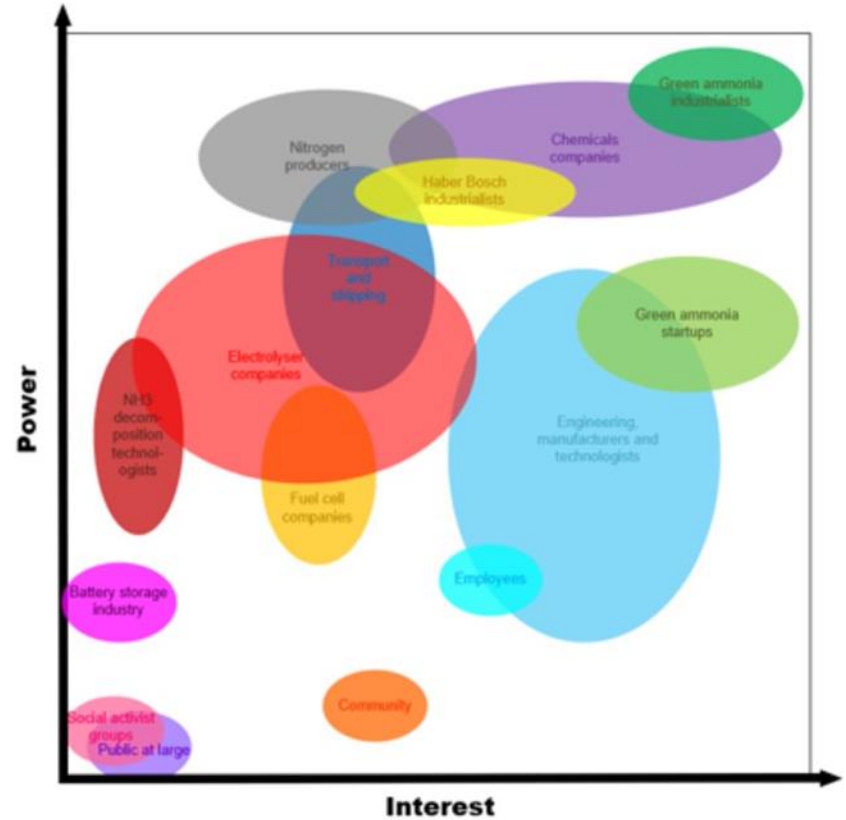

- Potential offtakes of green ammonia included the fertilizer industry, power generation, land transport sector and maritime sector.

## Business case definition

- Stakeholder mapping was carried out by estimating the power and the interest of stakeholders




Supplier stakeholder groupings along the ammonia value chain




Stakeholder mapping

- Many stakeholders belong to multiple stakeholder categories. This was mostly the case for large companies, whose activities encompass multiple stages of ammonia value chain.

# 6. Progress: WP1

## Business case definition

- Identification and assessment of the possible exploitable results develop in the frame of the ARENHA project

| Nº | Exploitable Result |
|---|---|
| 1 | Ammonia based energy storage system |
| 2 | Advanced Electrolyte Supported Cell SOEC electrolyser for renewable hydrogen production |
| 3 | Advanced Anode Supported Cell SOEC electrolyser for renewable hydrogen production |
| 4 | Elcogen stack module |
| 5 | Advanced ammonia synthesis unit |
| 6 | Advanced ammonia decomposition membrane reactor using DS Pd-based membranes |
| 7 | Carbon molecular sieve membranes selective to $NH_3$ in gas mixtures of $NH_3$ with $H_2$ and/or with $N_2$. |
| 8 | System to produce ultrapure hydrogen from ammonia |
| 9 | Advanced Pd-based membranes for hydrogen purification |
| 10 | Carbon molecular sieve membranes for hydrogen purification |
| 11 | Software tools (Membrane reactor design) |
| 12 | Consulting services on LCA for ammonia energy storage and supply system |
| 13 | Electrochemical $N_2$ production |
| 14 | Ammonia electrosynthesis |
| 15 | Ammonia solid state storage |
| 16 | Absorbent materials for ammonia synthesis (based on Haber Bosch system) |
| **Nº** | **Exploitable Result** |
| 17 | Novel catalyst for ammonia synthesis |
| 18 | Novel catalyst for ammonia decomposition |
| 19 | Recycling of Pd-based membranes |
| 20 | Ammonia SOFC, SOFC systems and system simulation for power generation |
| 21 | Ammonia combustion engine |

Orange background: proposal KERs; Clear orange: original KER split in two.

# 6. Progress: WP 2

## System requirements, design and modelling

### Objectives

- Define the industrial requirements for a novel integrated system for ammonia-based energy storage system including a green hydrogen production unit, an ammonia production unit and an ammonia decomposition membrane reactor together with an ammonia storage
- Material modelling for selection of the best candidates
- Reactor modelling, simulation and design
- Process simulation (process design and optimization)
- Pilot plant simulation / Modelling of the complete system
- Techno-economic assessment of the integrated plant and comparison with benchmark technologies
- Define the roadmap for future technology deployment

# 6. Progress: WP2

## System requirements, design and modelling

The following tasks have been achieved:

- The industrial requirements for a novel integrated system ammonia-based storage energy supply system consisting of a SOEC electrolyzer, an ammonia production unit, an ammonia decomposition membrane reactor and an ammonia storage unit have been defined.
- SOEC electrolysis modelling
- Ammonia synthesis modelling
- Ammonia storage modelling
- Ammonia decomposition modelling

# 6. Progress: WP2

## System requirements, design and modelling

### Industrial requirements

- The process parameters for the ARENHA process have been defined.
- Mass and energy balance of each individual process unit were conducted to define the inputs and outputs parameters of each process block.

# 6. Progress: WP2

## System requirements, design and modelling

### SOEC electrolysis modelling

- Review of SOEC model with various level of complexity (from 0D to 2D).
- Identification of key experimental parameters required for lumped model definition.
- Summarize and review current level of development in modelling SOEC systems.
- Aspen Plus SOEC model updated with experimental results (FhG-IKTS).
- A first implementation concept of the SOEC-model in Aspen Custom Modeler was developed.

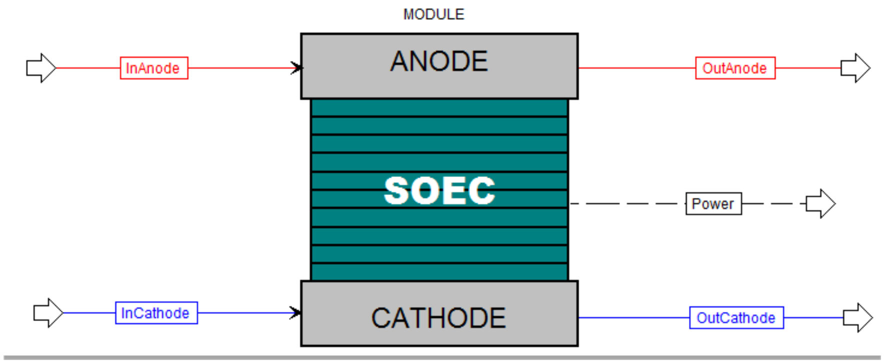
- Development of a steady state SOEC system model
- Development of a dynamic state SOEC system model

# 6. Progress: WP2

## System requirements, design and modelling

### SOEC electrolysis modelling

- Two SOEC 0D model developed in Aspen Custom Modeler and validated with experimental data from FhG-IKTS (Electrolyte Supported Cells) and Elcogen (Cathode Supported Cells);




- Hydrogen compression and storage unit added to electrolyser balance of plant model in Aspen Plus;
- Simulation export in Aspen Plus Dynamics and implementation of control strategy for system dynamic operation;
- First tests of dynamic operation using renewable energy power profiles as input.

# 6. Progress: WP2

## System requirements, design and modelling

### Ammonia synthesis modelling

- A dynamic model of the ammonia synthesis unit is required to optimize the reactor-catalyst synergy towards minimal losses due to pressure and temperature. The modelling will be used to translate the pilot plant results to relevant product-scale.
- Density Functional Theory (DFT) calculations and experimental characterization with Differential Electrochemical Mass Spectrometry (DEMS) were used to screen and optimize electrocatalysts for ammonia electrosynthesis
- The optimized composition of sorption materials and characterization of the absorption kinetics and thermodynamic equilibrium was determined with DFTcalculation using a genetic-algorithm (GA-DFT).
- Dynamic simulation of the fixed bed absorption and regeneration processes. The geometry and design of the bed have been optimized by performing COMSOL Multiphysics 3D simulations.
- A quasi-steady state and a dynamic ammonia synthesis process simulation were built.

# 6. Progress: WP2

## System requirements, design and modelling

### Ammonia storage modelling

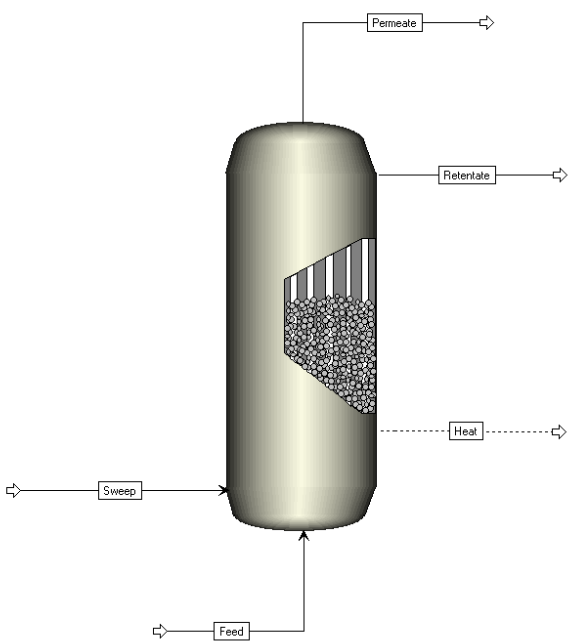
- The composition of the mixed metal halides to be synthesized for ammonia storage have been selected at DTU by performing calculations with the GA-DFT algorithm.
- The expertise and knowledge acquired from the COMSOL Multiphysics 3D simulations on the absorbent bed have been used to develop a model for the ammonia storage.
- Model validation was also performed using experimental data obtained on 10 g of sorbent.

