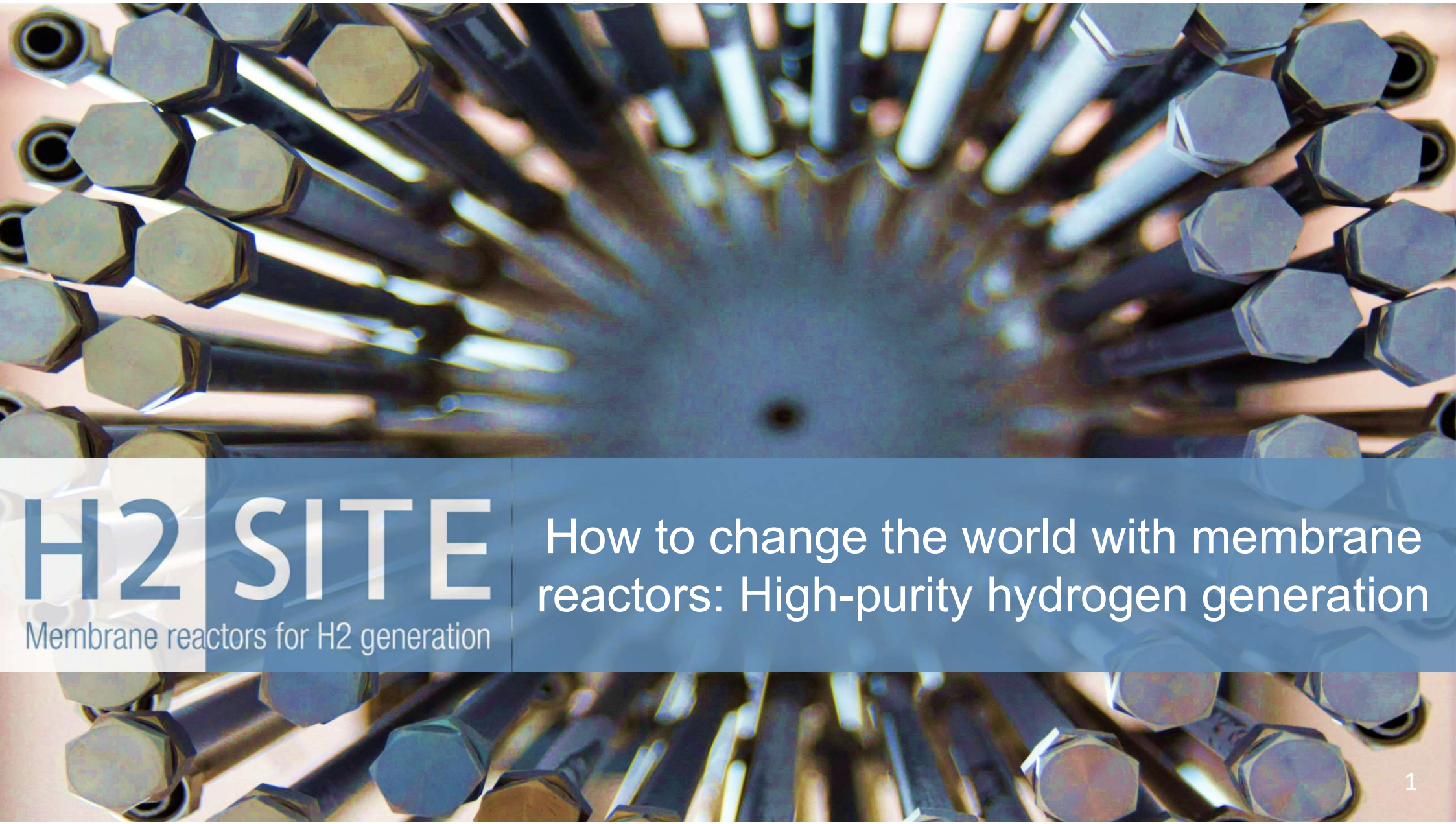


H2 SITE

Membrane reactors for H2 generation

How to change the world with membrane reactors: High-purity hydrogen generation

Outlook

- Who we are?
- Our Mission and Vision
- When did this story begin?
- Foundation and current projects
- Future challanges

Who we are?

- Patented membrane technology for gas separation developed over >10 years
- Commited with **net-zero emisión in 2050** thanks to Hydrogen utilisation
- We design and manufacture entire balace of plant for **high purity hydrogen** production from different feedstocks
- Technology based on **catalytic membrane reactors** thanks to long time R&D collaboration and technology transfer (Tecnalia / TUe)

What is H2SITE's technology?

Palladium-Alloy membranes that produce **high purity hydrogen** (99.97%)…

…to **recover up to 98% of the hydrogen** from wide variety of feedstocks…

…for **on site generation** in a reduced footprint

Hydrogen separators and purifiers

Crackers, reformers and WGS reactors

H2SITE MISSION & VISION

Transport through hydrogen carriers can be done more easily done than gaseous or liquid hydrogen

Development of hydrogen storage strategies, is the key to the successful deployment of hydrogen, including its economic sustainability.

H2SITE MISSION & VISION

Hydrogen will be produced where it is cheaper but consumed where it is needed

WE SOLVE THE PROBLEM OF HYDROGEN TRANSPORT

THE MISSING LINK BETWEEN THE UPSTREAM AND DOWNSTREAM

This is our story

THE TECHNOLOGY KEY COLLABORATION
TECNALIA – TU/e

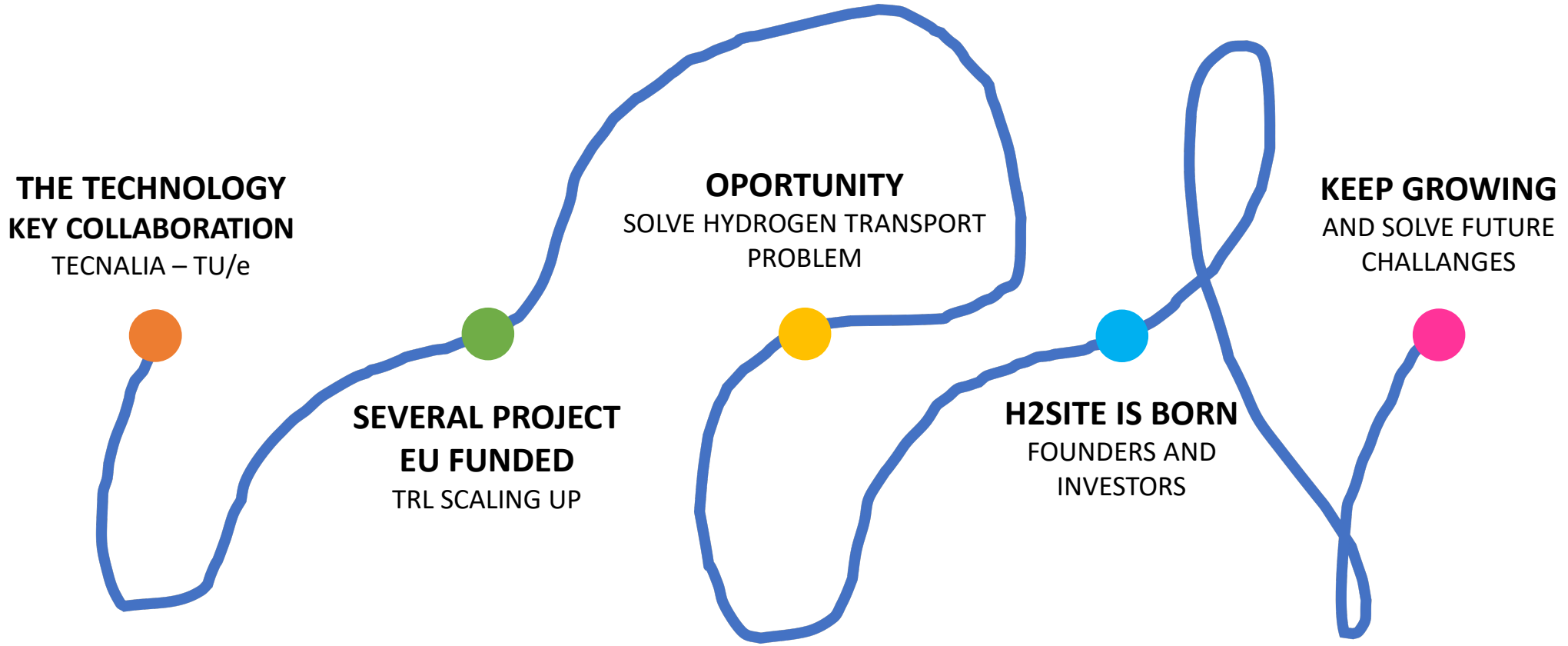
SEVERAL PROJECT EU FUNDED
TRL SCALING UP

OPORTUNITY
SOLVE HYDROGEN TRANSPORT PROBLEM

H2SITE IS HERE
FOUNDERS, INVESTORS AND CURRENT PROJECTS

KEEP GROWING
AND SOLVE FUTURE CHALLANGES

This is our story

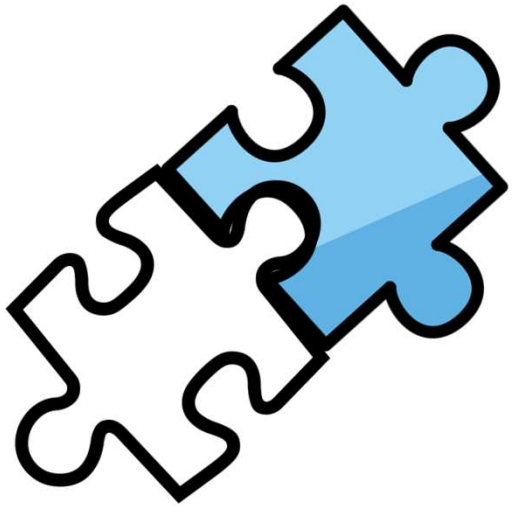


When did this story begin?

