HYGRID

FLEXIBLE HYBRID SEPARATION SYSTEM FOR H2 RECOVERY FROM NG GRIDS

FCH-2 GRANT AGREEMENT NUMBER: 700355

Start date of project: 01/05/2016 **Duration: 3 years**

WP10 –Exploitation workshop

D10.16

Topic: Development of technology to separate hydrogen from low-concentration hydrogen streams
Funding scheme: Research and Innovation Action
Call identifier: H2020-JTI-FCH-2015-1

Due date of deliverable: 01-05-2018	Actual submission date: 09-07-2018	Reference period: 01-05-2016 – 18-05-2018
Document classification code (*): HYGRID-WP10-D10.16-DLR-TUE-09072018-v01.docx		Prepared by (**): TUE

Version	DATE	Changes	CHECKED	APPROVED
v0.1	06-07-2018	First Release	TUE	S.Wassie

Project funded by the FCH-2 JU within the H2020 Programme (2014-2020)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	
CON	Confidential, only for members of the Consortium	

(*) for generating such code please refer to the Quality Management Plan, also to be included in the header of the following pages

(**) indicate the acronym of the partner that prepared the document

Project Number:

700355

Project acronym:

HYGRID

Project title:

FLEXIBLE HYBRID SEPARATION SYSTEM FOR H2 RECOVERY FROM NG GRIDS

Exploitation workshop

HYGRID Workshop 2018- on Flexible Hybrid Separation System for H_2 Recovery from Natural-Gas Grids

SAES hosted the HYGRID Exploitable Workshop on flexible hybrid separation for H_2 recovery from NG grids. The focus was on hydrogen generation, distribution and transportation, challenges of distributing hydrogen into the NG networks and the purity requirements.

The workshop was part of the first transfer of knowledge event of the HyGrid project, contributing to the increase of knowledge, and competitiveness of the hydrogen economy in the EU community.

In the following section the announcements, the presentations and some of the moments of the workshop are presented.

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 700355. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY

NEWS

HyGrid Workshops 2018
Exploitable Workshop on Flexible Hybrid Separation System for H_2 Recovery from NG Grids

May 17th, 2018, Lainate - Italy

On 17 May 2018, a Workshop will take place in SAES Getters SpA, Viale Italia 77, 20020 Lainate (MI), Italy.
Agenda and registration form available on this website.

Flexible **Hy**brid separation system for H2 recoveryfrom NG **Grid**s

Project Duration: 3 years   Starting date: 01-May-2016

Project Coordinator: Fausto Gallucci, TUE, The Netherlands

Grant agreement n°.: 700355

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 700355. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY

- Home
- Summary
- Objectives
- Partnership
- **Dissemination**
  - Communication
  - Presentations
  - Publications
  - Consortium Workshops
- Events
- Links
- Contact Us

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Consortium Workshops

Exploitation Workshop on Flexible Hybrid separation for H2 recovery from NG Grids

Lainate, Italy, May 17, 2018

We are pleased to invite you to the 1st Exploitation Workshop of the HyGrid Project.

HyGrid aims at developing an advanced high performance separation system for hydrogen recovery from NG grids. One of the main problems for the implementation of the hydrogen based economy is the transportation from production centres to the end user both industries and population. To solve this problem, besides the in-situ production of hydrogen, the use of the existing Natural Gas network has been proposed for storing and distributing hydrogen. However, cost effective separation technologies for direct separation of hydrogen from the natural network should be developed for separating and purifying the hydrogen to match the end user requirements.

HyGrid system combines three different technologies (electrochemical separation, membrane separation and temperature swing adsorption) to develop a cost effective H2 separation pilot from low (2-10%) and very low (< 2%) H_2 blends in natural gas grids.

The project targets a pure hydrogen separation system with power of < 5 kWh/kg_{H2} and cost of < 1.5 €/kg_{H2}. The pilot will be designed for the separation and purification of >25 kg/day of hydrogen (ISO 14687).