# 6. Progress: WP2

## System requirements, design and modelling

### Ammonia decomposition modelling

- A packed bed membrane reactor (PBMR) model for ammonia decomposition and pure hydrogen separation has been developed in ACM.




- The model was analyzed by means of a **sensitivity analysis**, showing that the model responds as expected to parameter changes.
- The model performance were **compared** to those of a model available in literature and it was concluded that the two models provide similar results
- A **validation with experimental data** obtained from lab tests was also performed and proved the model able to predict hydrogen production from ammonia decomposition with good accuracy.

# 6. Progress: WP2

## System requirements, design and modelling

**Modelling of the complete system and techno-economic analysis**

- Definition and implementation of constraints for ammonia synthesis operation for the integration with SOEC and hydrogen compression and storage model;
- Steady-state integration of ammonia synthesis and electrolysis processes in Aspen Plus;
- Evaluation of key performance indicators and energy integration potential between electrolysis and ammonia synthesis processes.

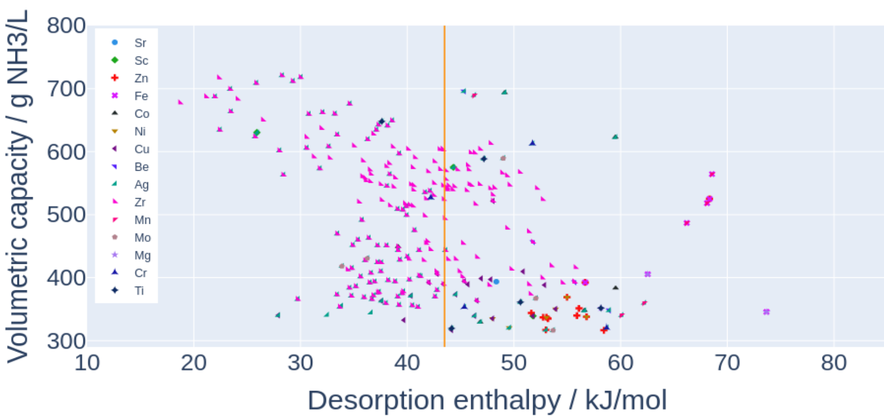
Next steps:

- System optimization in terms of key performance indicators;
- Dynamic simulation of the complete system;

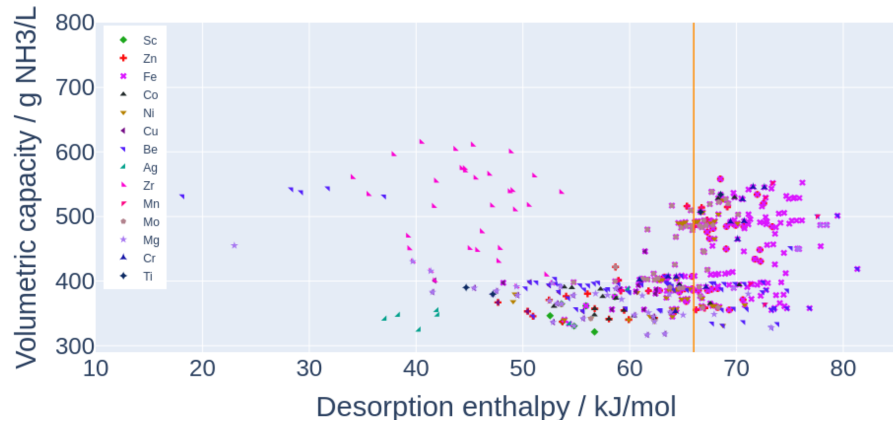
# 6. Progress: WP2

## System requirements, design and modelling

- Genetic algorithm with density functional theory for predication of $NH_3$ absorption and storage were finalized. Candidate materials are selected for further experimental validation

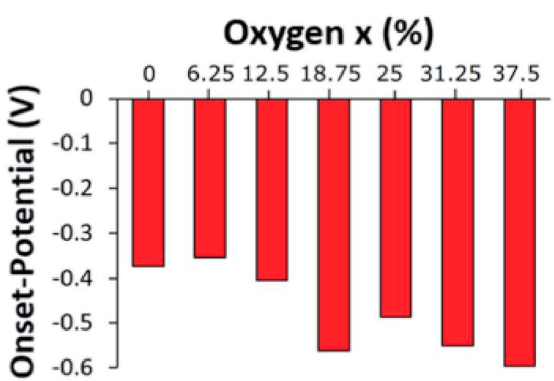



Candidate material for $NH_3$ storage. Targeted enthalpy: 43.5 KJ/mol

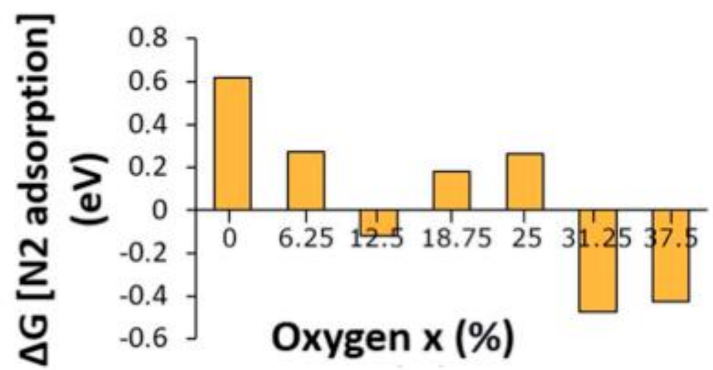



Candidate material for $NH_3$ absorber for HB process. Targeted enthalpy: 66 KJ/mol

- DFT calculation of electrocatalyst for $NH_3$ synthesis was finalized. VN materials with 12% O content ($VN_{0.88}O_{0.12}$ ) is considered the promising candidate electrocatalyst material.




Theoretical onset potential decrease with O concentration

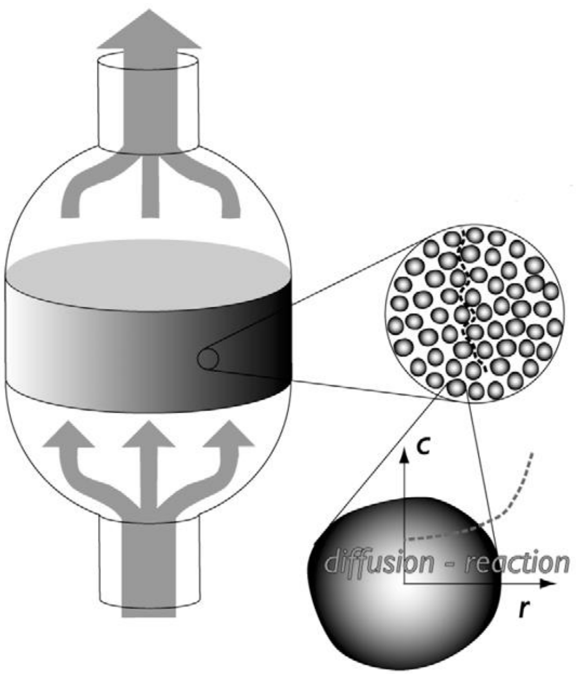


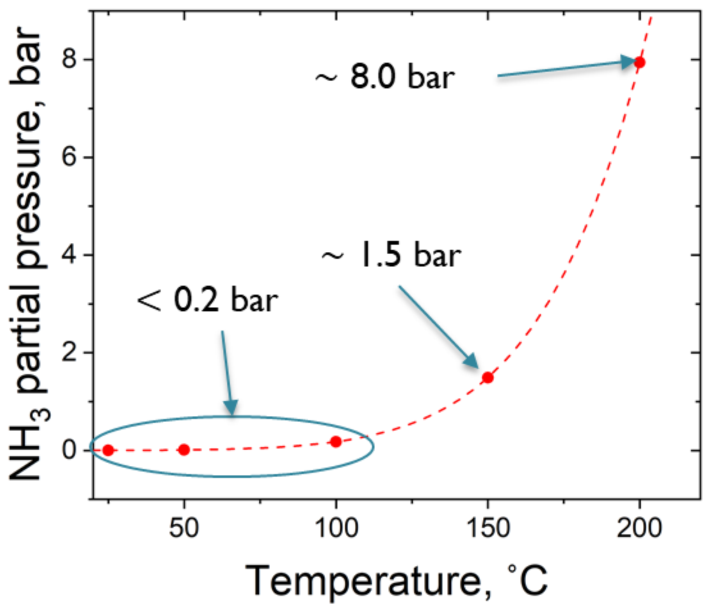

The thermodynamic barrier to $N_2$ adsorption decrease with O concentration

# 6. Progress: WP2

## System requirements, design and modelling

- COMSOL model with bi-modal porosity (macro- and microscales) were developed for modelling of absorber bed design
- Height of mass transfer zone (MTZ) and purity of outlet gas for various temperature and absorber radius



# 6. Progress: WP3

## Key component development

**Objectives**

The main objective of this Workpackage is the **development of the key components of the ammonia-based storage system**:

- New cell materials for optimized SOEC stacks for hydrogen production
- Materials for ammonia synthesis (electrosynthesis and advanced Haber Bosch)
- Materials for solid-state ammonia storage
- Membranes and membrane reactors for ammonia decomposition
- Materials and systems for power generation from green ammonia (SOFC and ammonia combustion)

# 6. Progress: WP3

## Key component development

**Main achievements:**

- New cell materials for optimised SOEC stacks for hydrogen production developed (using thinner electrolytes and/or improved electrodes (IKTS) and SOEC with modified active fuel and/or air electrode layers (ELCOGEN).
- Absorbent material for Haber-Bosch process developed (DTU).
- Electrochemical synthesis of ammonia: testing to be completed (DTU)
- Pd-based membranes for $H_2$ separation prepared by TECNALIA for lab-scale test.
- Recycling of Pd-based membranes developed by TECNALIA
- Lab-scale permeation test using $H_2/NH_3$ or $H_2/N_2$ mixtures on the Pd-based membranes and ammonia decomposition tests in a Pd-based membrane reactor over a Ru-based catalyst have been carried out by TUE. For temperatures from and above 425 $^{o}C$, full $NH_3$ conversion was achieved and more than 86% of $H_2$ fed to the system as ammonia was recovered with a purity of 99.998%.
- STFC have developed a new class of ammonia synthesis catalysts based on light metal amides.
- Stellantis (PSA ID) and UORL has demonstrated the potential of pure ammonia combustion in an internal combustion engine. A conventional Diesel engine was modified adding a spark plug for ammonia combustion ignition.