THE TECHNOLOGY
KEY COLLABORATION
TECNALIA – TU/e

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Membrane integrated reactors

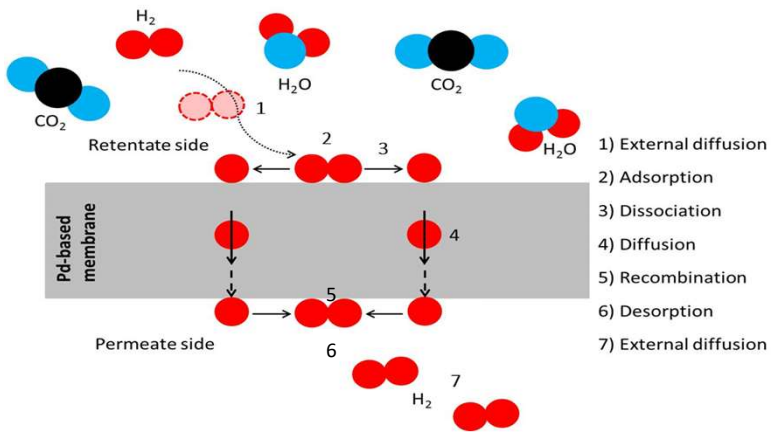


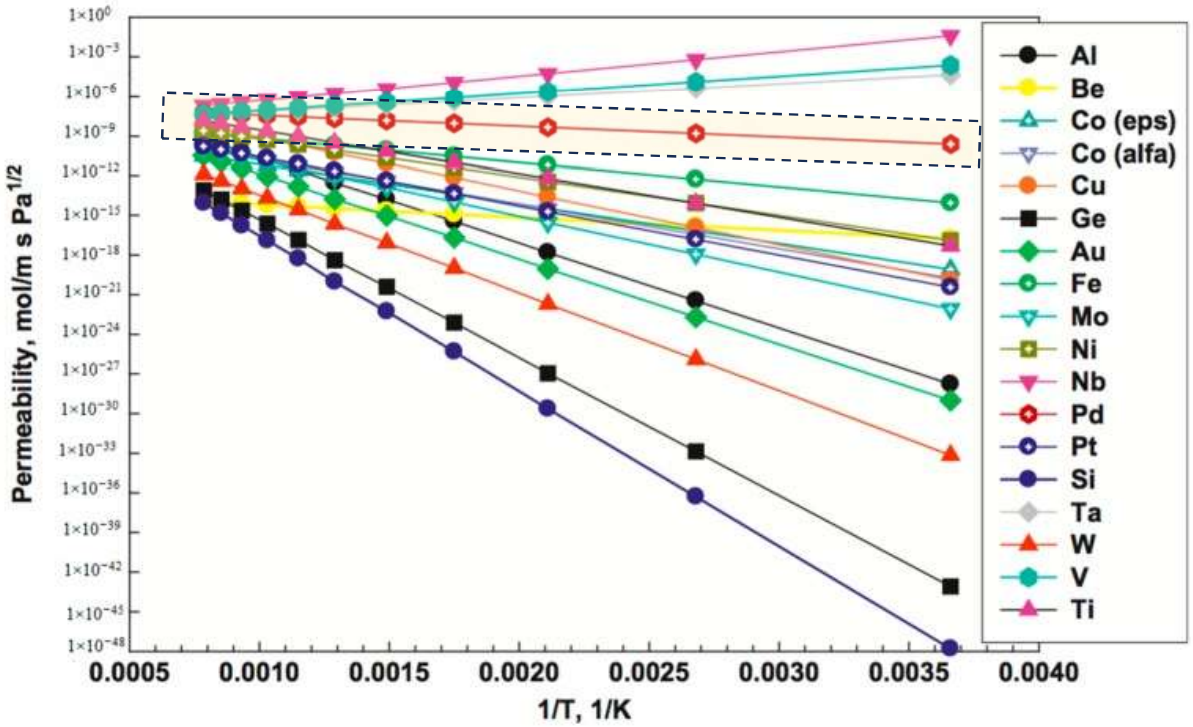
tecnalia

Pd-based membranes

Pd based membranes

SOLUTION DIFFUSION MODEL

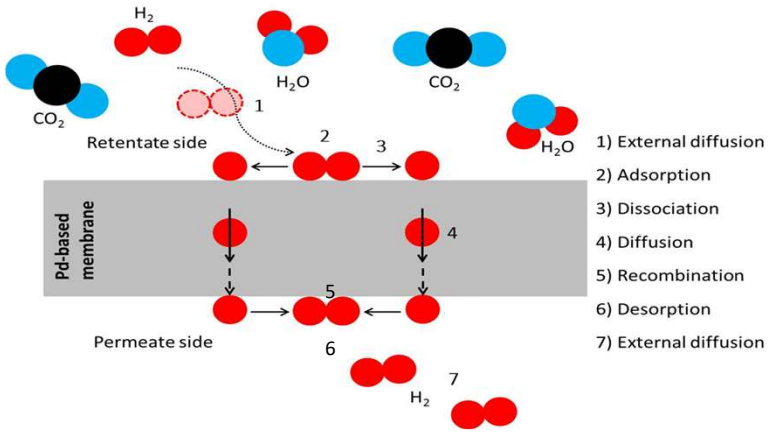


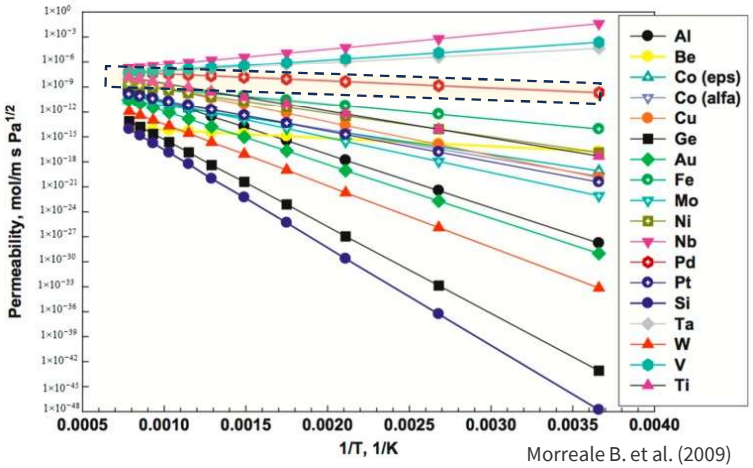


Morreale B. et al. (2009) Gasification and Associated Degradation Mechanisms Applicable to Dense Metal Hydrogen Membranes. In: Bose A.C. (eds) Inorganic Membranes for Energy and Environmental Applications. Springer, New York, NY