Programme

Presentations will be given by both Academia and Industry. The complete programme can be downloaded at the following link: **Agenda HyGrid Workshop 2018**.

Important dates

Date	Event
11^{th} May 2018	Deadline for registration
17^{th} May 2018	Workshop

Registration

Attendants should register filling in the attached file: **HyGrid_Workshop_Registration_Form** and sending it at the following email: HyGridWorkshop2018@tecnalia.com.

Participation to the workshop is free of charge.

Venue

The Conference will take place at SAES Getters SpA, Viale Italia 77, 20020 Lainate, Milan, Italy, www.saesgetters.com.

SAES is located about 36 Km from Malpensa Airport and about 22 Km from Milano city.
Taxi is recommended when landing at Malpensa airport.
Alternatively, every 30 minutes a train can be taken to Saronno station and then a taxi (about 8 km).

Accommodation

Hotel Litta Palace, Lainate, http://www.hotellittapalace.com/en/home/
Contact the hotel directly for the reservation and ask for the special fare guaranteed for SAES guests. Please make the reservation within April 15th
To reach the hotel, look at its web page: http://www.hotellittapalace.com/en/contacts/

Star Hotel Gran Milan, Saronno, https://www.starhotels.com/it/i-nostri-hotel/grand-milan-saronno/
Contact the hotel directly for the reservation and ask for the special fare guaranteed for SAES guests. Please make the reservation within April 15th
The hotel is at walking distance from Saronno train station and there is a direct train line from Malpensa.

HYGRID

FLEXIBLE HYBRID SEPARATION SYSTEM FOR H2 RECOVERY FROM NG GRIDS

FCH-2 GRANT AGREEMENT NUMBER: 700355

Exploitation Workshop on Hydrogen Recovery with Hybrid separation systems

SAES Getters SpA, Viale Italia 77 - Lainate (Mi), May 17th, 2018

Agenda

10:30 - 11:00 Registration/Coffee

11:00 – 11:15 Introduction to SAES Group and SAES H_2 purifiers
Marco Succi (SAES).

11:15 – 11:30 HyGrid Project: objective and scope
Fausto Gallucci (TUE).

11:30 – Session 1 – Industrial presentations

11:30 - 11:50 H_2 generation by steam reforming
Emma Palo (KT Kinetics Technology SpA).

11:50 - 12:10 Pressurized Alkaline and PEM electrolyzers for Power To Gas applications
Guy Verkoeyen (Hydrogenics).

12:10 - 12:30 The challenge of distributing Hydrogen into the natural gas network
Angel Gutierrez (NORTEGAS).

12:30 – 13:30 Lunch

13:30 – Session 2 – HyGrid presentations

13:30 - 14:00 Hydrogen separation using membranes
Alfredo Pacheco (TECNALIA) & Giorgio Macchi (SAES).

14:00 - 14:30 Electrochemical hydrogen compression and purification
Leonard Raymakers (HYET).

14:30 - 15:00 Design of the HyGrid prototype
Leonardo Roses (HYGEAR).

15:00 – 15:30 Coffee Break

15:30 - 15:50 Purity requirements for hydrogen applications: the latest on the ISO14687
Arul Murugan (NPL).

16:00 - 17:30 Visit to SAES Pure Gas Handling and other SAES Laboratories (SAES).