# 6. Progress: WP3

## Key component development

### Elcogen: Development of modified anode supported cells for SOEC

- The state-of-the-art SOFC is not optimized for electrolysis operation at high current density.
- New materials and microstructural changes in the air active layer and fuel active layer have been explored to optimise cell for SOEC mode.
- New SOECs has been manufactured incorporating all the findings and then assembled in stack to be tested in a 5kW system for validation.

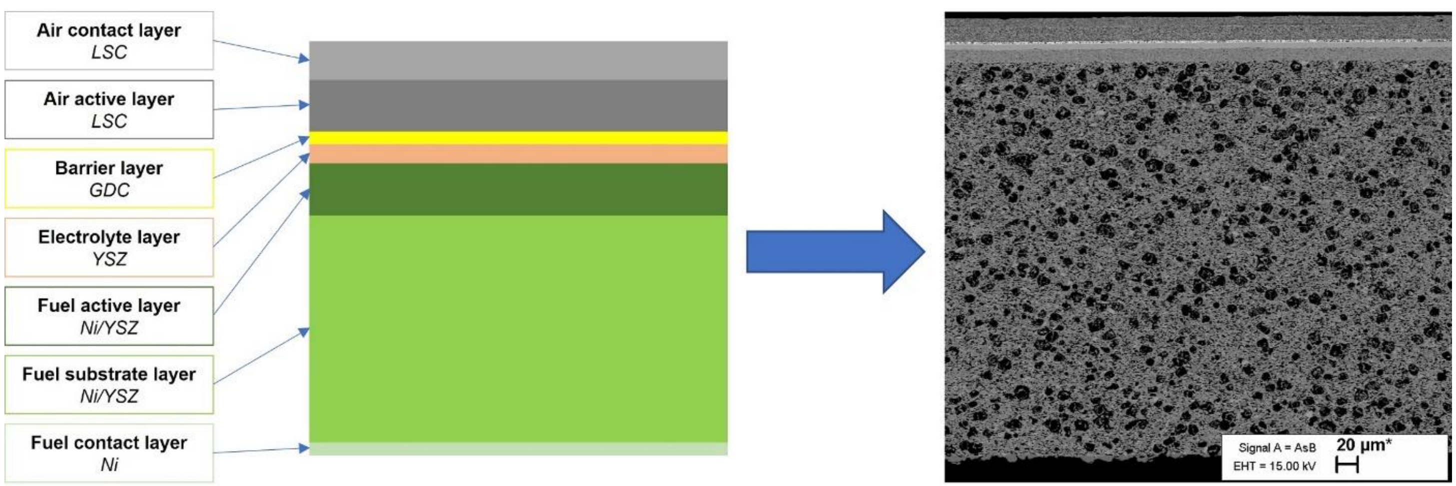



***Figure 1**: Schematic representation (left) and polished SEM cross-section (right) of a State-of-the-Art Elcogen commercial cell.*

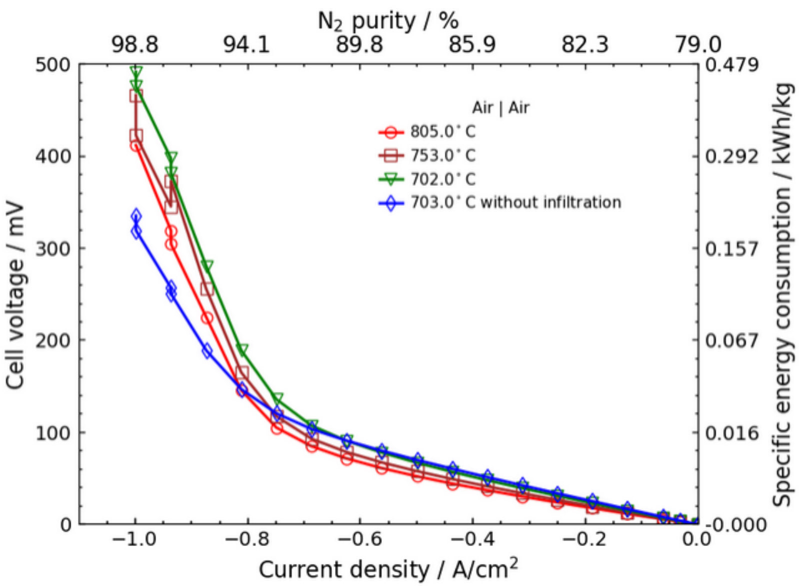
# 6. Progress: WP3

## Key component development

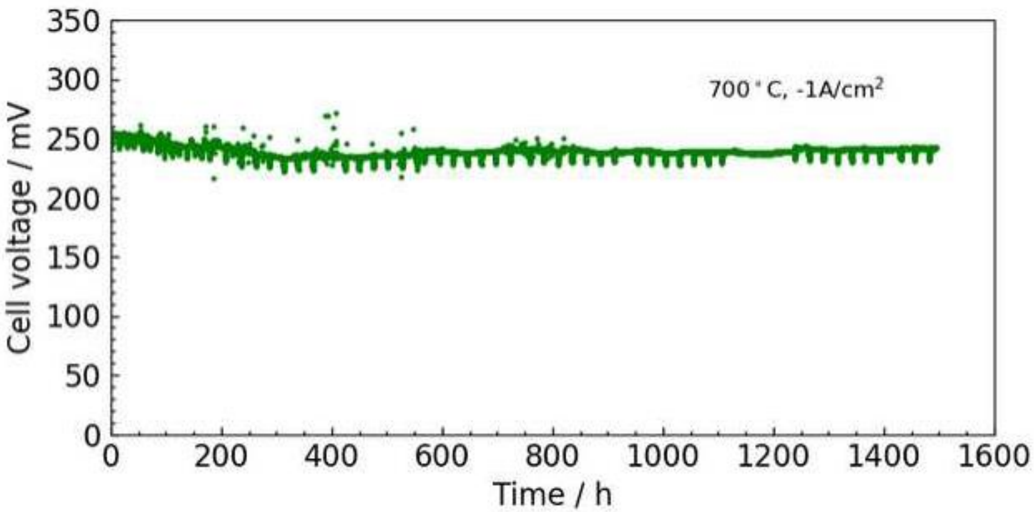
### FhG-IKTS: Development of modified electrolyte supported cells for SOEC

- Development of improved cell
  - Improvement on electrode architecture
    - Promising electrode powder compositions investigated by printing on full cells and characterizing by area specific resistance (ASR) amongst others
    - Decrease of ASR of full cells by approx. 25% at 800°C compared to standard cells
  - Utilization of thinner electrolyte
    - Investigation of electrolytes with thickness < 165 μm
    - Investigation of different adhesion layers with promising results for electrolytes with a thickness of 165 μm and 110 μm
    - Decrease of ASR of full cells with 110 μm electrolyte and adhesion layer by approx. 29% at 800°C compared to standard cells

### Electrochemical cell for $N_2$ production



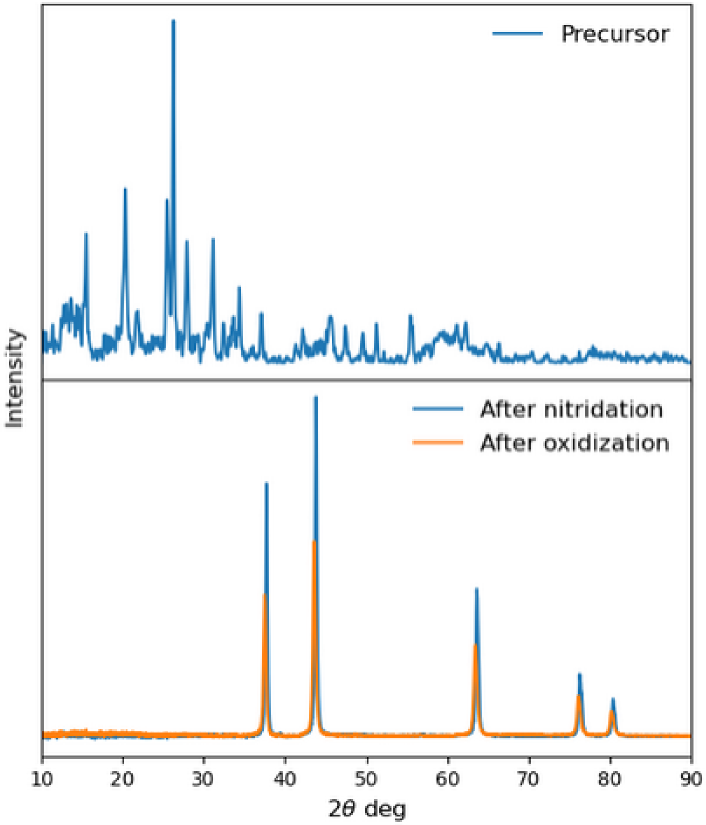

Pr infiltrated LSCF-CGO cell

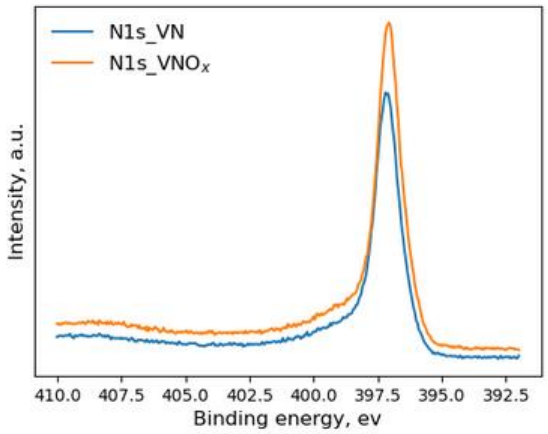


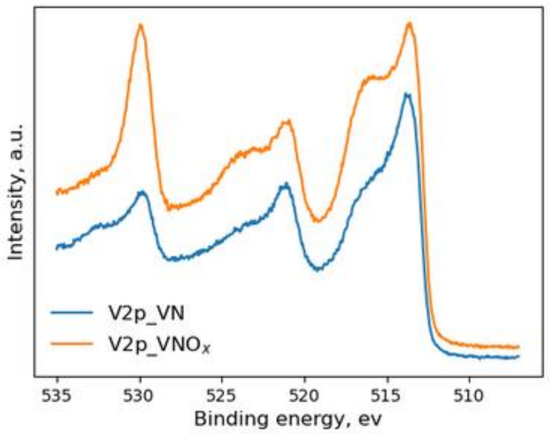

Pr infiltrated LSF-CGO cell

- High purity of $N_2$ can be produced at a voltage below 500mV with Pr infiltrated LSCF-CGO cell.
- Demonstrated 1500 hours operation at -1A/cm$^2$ with $N_2$ purity >98.3% with out degradation.