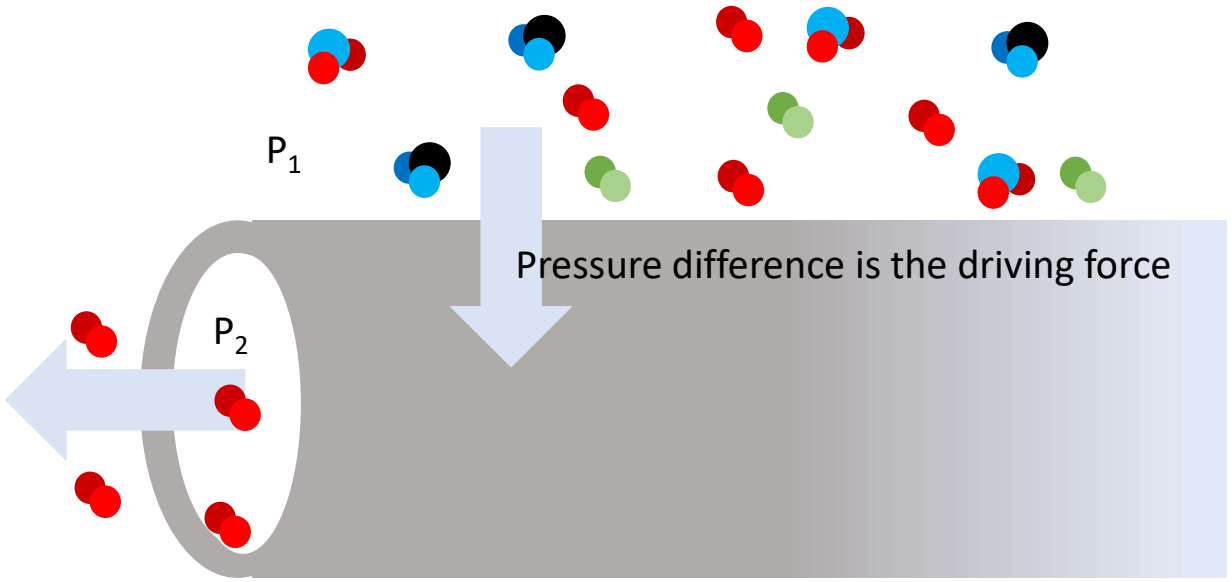
The Technology

Pd based membranes





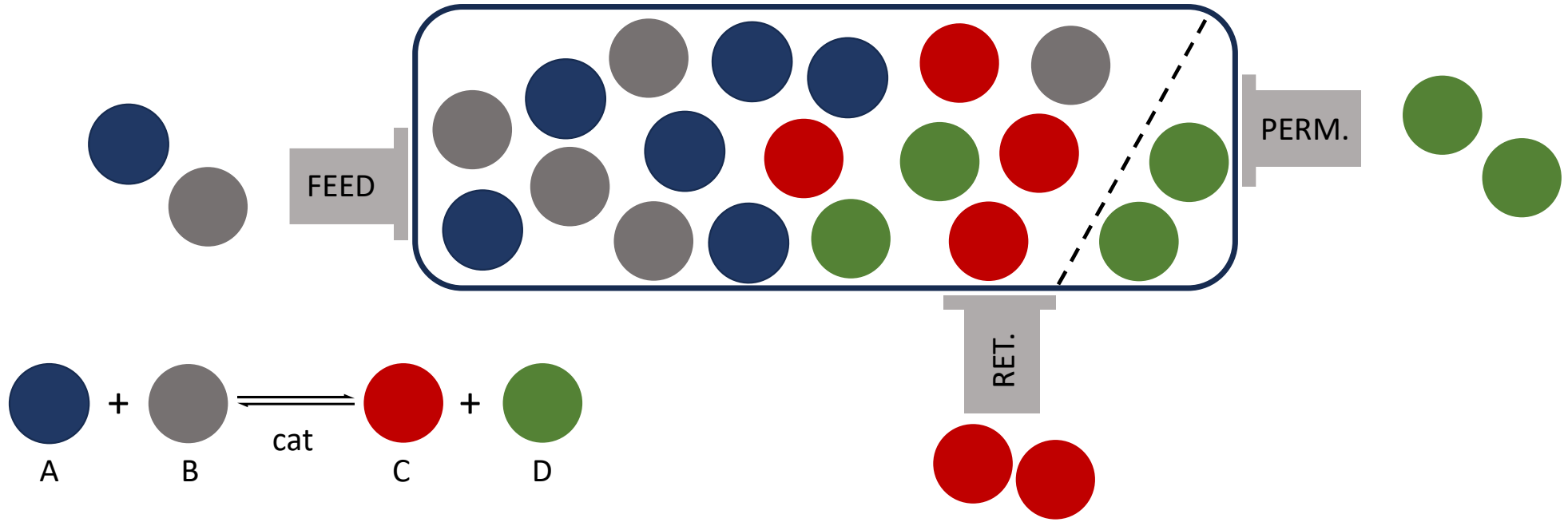
Morreale B. et al. (2009)



$P_1 > P_2$

High permeability,
infinite **selectivity** and
stable at **high temperatures**

Membrane integrated reactors



Conversion enhancement by selective permeation of a reactant product of an equilibrium limited reaction

"When a simple system in thermodynamic equilibrium is subjected to a change in concentration, temperature, volume, or pressure, the system changes to a new equilibrium, and this change partly counteracts the applied change." Le Chatelier's principle

Membrane integrated reactors

Steam Methane Reforming (SMR) reactions

Water Gas Shift (WGS)

Methanol decomposition

Ammonia decomposition

Ethanol reforming

Autothermal Reforming (ATR) reactions

Methanol Steam Reforming

Conversion enhancement by selective permeation of a reactant product of an equilibrium limited reaction

"When a simple system in thermodynamic equilibrium is subjected to a change in concentration, temperature, volume, or pressure, the system changes to a new equilibrium, and this change partly counteracts the applied change." Le Chatelier's principle

Membrane integrated reactors

COMPACTNESS: 4 UNITS VS 1

↓↓↓ CAPEX/OPEX
- MATERIALS
- ENERGY

INNOVATION CATALYTIC MEMBRANE REACTORS:
↑↑↑ EFICIENCIES

LESS CO_2 EMMISIONS

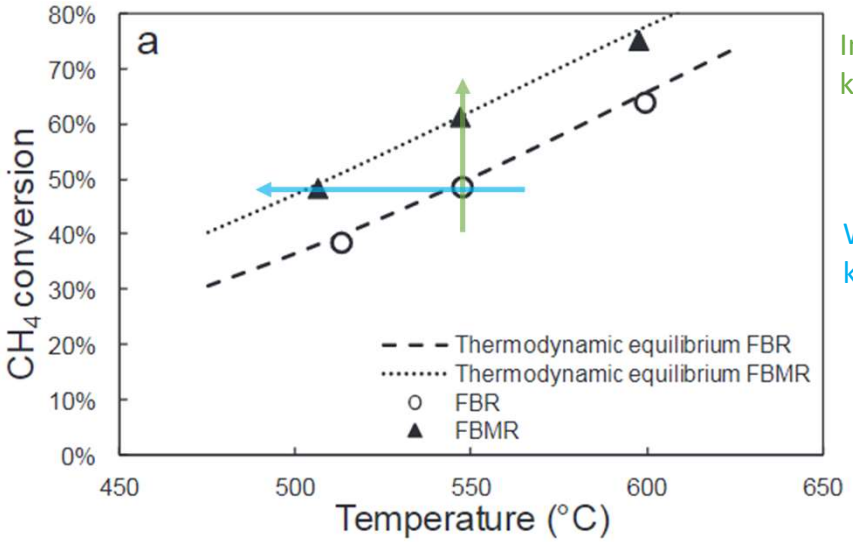
Conversion enhancement by selective permeation of a reactant product of an equilibrium limited reaction

"When a simple system in thermodynamic equilibrium is subjected to a change in concentration, temperature, volume, or pressure, the system changes to a new equilibrium, and this change partly counteracts the applied change." Le Chatelier's principle

Why integrate membranes inside the reactor

Example of impact of equilibrium shifting on methane reforming and ammonia cracking reactions

FBR: Fluidized Bed Reactor
FBMR: Fluidized Bed **Membrane** Reactor



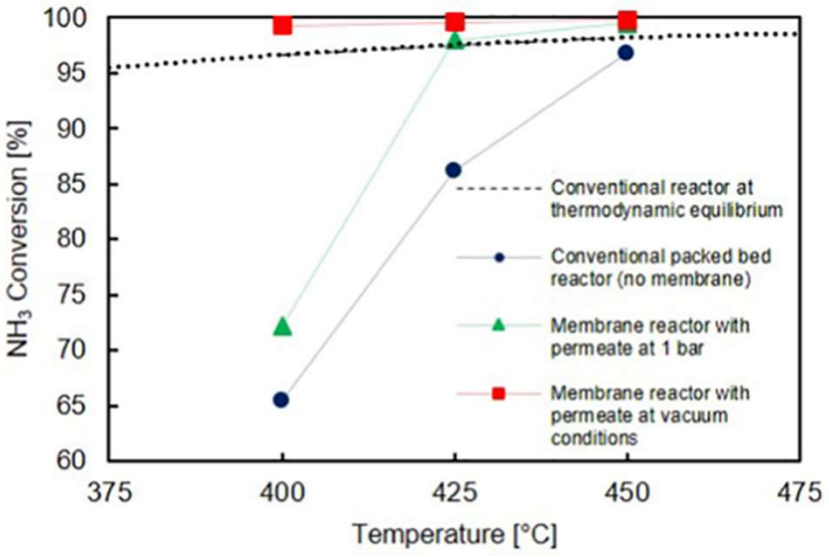
Increase the conversion keeping the temperature
✓ More hydrogen recovery

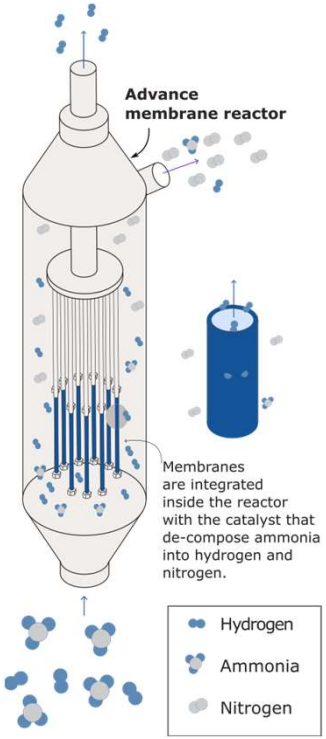
Working at lower temperature keeping the H_2 recovery
✓ More efficiency, less opex

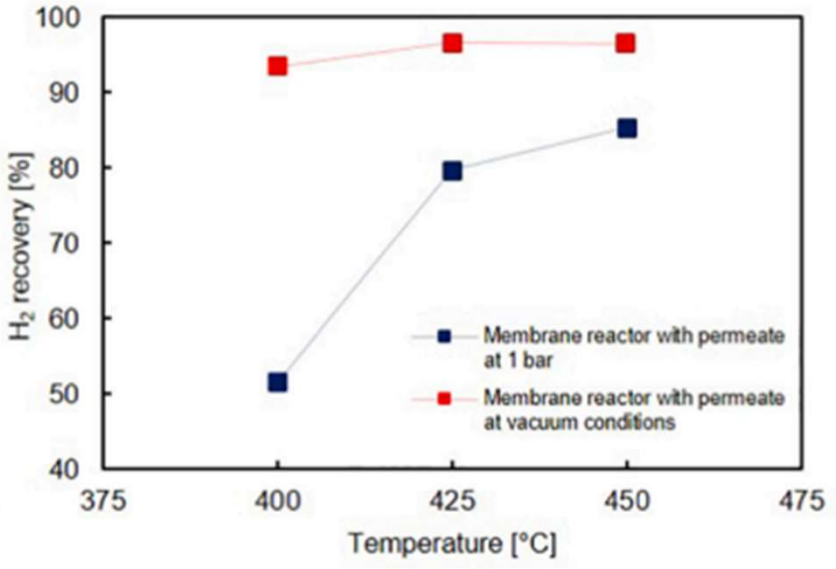
Medrano, J. A., Fernandez, E., Melendez, J., Parco, M., Tanaka, D. A. P., van Sint Annaland, M., & Gallucci, F. (2016). Pd-based metallic supported membranes: High-temperature stability and fluidized bed reactor testing. *International Journal of Hydrogen Energy*, *41*(20), 8706–8718. https://doi.org/10.1016/j.ijhydene.2015.10.094

Why integrate membranes inside the reactor

Example of impact of equilibrium shifting on methane reforming and ammonia cracking reactions





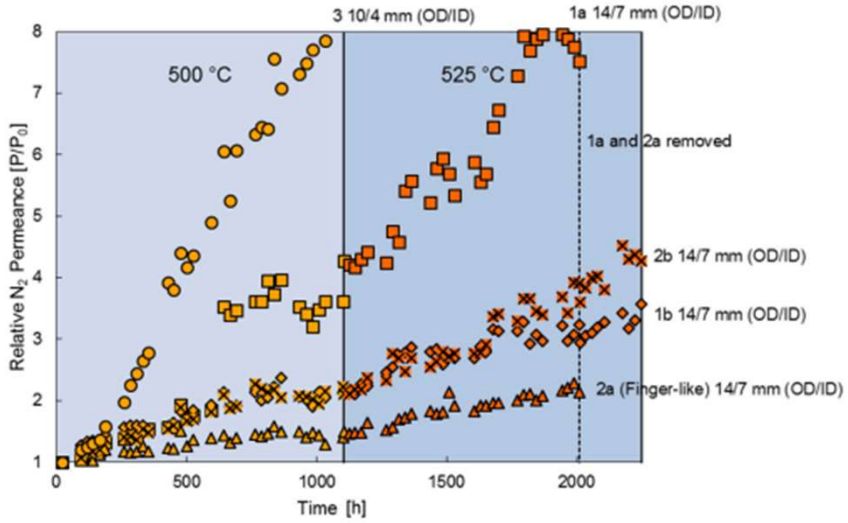


Cechetto, V., di Felice, L., Medrano, J. A., Makhloufi, C., Zuniga, J., & Gallucci, F. (2021). H2 production via ammonia decomposition in a catalytic membrane reactor. Fuel Processing Technology, 216. https://doi.org/10.1016/j.fuproc.2021.106772

The Technology – Double skin membranes

The long-term stability of the membranes in fluidized bed membrane reactors at high temperatures (> 400 °C) might be a problem:

- defects due to the mobility of the atoms present in the selective layer or
- consequence of the attrition by the fluidized particles.



Nooijer, N.d.; Arratibel Plazaola, A.; Meléndez Rey, J.; Fernandez, E.; Pacheco Tanaka, D.A.; Sint Annaland, M.v.; Gallucci, F. Long-Term Stability of Thin-Film Pd-Based Supported Membranes. *Processes* **2019**, *7*, 106.

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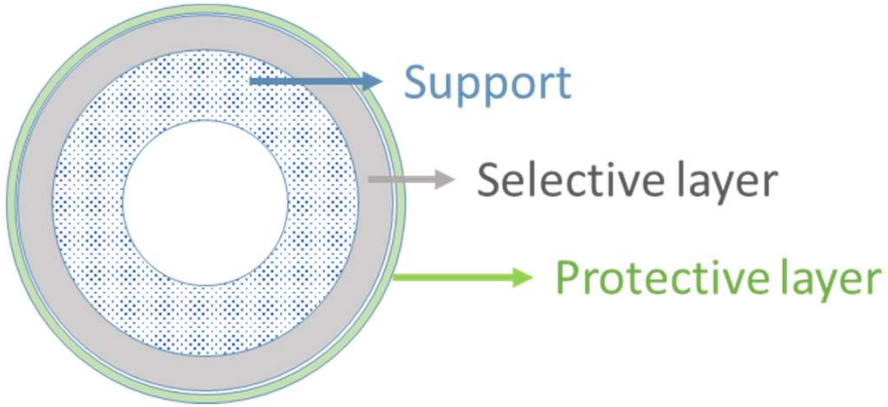
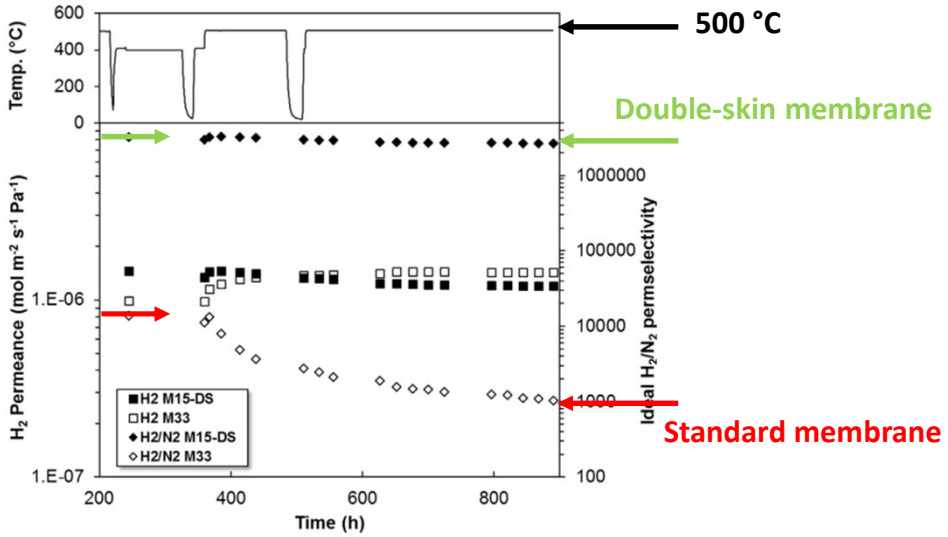
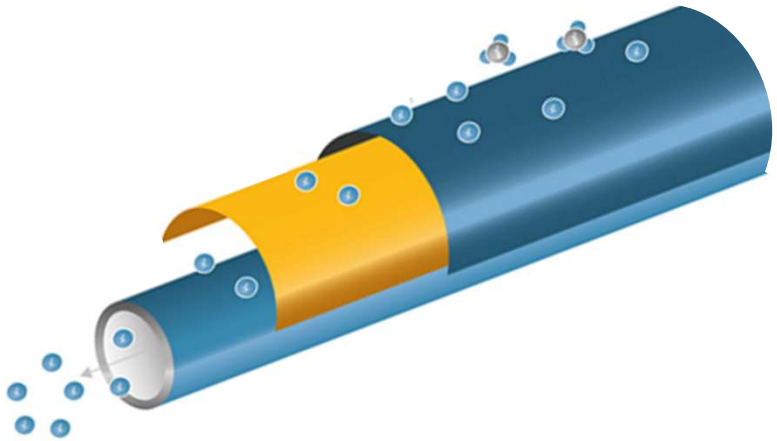




Arratibel.A , Medrano.J, Melendez.J, Pacheco Tanaka.D.A, van Sint Annaland.M, Gallucci.F, Attrition-resistant membranes for fluidized-bed membrane reactors: Double-skin membranes, Journal of Membrane Science, Volume 563,2018, Pages 419-426,

Outstanding H2SITE membranes

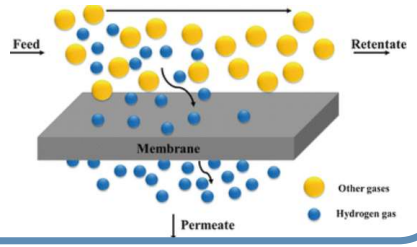


- Thin selective layer
- Porous supported membranes
- Protection against attrition which means we can target H_2 generation (unique)
- Very high reported H_2 flux [(a)]
  - Up to 2.2 10^{-6} mol s^{-1} m^{-2} Pa^{-1} at 450 ºC
- Purities of 99.98% achieved in ammonia cracking application [(b)]

(a) https://doi.org/10.1016/j.ijhydene.2022.04.240
(b) https://doi.org/10.1016/j.fuproc.2021.106772