### Synthesis of electrocatalyst VNOx



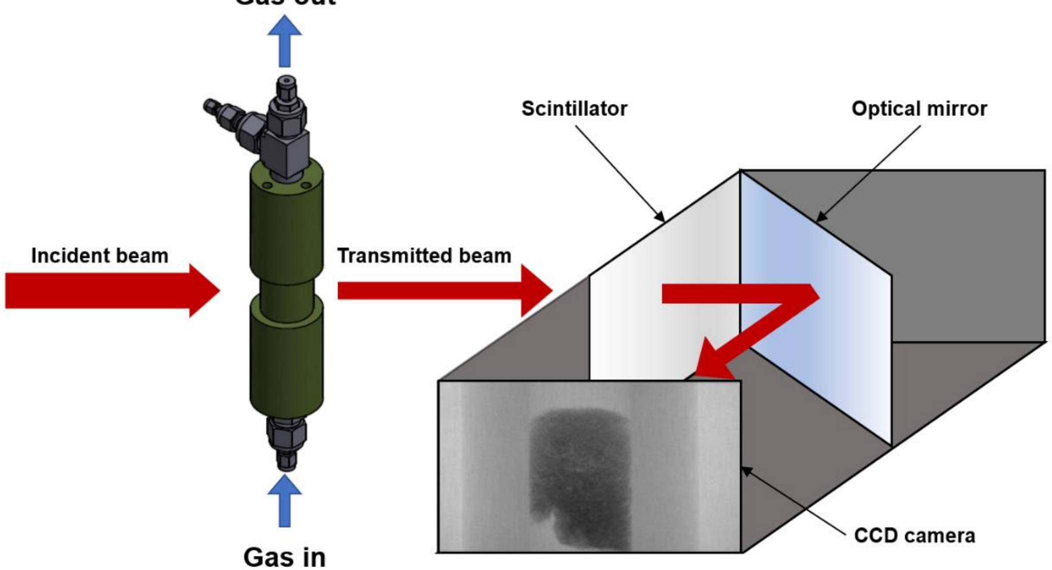




- VN and VNOx has been synthesized and characterized with XPS

# 6. Progress: WP3

## Key component development

### $NH_3$ absorbent synthesis and characterization




*Configuration of neutron radiography experiment*

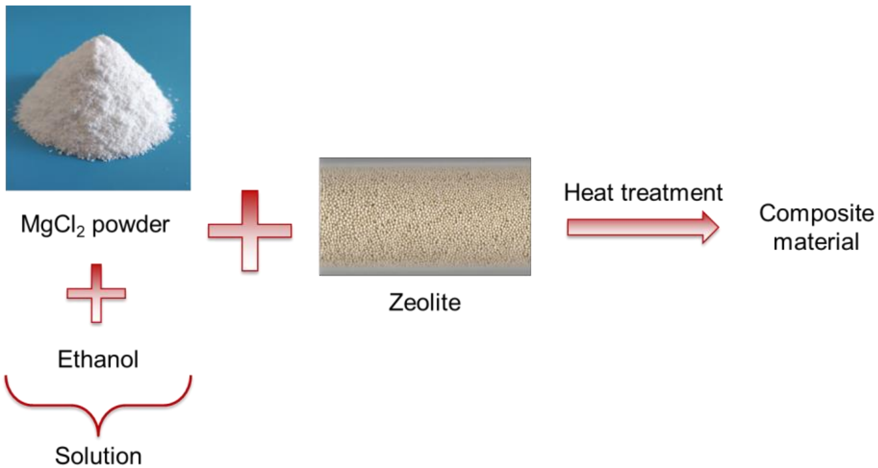
- Using various characterization techniques, including neutron imaging, optimal composition of composite ammonia sorbent was determined

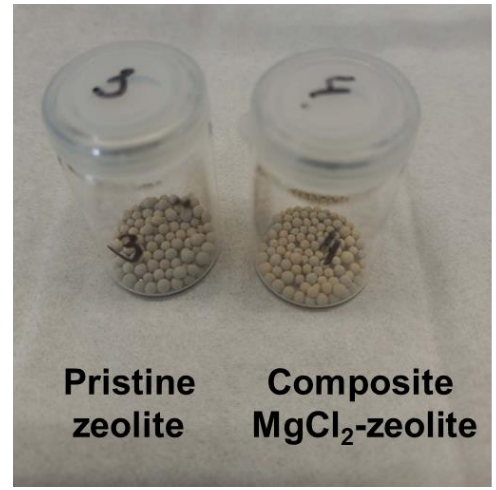
*2 kg of composite material with optimal concentration of salt was produced*

# 6. Progress: WP3

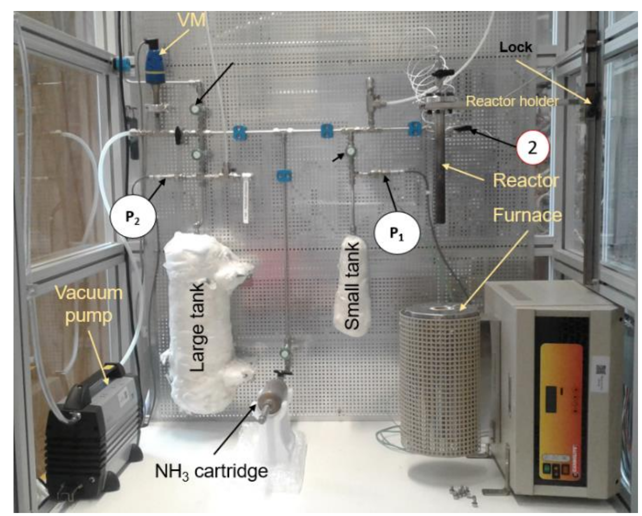
## Key component development

### Absorber materials $MgCl_2$ loaded in zeolite were produced




- Sieverts setup for identification of thermodynamic and kinetic parameters of absorber materials is upgraded.



# 6. Progress: WP3
## Key component development

**Development of double skin (DS) Pd based membranes for hydrogen separation membranes for ammonia decomposition reaction**

**Conventional Pd based membrane**

$\alpha$-$Al_2O_3$

Support

Pore size (nm): 100 nm
OD/ID (mm): 14/7

PdAg (1-4 μm)

Selective layer

*Electroless plating*
Annealing 550 °C

**Double skin membrane**

YSZ/γ-$Al_2O_3$ (1 μm)

Protective layer

*Dip coating*
Calcination 550 °C


**Goal:** High $H_2$ permeance and $H_2/N_2$ & $H_2/NH_3$ selectivity

**Target:** Low $N_2$ permeance/leakage at RT

- 1st generation membranes: **< $2 \cdot 10^{-10}$ mol $m^{-2}$ $s^{-1}$ $Pa^{-1}$** **Achieved**
- 2nd generation membranes: **< $4 \cdot 10^{-11}$ mol $m^{-2}$ $s^{-1}$ $Pa^{-1}$** **Achieved**

# 6. Progress: WP3

## Key component development

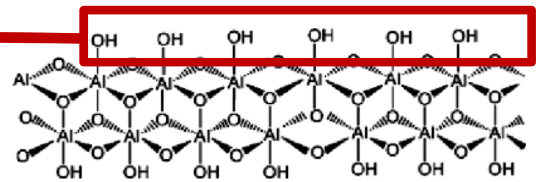
**Development of composite-carbon molecular sieve membranes (Al-CMSM) for hydrogen separation for ammonia decomposition reaction**

- Development of Carbon Molecular Sieve Membranes wiht the addition of boehmite nanoparticles by the one-dip-dry-carbonization technique.
- Carbonization at various T (500 – 700 ° C) under nitrogen.

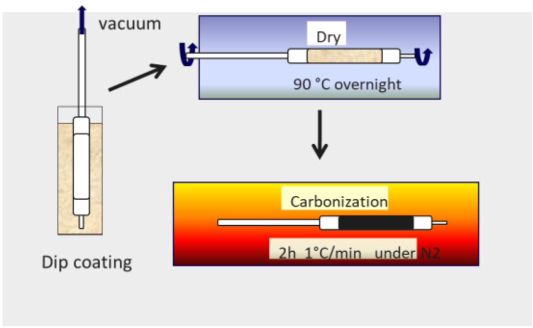
**Dipping solution**

| | |
|---|---|
| **Boehmite nanoparticles** | **0,8 %** |
| Novolac resin | 13,0 % |
| Formaldehyde | 2,0 % |
| Ethylenediamine | 0,6 % |
| Solvent | NMP |

**Boehmite**



**One dip- dry- carbonization method**




**Goal:** High $H_2$ permeance and $H_2/N_2$ & $H_2/NH_3$ selectivity

**Target:** Low $N_2$ permeance at RT

- 1st generation membranes: **< 2 ·10$^{-9}$ mol m$^{-2}$ s$^{-1}$ Pa$^{-1}$** **Achieved**

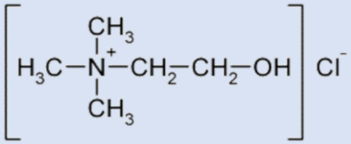
# 6. Progress: WP3

## Recycling of Pd-basedmembranes

### Evaluation of different DES leaching medias

**Hydrogen bond acceptor**

Choline Chloride

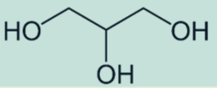


**Hydrogen bond donors**

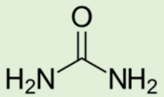
**Alcohols**

Ethylene glycol

Glycerol

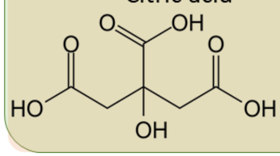


Urea

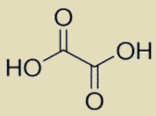


**Acids**

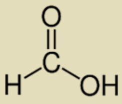
Citric acid



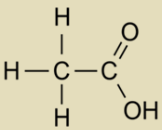
Oxalic acid

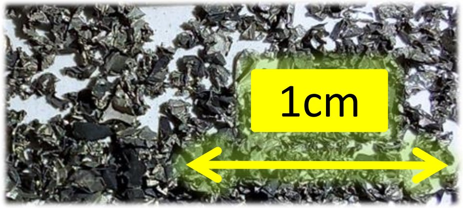


Formic acid



Acetic acid

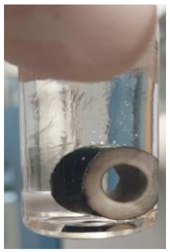





**+ additives**

| | | | | | |
|---|---|---|---|---|---|
| **Acid** | HCl | **Chloride** | NaCl | **Oxidizing agent** | $H_2O_2$ |

>90% Pd & Ag leaching (grinded residue)



Similar recovery yield for full spent membrane

# 6. Progress: WP3

## Key component development

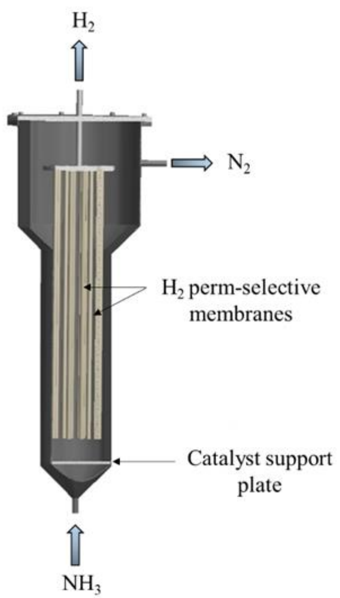
### $H_2$ production via ammonia decomposition

The Pd-based **membrane reactor** is a technology with high potential to efficiently recover $H_2$ from $NH_3$

**Ammonia decomposition**

$$2\,NH_3 \leftrightarrow N_2 + 3\,H_2$$

$NH_3$ decomposition reaction into $H_2$ and $N_2$ and high-purity $H_2$ separation are simultaneously performed

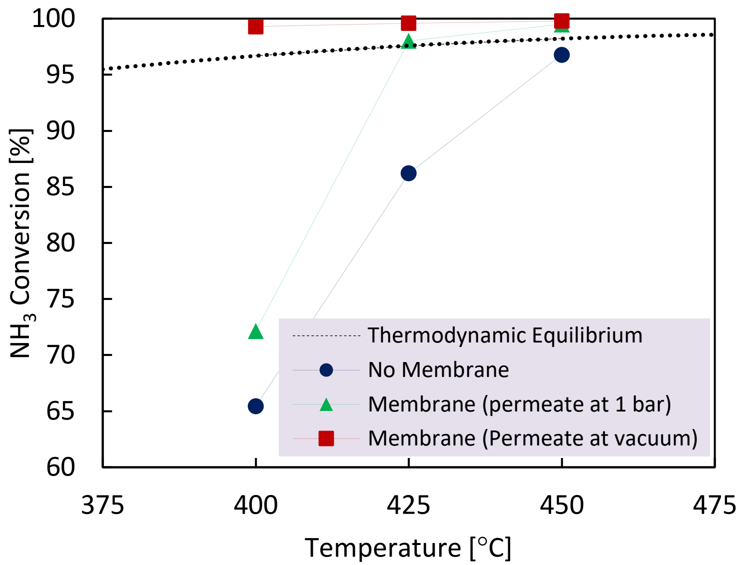


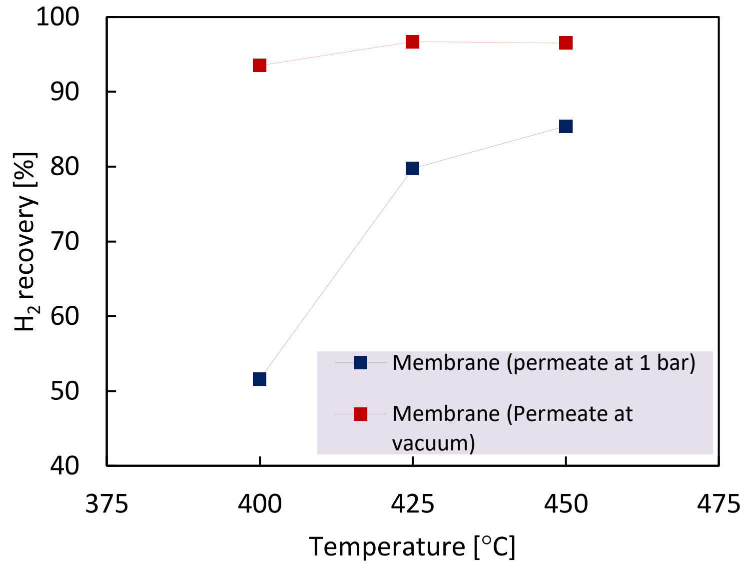

- the high-purity $H_2$ recovered through the membranes can be fed directly to FCs avoiding the need to introduce any costly separation/purification unit
- full $NH_3$ conversion can be achieved reducing the downstream cleaning of unconverted species
- high $H_2$ separation efficiencies of $H_2$ can be achieved at lower operating temperatures compared to conventional systems, with benefits from an energetic point of view
- since the whole process occurs in a single unit, the footprint of this technology is reduced

# 6. Progress: WP3

## Key component development

*The catalytic membrane reactor for $NH_3$ decomposition (*)*




| Experimental conditions | |
|---|---|
| ΔP | 3 bar |
| Permeate pressure | 0.01-1 bar |
| Feed flow rate | 0.5 LN/min |
| Temp. | 400, 425, 450 °C |

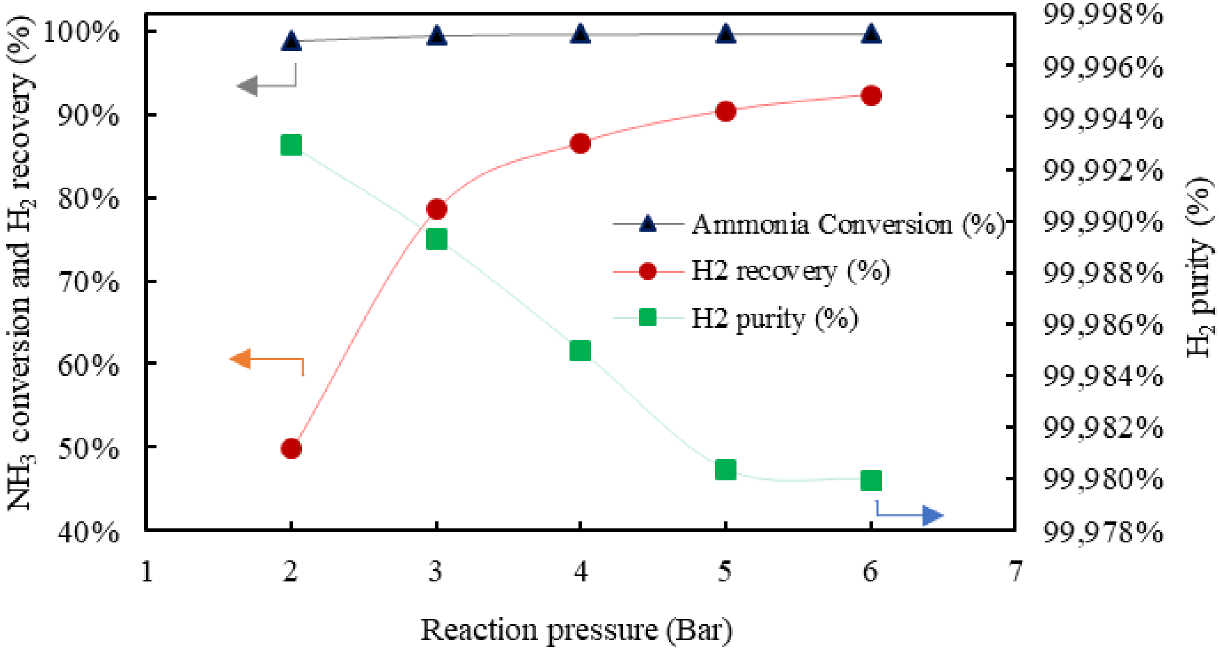
- In a **conventional packed bed reactor**, the conversion achieved is limited, and cannot reach the thermodynamic equilibrium conversion.
- When the **membrane reactor** is adopted, the conversion is increased and for temperatures from and above 425 ◦C $NH_3$ conversions higher than the equilibrium without the membrane are achieved.
- The use of vacuum at the permeate side of the membrane enhances the performance of the membrane reactor technology.