We are not alone in the market

Catalytic membrane reactors

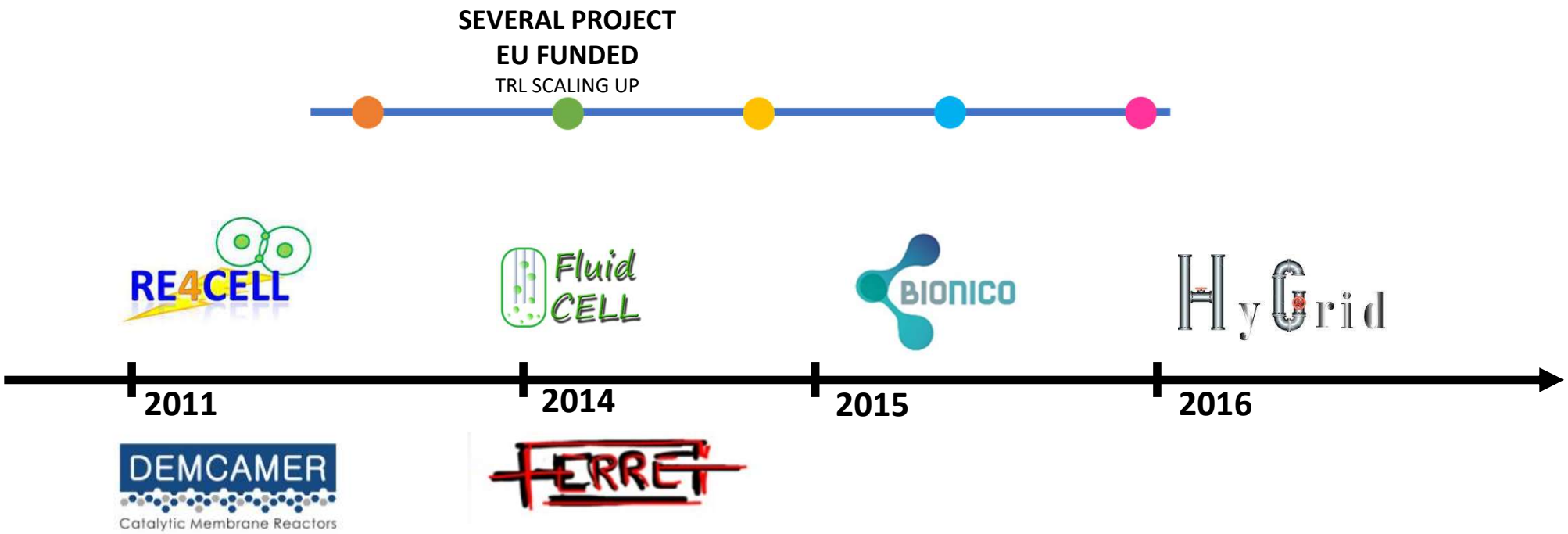


Electrochemical separation

Pressure Swing Adsorption

- CMR capable of solving hydrogen transport problem
- CMR are capable of separation when $\%H_2$ is low (<20%)
- CMR can resist some pollutants than others (EHC) don't
- CMR can be scalable (tons/day) in a compact solution with a reduced footprint
- Recovery is not hampered by reaching higher purity for CMR in the same way as PSA does
- CMR needs lower maintenance in continuous operation (unlike PSA)

Everything started long time ago…



- Fluidized/Packbed configuration
- Scaling up of reactors and H_2 production
- Different feedstocks (mainly methane but also bio-ethanol and biogas)
- Boost Pd membrane properties

- Authothermal reforming
- Targeting high H_2 purities
- Not only H2 generation (separation from the grid)
- LCA and techno-economic analysis

Being in the right place at the right time

OPORTUNITY
SOLVE HYDROGEN
TRANSPORT PROBLEM

- Existing technology for H_2 production in a compact and more efficient solution
- H_2 transport not been solved yet (although it is considered as a key enabler for the energy transition)
  - Transport cost adds 80% - 300% to the H_2 generation cost and
  - Inefficient: leaks of >10% H2

H2SITE is here

H2SITE IS HERE

FOUNDERS, INVESTORS AND
CURRENT PROJECTS

Founders and investors

2009-18

R&D

- +10 EU R&D projects
- 3 Patents

2019-21

Company creation & SEED round

Headcount: 3

- Technology demonstrators
- Business creation
- PoC for commercial customer

2022

Series A round

Membrane manufacturing line start-up

HC: 18

- New offices and industrial factory

2023

Delivery of first H2SITE systems

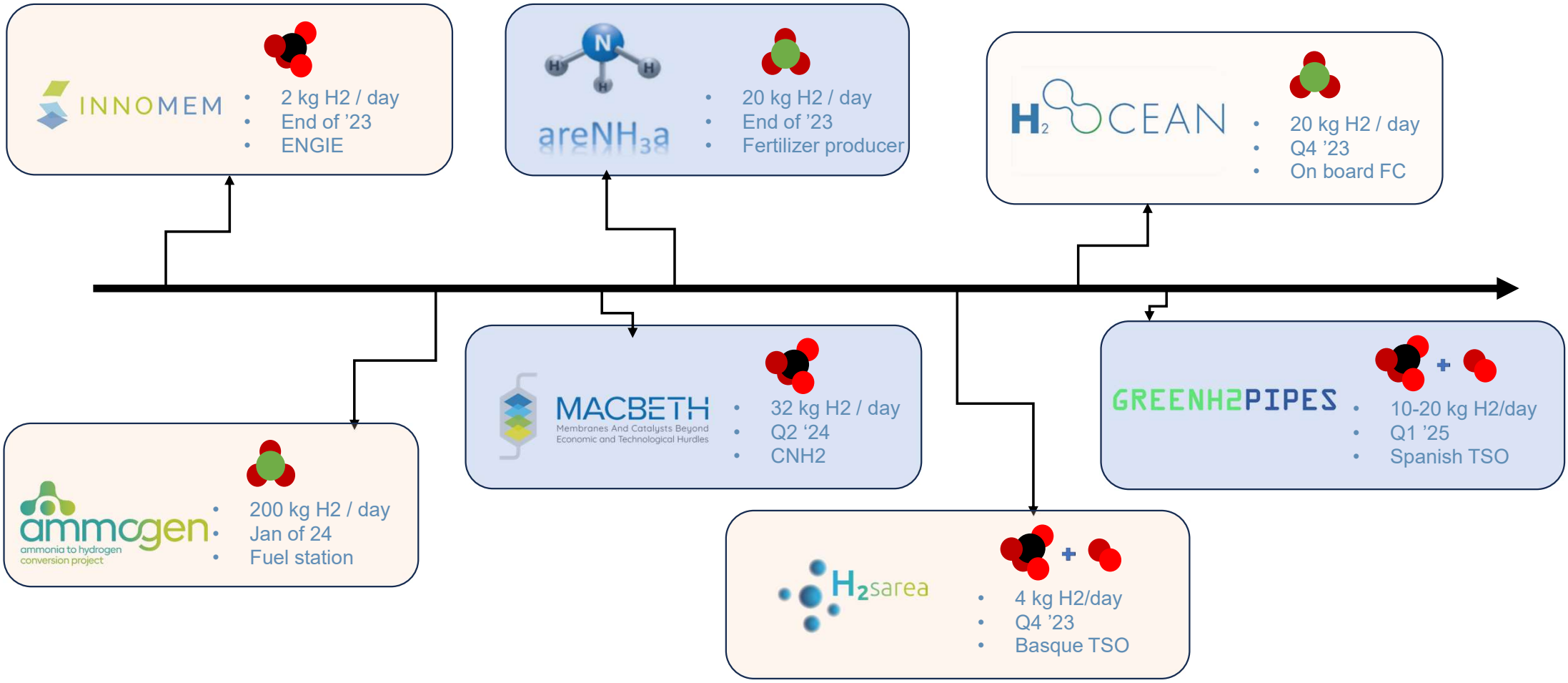
HC: 32

Membrane Manufacturing Line

Figure from ELPAIS

- First Pd-membrane industrial plant
- To feed our own H_2 production commercial systems
- Working with several batches at different stages
- Membrane production equivalent to 9000 tons H_2/year (ammonia application)
- Traceability and quality is essential to ensure later performance
- We do not sell membranes separately!

Current projects…

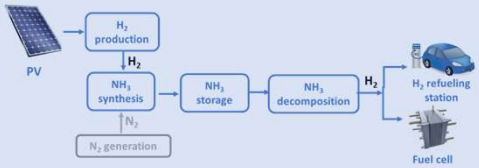


Currents projects…

areNH$_3$a

- Ammonia as a green H_2 carrier
- main activities around:
  - a) green H_2 production
  - b) NH_3 synthesis
  - c) storage and
  - d) NH_3 cracking

20 kg H2 / day
End of ’23
Fertilizer producer



MACBETH
Membranes And Catalysts Beyond Economic and Technological Hurdles

- Efficient CMR for relevant and large-scale processes:
  - Hydroformylation (HYFO);
  - Hydrogen production
  - Propane dehydrogenation
- Scaling up of key elements. Demonstration at industrial facilities (Evonik, CNH2 and ENGIE)

32 kg H2 / day
Q2 ‘24
CNH2

GREENH2PIPES

- Green H2 generation (electrolysis)
- Transport alternatives:
  - LOHC (Liquid Organic Hydrogen Carriers) and
  - H_2 in the grid
- H_2 separation (high purity grade)