*(*) Valentina Cechetto et al. Fuel Processing Technology 216 (2021) 106772.* https://doi.org/10.1016/j.fuproc.2021.106772

# 6. Progress: WP3

## Key component development

*Effect of pressure*




EXPERIMENTAL CONDITIONS

- T= 450 °C
- Feed = 0.5 $L_N$/min $NH_3$
- Pd-based membrane, dead-end configuration

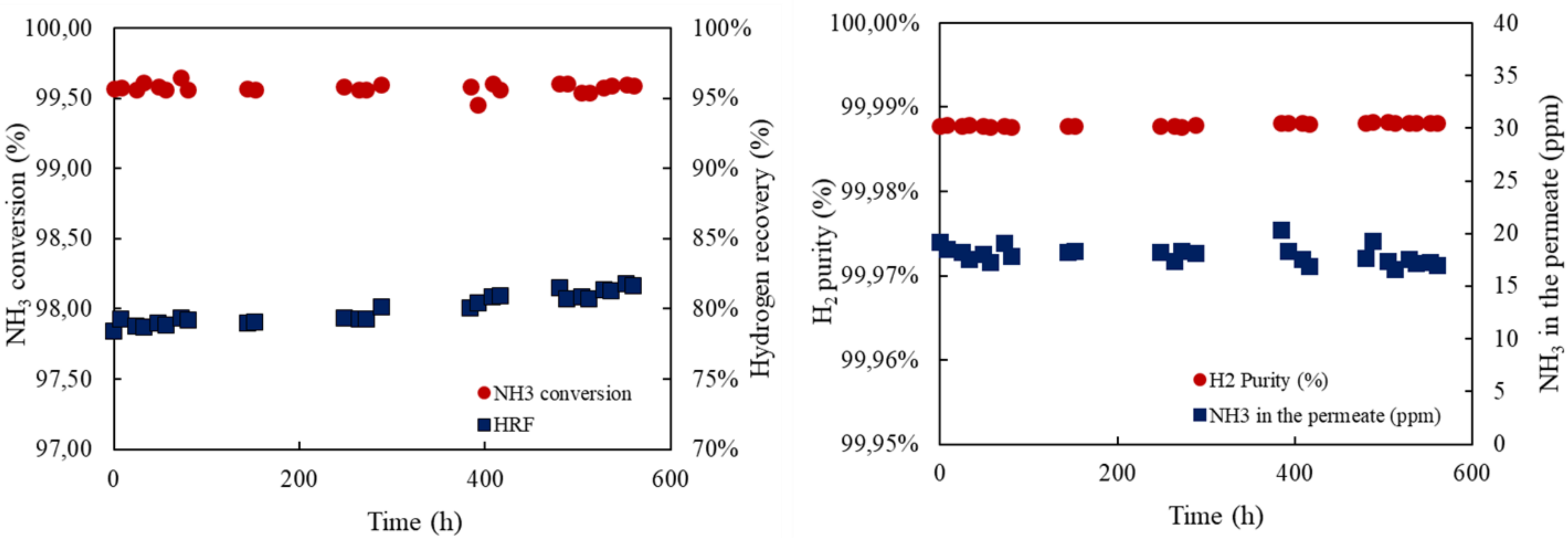
**By increasing pressure in the retentate:**

- $H_2$ recovery increases. Values above 90% are achieved for operating pressures higher than 5 bar.
- $H_2$ purity in the permeate decreases.

*(*) Valentina Cechetto et al. Fuel Processing Technology 216 (2021) 106772. https://doi.org/10.1016/j.fuproc.2021.106772*

# 6. Progress: WP3
## Key component development

*Long term ammonia decomposition test in the membrane reactor (*)*

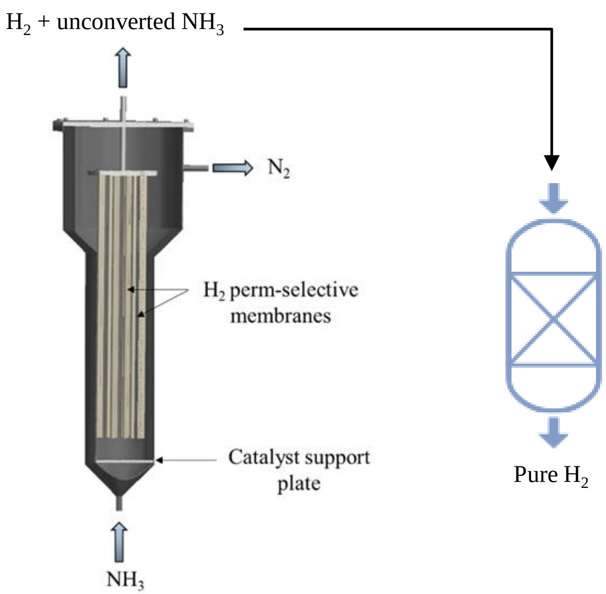


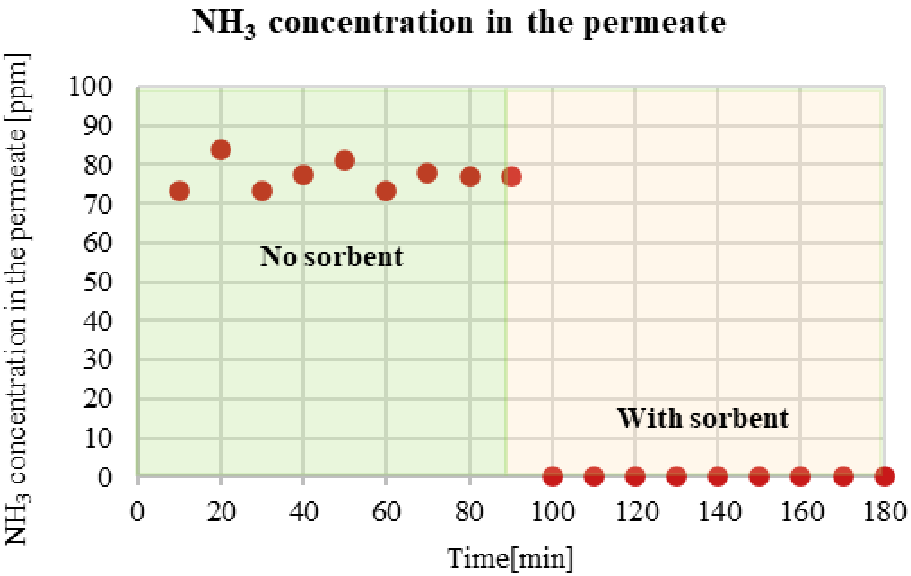

*Experimental conditions: T= 450 °C, $P_{retentate}$= 3 bar, $P_{permeate}$= atmospheric, Feed= 0.5 $L_N$/min $NH_3$*

*(*) Valentina Cechetto et al. Fuel Processing Technology 216 (2021) 106772. https://doi.org/10.1016/j.fuproc.2021.106772*

# 6. Progress: WP3
## Key component development

*Addition of a $H_2$ purification stage*




*Experimental conditions: T= 400 °C, $P_{retentate}$= 3 bar, $P_{permeate}$= 1 bar, Feed flow rate = 2 $L_N$/min $NH_3$, Feed composition: 5% $NH_3$ and 95% $H_2$*

- In order to purify $H_2$ from unreacted ammonia produced during dehydrogenation reactor, a $H_2$ purification stage on the permeate side of the membrane was added.
- A commercial **zeolite 13X** was tested as adsorbent material.

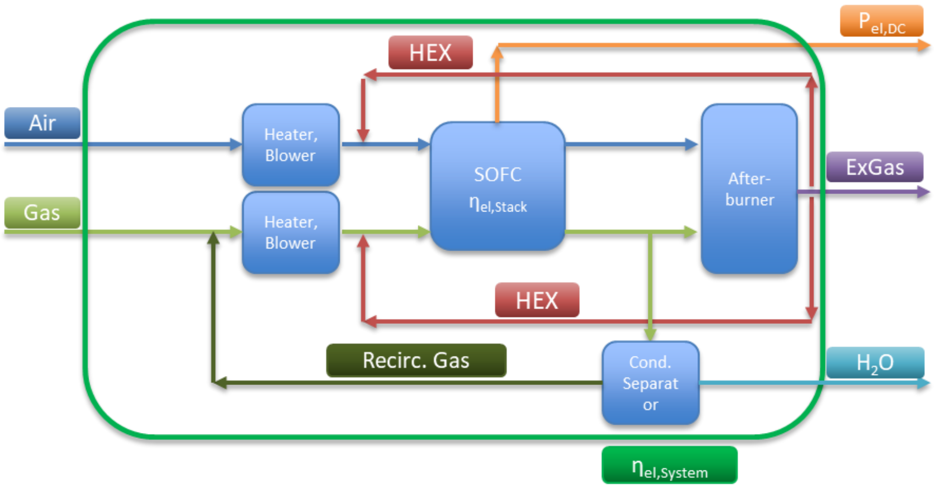
*(*) Valentina Cechetto et al. World Online Conference on Sustainable technologies. March 17-19, 2021.*

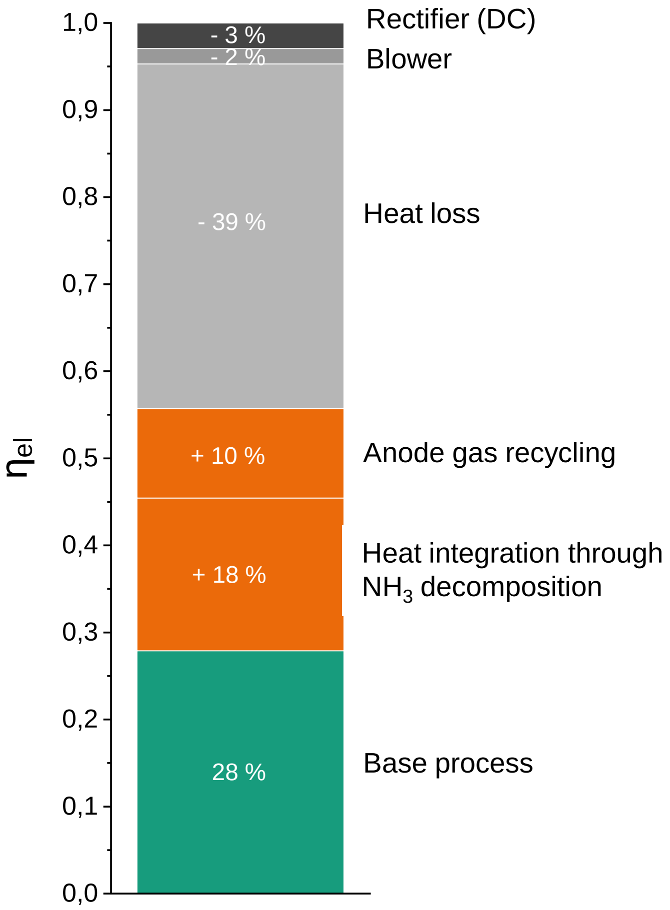
# 6. Progress: WP3

## Key component development

## SOFC system for power generation from ammonia

- Simulation of SOFC using ammonia fuel:
  - 100 % ammonia, anode gas recycling
  - System efficiency: 56 %



# 6. Progress: WP4

## Key component scale up

**Objectives**

The main objective of this work package is the scale-up of the key components and the design, construction, safety and commissioning of the ammonia-based energy storage system pilot plant:

- SOEC stack modules and balance of plant components (BoP) of electrolyser system for hydrogen production
- Ammonia synthesis system prototype based on Haber Bosch with an advanced absorber.
- Ammonia decomposition membrane reactor prototype:
  - To design (basic and detailed engineering) an $NH_3$ cracker for the production of ultra-pure $H_2$ for its use in the mobility sector.
  - To manufacture $H_2$-selective membranes resistant to $NH_3$ cracking environment
  - Build, commission and test the $NH_3$ cracker for a $H_2$ production capacity of 20 kg/d

# 6. Progress: WP4
## Key component scale up

**Design and construction of SOEC electrolyser for hydrogen production**

### Elcogen – Development of improved SOEC

- SOEC were produced according to the results received in WP3.
- Produced SOEC were tested in a preliminary short stack with good results.
- More SOEC were produced and a full 5 kW electrolysis stack assembled for the demonstration unit.

# 6. Progress: WP4

## Key component scale up

### Design and construction of SOEC electrolyser for hydrogen production

Comissioning of IKTS stack module


Status:

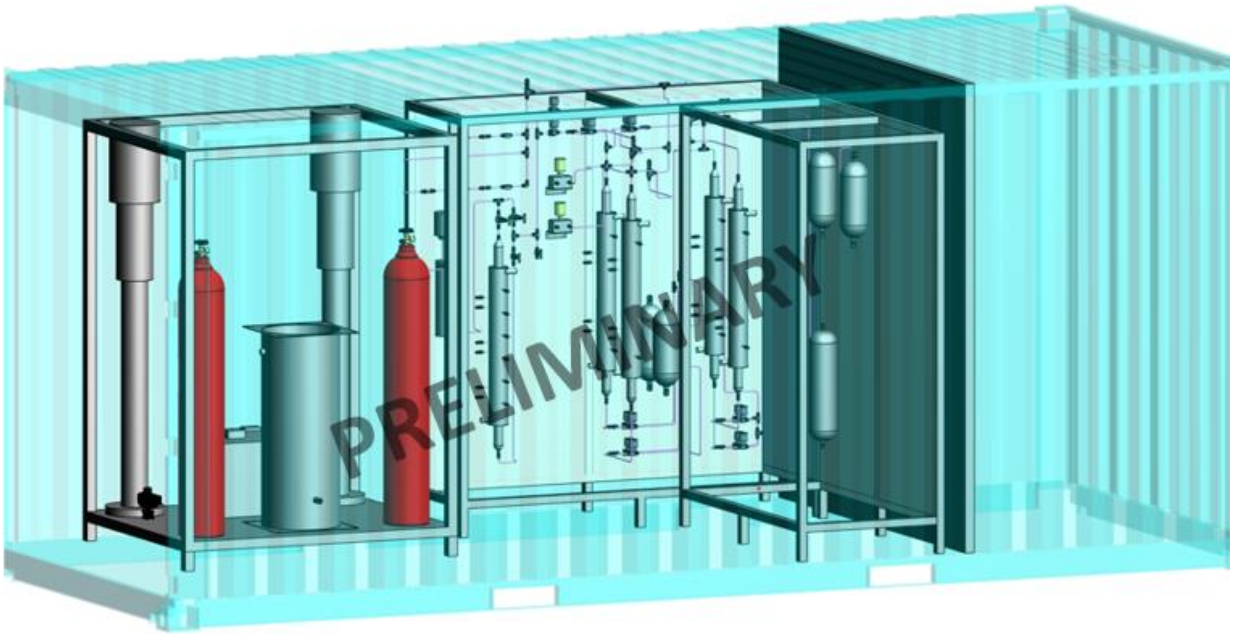
- Two 5 kWel stack modules manufactured and delivered at demo-site.
- BoP balance of plant for integration at demo site.
- System ready for testing and validation in Q1 2024.

# 6. Progress: WP4

## Key component scale up

### Advanced Ammonia Synthesis Loop Prototype

- Unit fully designed and ongoing with construction
- HAZOP Studies carried out to ensure safe operation
- System will be delivered on site in Q1 2024 for commissioning



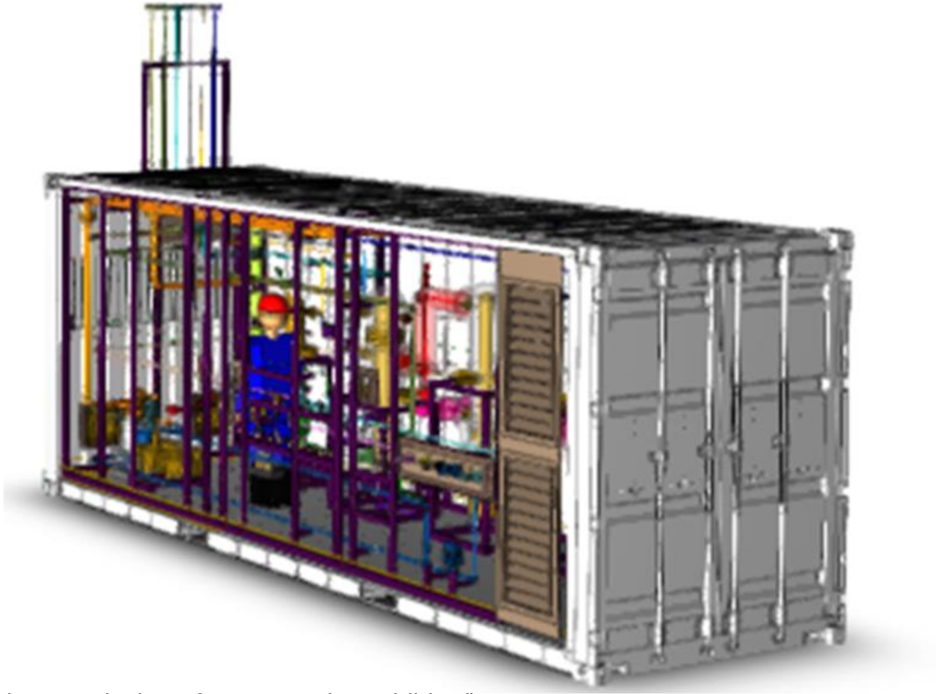

Proton Ventures Containerized $NH_3$ Synthesis Loop Prototype. Preliminary 3D model for Impressiom Only. The arrangement of the system may be subject to change

# 6. Progress: WP4
## Key component scale up

### Advanced cracker Prototype

- Unit fully designed and constructed
- HAZOP, LOPA, and ATEX Studies carried out to ensure safe operation
- All the $H_2$-selective membranes manufactured
- System undergoing commissioning and ready for operation in Q1 2024



# 6. Progress: WP6

## Environmental LCA, Economic and Safety Assessment

- Preliminary results on the sociological and environmental impact of the technological solutions offered by the project.

| Acceptance issues and green ammonia technological system | | Renewable power related to green ammonia production | Green ammonia production | Green ammonia use in Energy sector | Green ammonia use in Maritime sector | Green ammonia use in river transportation | Green ammonia use in road transportation | Green ammonia use in fertilizer sector |
|---|---|---|---|---|---|---|---|---|
| *Community acceptance* | Distributive justice | Red | | | | | | Green |
| | Procedural justice | Red | | | | | | Green |
| *Socio-politcal acceptance* | Environmental impacts | Red | Orange | Green | Orange | Orange | | Orange |
| | Risks perception | | Orange | Orange | Orange | Orange | | Orange |
| | Regulation | | | Orange | Orange | Orange | Orange | |
| *Market acceptance* | Availability of infrastructure | Orange | Orange | Orange | Orange | Orange | Orange | |
| | Costs | | Orange | Orange | Orange | Orange | Orange | Orange |
| | Availability of technologies | | Orange | Green | Green | Orange | Green | Orange |

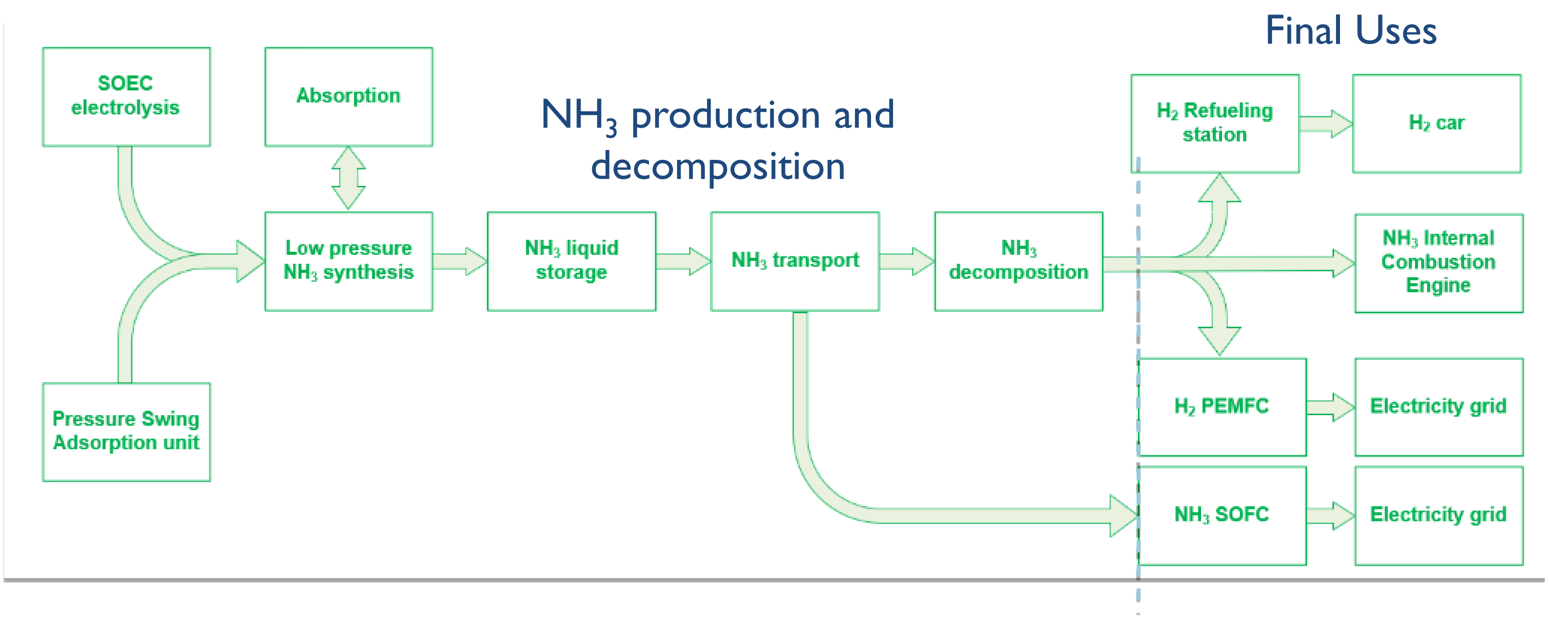
***Matrix of social acceptance issues of the ammonia value chain. Red: critical issues for acceptance. Orange: uncertain issues. Green: no major issue for acceptance***

# 6. Progress: WP6

## Environmental LCA, Economic and Safety Assessment

### Life Cycle Cost Analysis

- Life Cycle Cost estimation for green ammonia production pathway and comparison with blue and grey ammonia production pathways;
- Life Cycle Cost for ammonia cracking and cost estimation for different hydrogen and ammonia transportation options;
- Life Cycle Cost estimation for final uses of ammonia or hydrogen from ammonia (PEMFCs, SOFC).