10-20 kg H2/day
Q1 ’25
Spanish TSO

INNOMEM

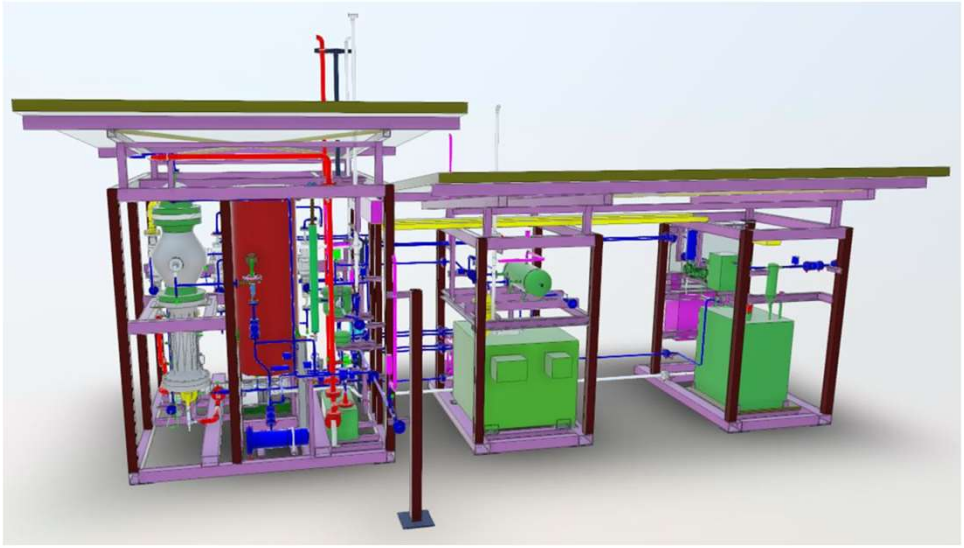


Figure from H2SITE

- 32 partners in project. Develop and organize a sustainable Open Innovation Test Bed (OITB) and membranes for different applications.
  - Key for membrane development
- **H_2 from biogas** at 450-500 ºC
- First H2SITE's prototype system delivered
- **Performance targets:**
  - > 99,9 % H_2 **purity**
  - 100 hours **continuous running**
  - 2 Nm3/h **H_2 production** (≈ 4 Kg H_2/day)

This project has received funding from the European Union´s Horizon 2020 research and innovation program under grant agreement No 862330 (INNOMEM project).

INNOMEM

Figure from H2SITE

- Biogas naturally generated from the decomposing of the organic matter by anaerobic bacteria.
- Biogas is susceptible for energy production
  - Depending of source, biogas ranges from 45% to 70% CH_4 and from 30% to 45% CO_2 [2]
- In 2019 there were over 18,943 biogas plants in Europe, with an installed capacity of 193 TWh [3]
- BG offers several advantages;
  - bio-renewable fuel, easily generated from local agricultural wastes
  - converting BG into H2 via SMR; less CO_2/kg H_2
  - 5.6 kg CO_2/kg H_2 vs 11-13.5 kg CO_2/kg H_2 [4]

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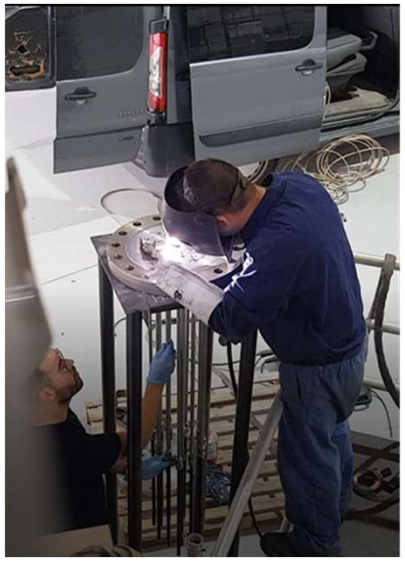
[2] Gioele Di Marcoberardino et al; Potentiality of a biogas membrane reformer for decentralized hydrogen production, Chemical Engineering and Processing - Process Intensification, Volume 129, 2018, Pages 131-141,
[3] European Biogas Association. EBA Annual Report 2020; European Biogas Association: Brussels, Belgium, 2020
[4] Noureddine Hajjaji et al. Life cycle assessment of hydrogen production from biogas reforming, International Journal of Hydrogen Energy, Volume 41, Issue 14, 2016, Pages 6064-6075



Figures from H2SITE

Main outcomes:

- KPI's achieved:
  - 100 hours (five days and nights) of continuous operation without any technical or safety issue
  - High-purity hydrogen obtained → 99,95 % H_2
  - 75% of H_2 h production capacity achieved
- Optimizing design, procurement, construction, operation and maintenance

This project has received funding from the European Union´s Horizon 2020 research and innovation program under grant agreement No 862330 (INNOMEM project).

Ammogen

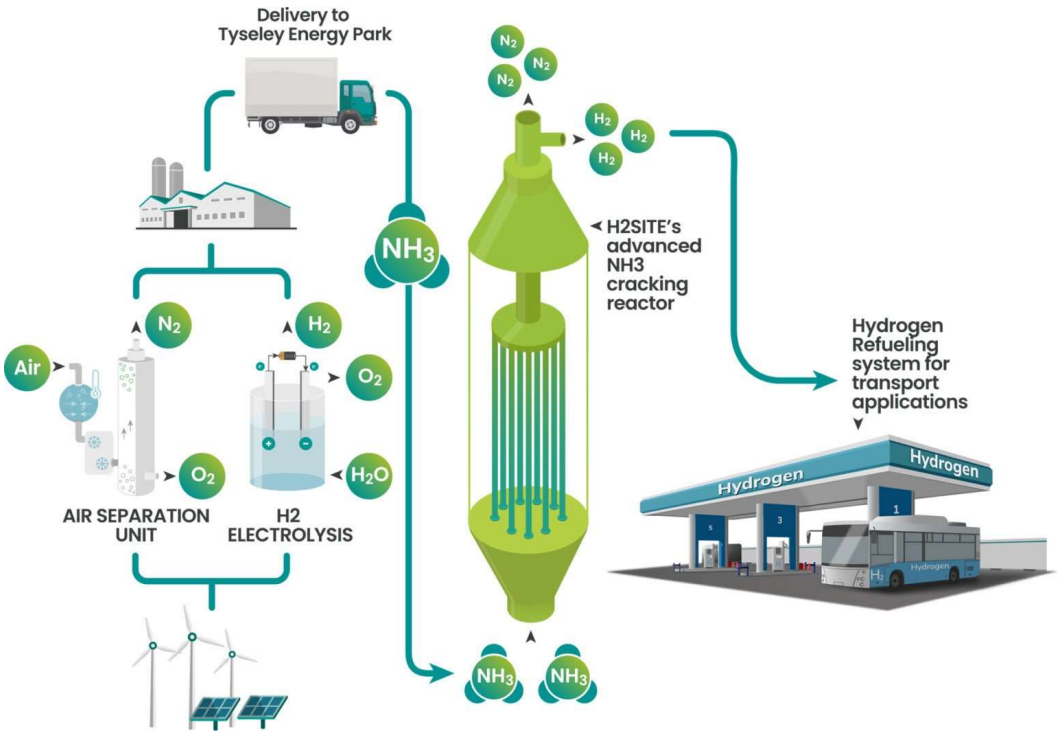


Figure from Ammogen Project website

- Project is part of UK's BEIS low carbon H2 competition (Business, Energy & Industrial Strategy) launched in 2021.
- Demonstrator of the use of ammonia as an energy carrier
  - transport larger amounts of energy in less space (more energy-efficient)
- H2SITE's technology will be used to produce H_2 for the bus fleet of the city of Birmingham.
  - Ammonia cracker will deliver 200kg/day of transport-grade H_2

Ammogen

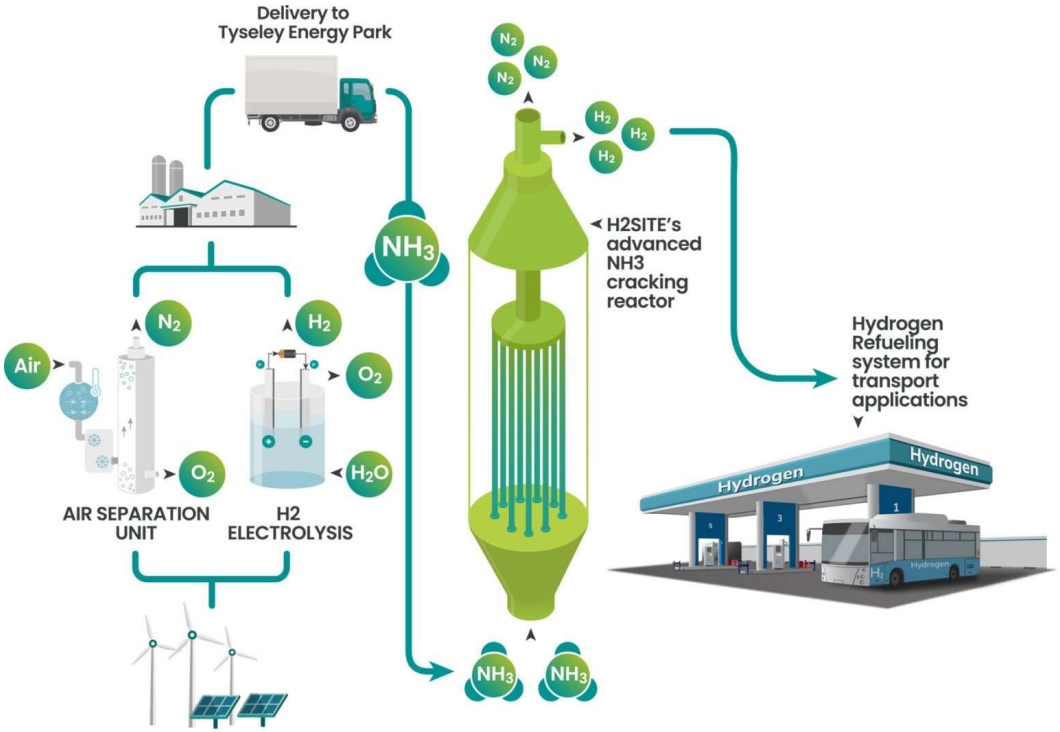


Figure from Ammogen Project website

- Ammonia cracker will fit in a 20-ft container to be delivered Jan'24
- To an existing and co-located hydrogen refuelling station at Tyseley Energy Park
  - Purity target: ISO 14687-2:2021
- Partners within the value chain of ammonia as Hydrogen Carrier (i.e YARA)