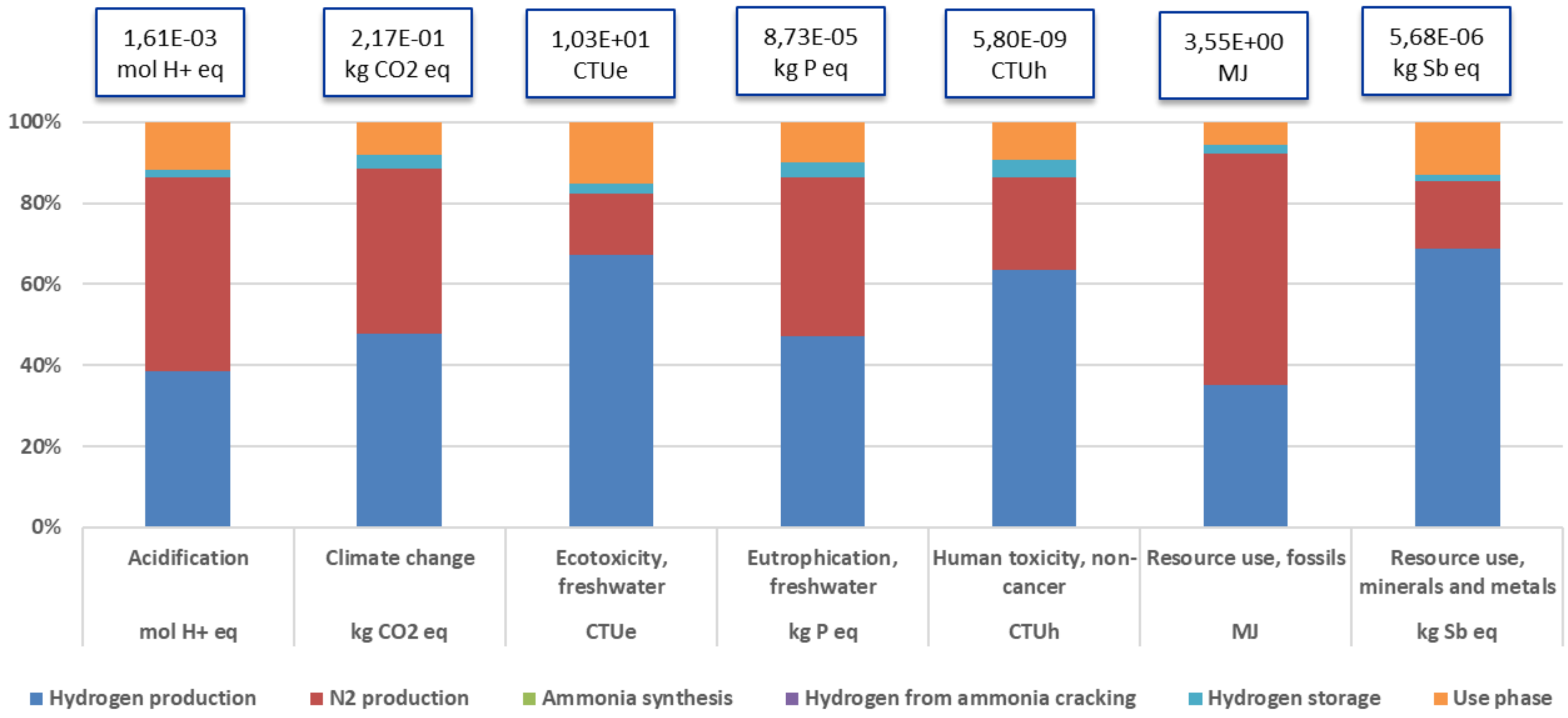


# 6. Progress: WP6

## Environmental LCA, Economic and Safety Assessment

Analysis of the first results for the reference scenario:

### Environmental impacts of the use of green ammonia for electricity production



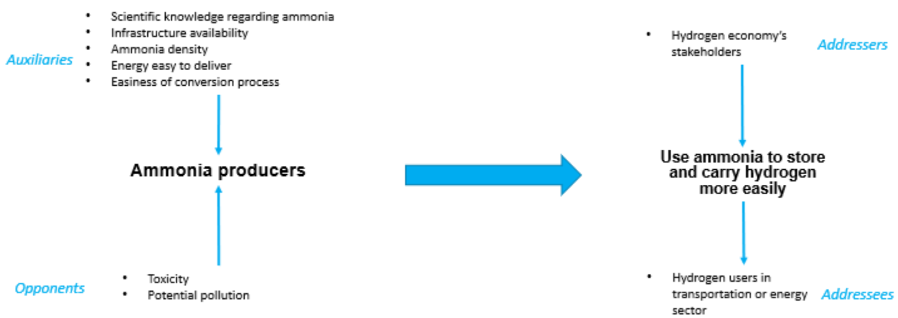

***Contribution analysis of the results of the green ammonia scenario for 1 kWh of electricity.***

# 6. Progress: WP6

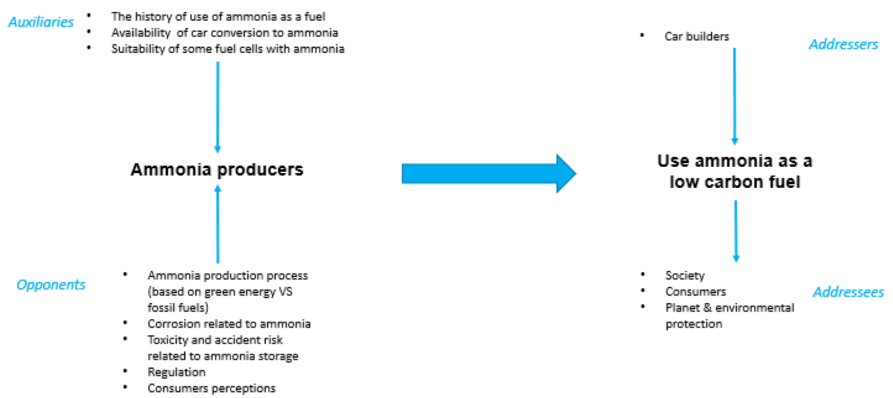
## Environmental LCA, Economic and Safety Assessment

### Social Acceptance: Identification of various narratives related to Ammonia

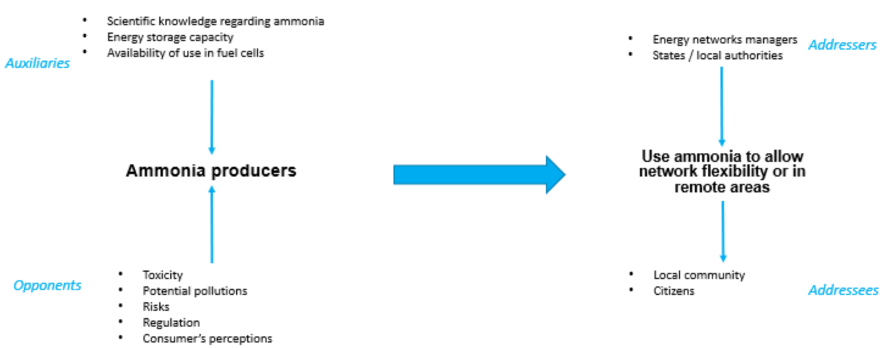
#### Narrative regarding ammonia as a $H_2$ carrier




#### Narrative regarding ammonia as a new fuel




#### Narrative regarding ammonia stationary application




- Main narratives related to Ammonia where first identified in literature
- A deeper exploration through interview was engaged
- Next steps :
  - Continue exploration through interviews in shipping sector
  - Design & pass a questionnaire to test opinion on theses narratives

# 6. Progress: WP7

## Dissemination and communication

- Project logo and set of public document templates
- Public Project website: [Home | ARENHA]
- Dissemination and Communication Plan updated M3
- Dissemination and Communication Plan updated M12
- Dissemination and Communication Plan updated M30
- First Public Presentation
- Second Public Presentation
- 6 months periodic Project newsletter M6, M12, M18, M26, M32, M38
- ARENHA First dissemination video
- ARENHA dissemination activities


# 6. Progress: WP7

## Dissemination and communication

*Website:* *https://arenha.eu/*

Follow us:

| Scientific publications | Conferences, Workshops | Patent request | Newsletters | Others: press, video, report,… |
|---|---|---|---|---|
| >10 | >25 | 2 | 6 | >10 |

# 7. Impact

Decrease energy import dependency.

Promote the integration of offshore renewables for energy dependency.

Integration of renewable in power systems with large scale energy storage.

Strategic European leadership in energy storage.

Ammonia to diversify energy supply from third countries

**Alternative energy import through renewable electricity storage and long distance transportation.**

-  > $2.5 trillion per year
-  > 5000 future jobs
- Reduction of NOx-emission = Increase quality of life
- Avoid 20 million barrels of oil per day

# Advanced materials and Reactors for Energy storage tHrough Ammonia

## *Thank you for your attention*

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*LinkedIn: ARENHA Project*
*Twitter: @ARENHA_H2020*