Ammogen

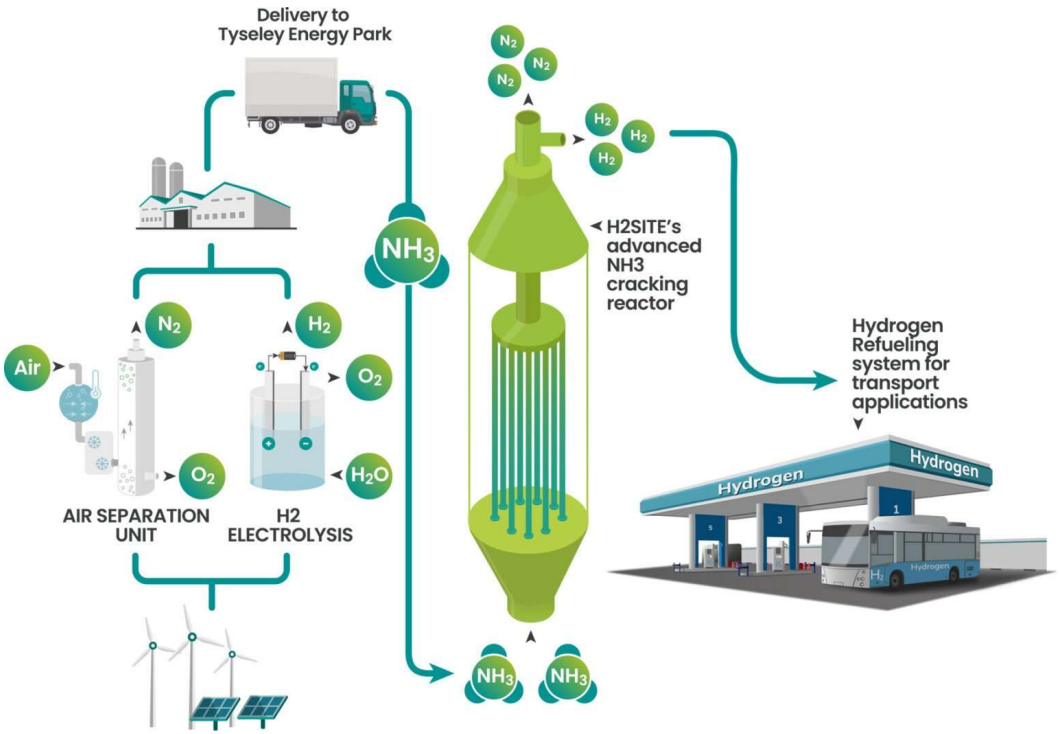


Figure from Ammogen Project website

Main outcomes:

- Biggest ammonia cracking membrane reactor for mobility solutions
  - Improvement in reactor heat integration and membrane installation
- Compact and commercial housing
  - Container / plug and play
- It matches three main players in the green hydrogen economy:
  - Feed supplier
  - Technology enabler
  - End-user (mobility sector)

H2SAREA

Figure from H2SITE

Figure from ELPAIS

- Validation of entire ecosystem for a CH_4 grid with (up to) 20% of H_2 .

H2SAREA

Figure from H2SITE

Figure from ELPAIS

- "European Hydrogen Backbone EHB"
- Accelerate Europe's decarbonisation journey based on existing and new pipelines
- 75% of the infraestruture could be used for H_2 transport
  - Efficient, safe and cost-effective
- Materials, compounds and systems must be developed.

H2SAREA

Figure from H2SITE

Figure from ELPAIS

- Validation of entire ecosystem for a CH_4 grid with (up to) 20% of H_2 .
- Loop facility to test those elements being part of the infrastructure grid such as:
  - Materials
    - Compressors to feed gas stations
    - Behaviour towards embrittlement
  - Security issues (detectors and procedures)
  - Applications
    - H_2/CH_4 separation
    - H_2/CH_4 burner

H2SAREA

Figure from H2SITE

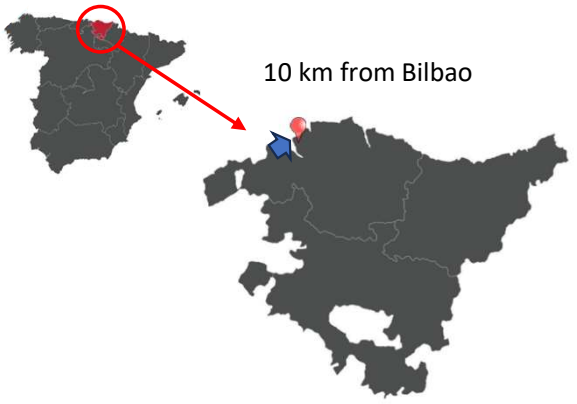


Figure from ELPAIS

- H2SITE deblender will deliver up to 4 kg H_2 /day of pure hydrogen
- % H_2 can be tunned (5 - 20%) in the feed
- System already in TSO facilities since Sep ‘23
- Commissioning ongoing (more than 20 hours running). Recovery >95%, H_2 < 2% and H_2 purity: fuel cell

H2SAREA

Figure from H2SITE

Figure from ELPAIS

Main outcomes:

- First industrial deblending plant in Spain from NG + H2 mix
- Working in a closed loop feed with actual NG from the grid and operating conditions similar.
- Scaling system towards higher pressures (80 bar) and bigger systems (100 kg H_2/day) will come next

H2OCEAN

Figure from Ammogen Project website

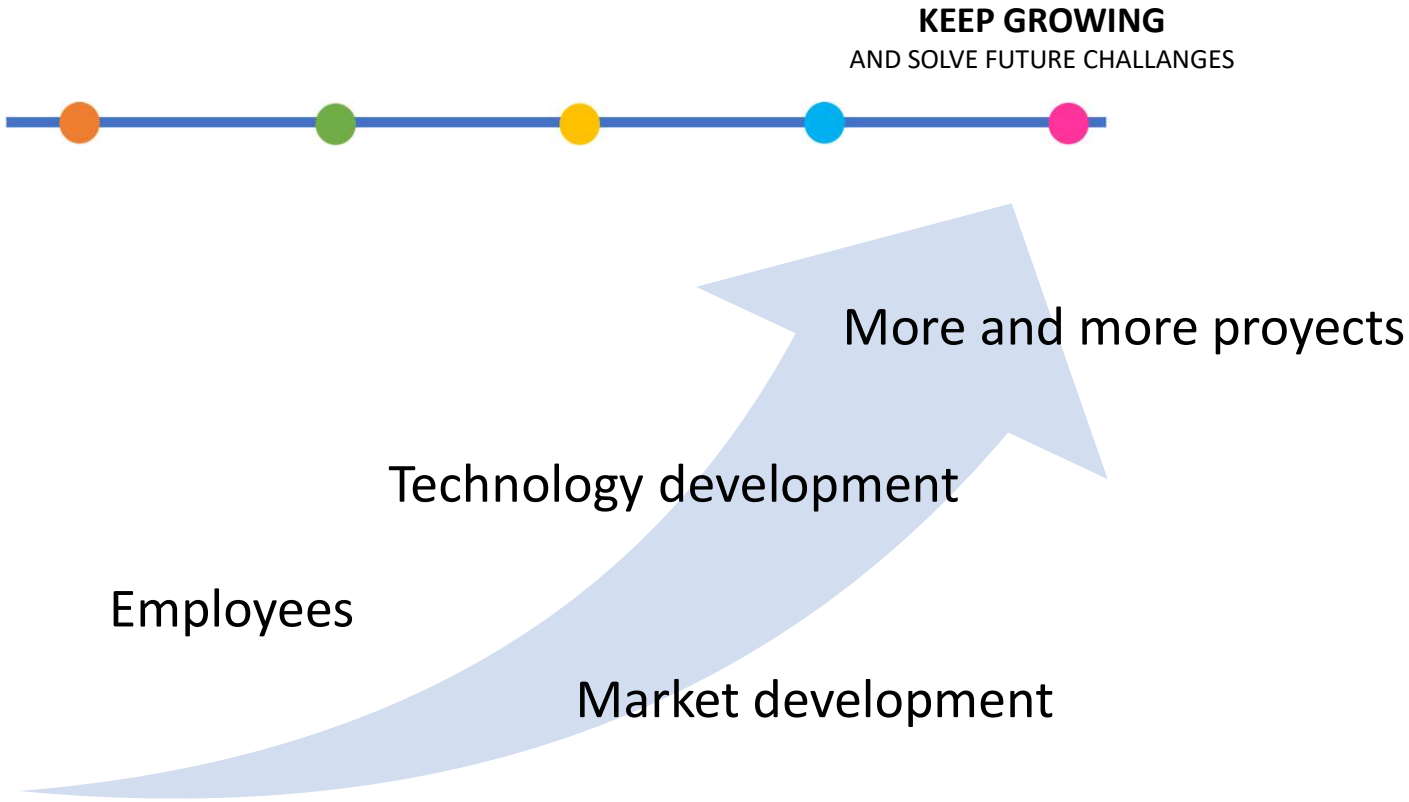
- Local project
- Demonstrator of the use of ammonia in on-board generation
- H2SITE's technology used to produce H_2 for fuel cell and make boat work
  - 20kg/day of transport-grade H_2

H2OCEAN

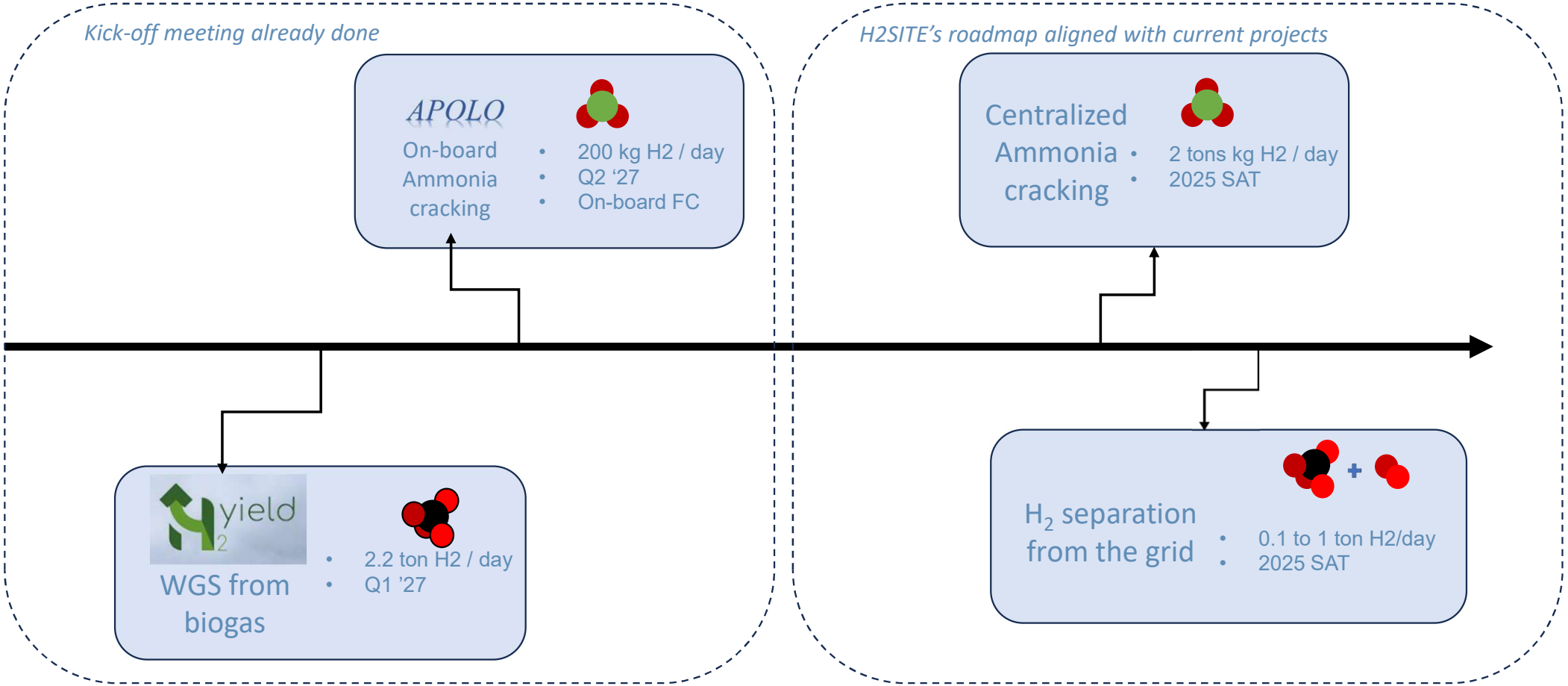
Figure from Ammogen Project website

- Boat trip of ≈ 20 km
- Hydrogen production from ammonia the entire trip
- 1 kg H_2/hour produced during several hours, able to feed 20 kW fuel cell (not linked to critical engine parts)

…and what comes next?

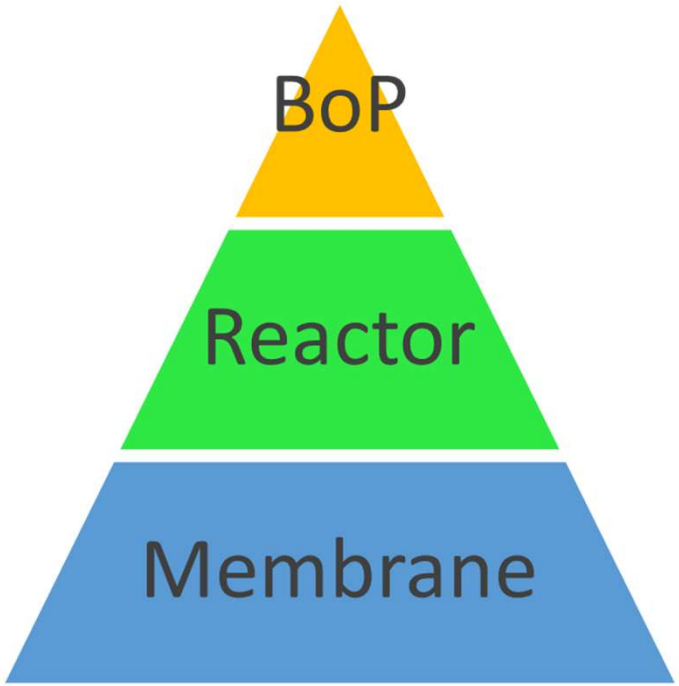


Future projects



H2SITE wants to enable (and lead) the Hydrogen economy in the future

…thanks to **cost**, **efficiency** and **footprint**…



to achieve more competitive solutions

.. in bigger and more efficient reactors…

Making productive membranes…

Which is the way to achive the best H_2 selective membrane?

High H2 flux
(Recovery)

Stability during
perfomance
(Lifespan)

High selectivity
(Purity)

Membranes are like a three-legged chair

What is H2SITE caring about and how we could collaborate?

Cost of membranes is obviously something everybody cares, but we pay attention to…

Support

Mechanical strenght

- Porosity
- Material

Size and form

- Membrane distance limitation
- CAPEX

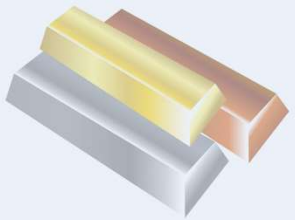
Surface quality

- Mean pore size
- Roughness

What is H2SITE caring about to have the best H_2 selective membrane?

Cost of membranes is obviously something everybody cares, but we pay attention to…

Selective layer



Alloy

- Permeability
- Resistance to contaminants

Thickness

- Permeance (flux)
- Defect-free

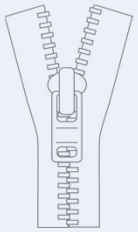
Sustainable process

- Deposition efficiency
- Metal recovery

What is H2SITE caring about to have the best H_2 selective membrane?

Cost of membranes is obviously something everybody cares, but we pay attention to…

Sealing



Defect-free

- Impurities
- % H_2 purity

Geometry

- Membrane distance limitation
- CAPEX

Large scale

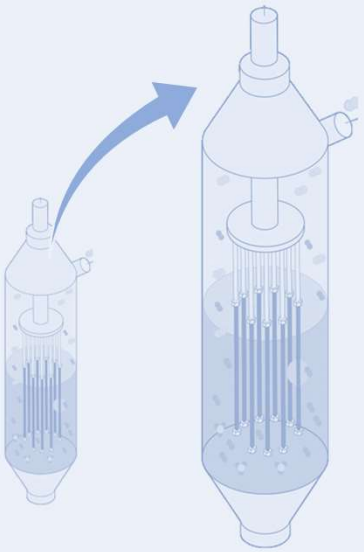
- Integration philosophy
- Reproducibility

What is H2SITE caring about to have the best H_2 selective membrane?

Not only about membranes but also about…

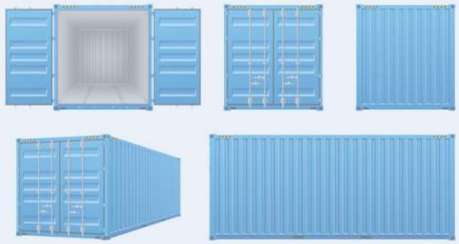
Reactors

- Flow optimization
- Catalysis
- Heat integration
- Maximum diameter/height



Balance of plant (BoP)

- Power needs / efficiency
- Standarization
- Outlet pressure
- Safety & ESD



Main outcomes

- ≈ 300 kg H_2 /day in 7 systems from 3 different feedstocks, right now.
- Demonstrated of first on-board ammonia cracking producing H_2 continuously
- Up coming project including a 2.2 ton H_2 / day to be delivered in ‘27
- Short-term future will demand a huge effort in terms of development at three levels:
  - Membrane, Reactor and BoP to gain in cost reduction, efficiency and footprint
- H2SITE’s technology shows great performance (HRF and purity) and can be competitive compared with PSA and EHC
- Small scale separation molecules will lead H2SITE to have big impact in the world
  - Think about hydrogen molecule size and the change in energy economy we want to lead

H2 SITE

Membrane reactors for H2 generation

Thanks for your attention

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