17:30 – End of the meeting

About SAES Group

making innovation happen, together

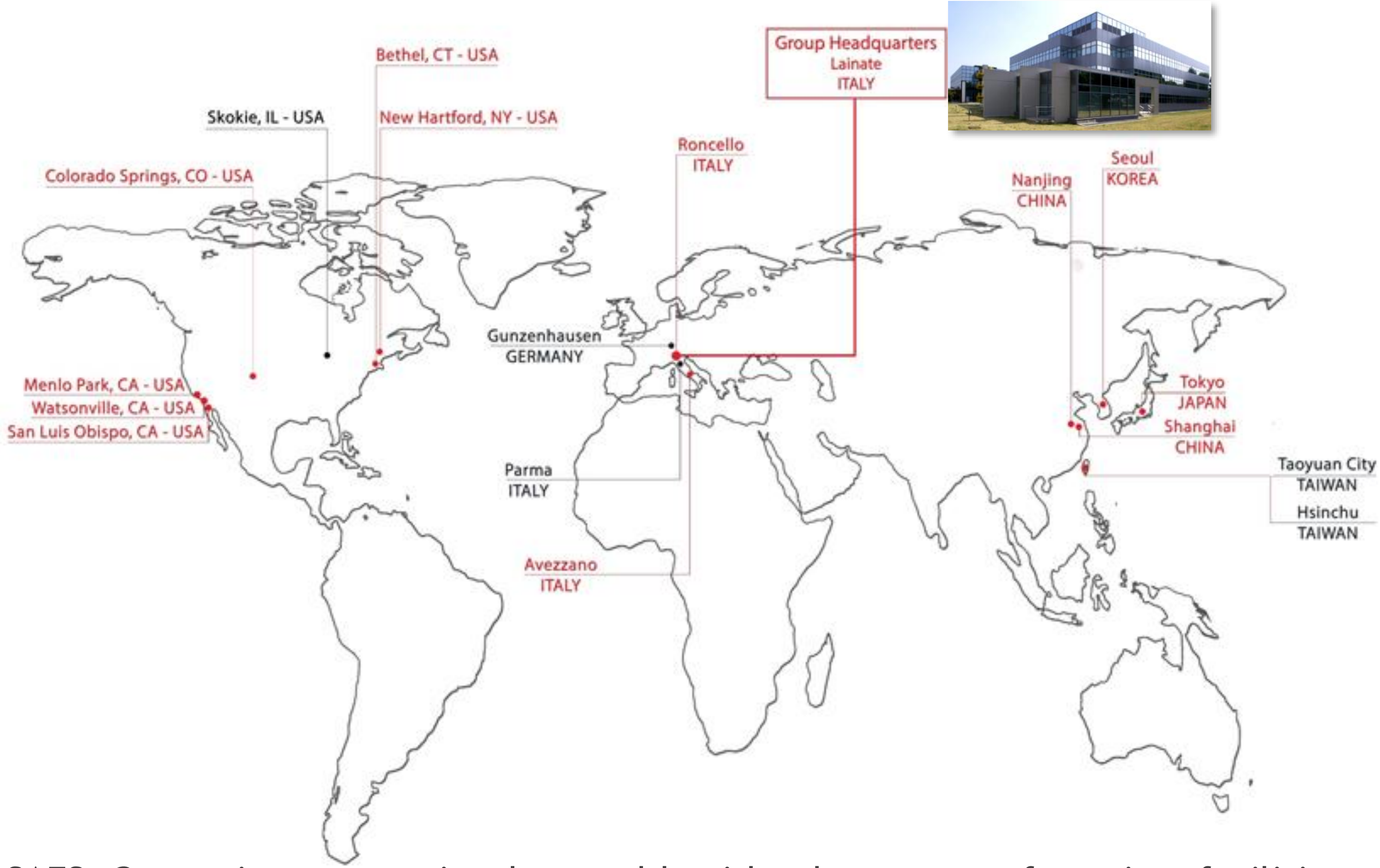
Core Business

SAES® is an **advanced functional materials** Group, focusing its business on the **development and production of proprietary and specifically engineered solution** (components and systems) for many industrial and scientific applications.

The wide technological portfolio and the full vertically integrated production processes make SAES a **world leader** supplier of hi-tech, high quality solutions like:

- **Getters components and systems**
  to guarantee the proper vacuum conditions, modified atmosphere or gas purity in a variety of applications spanning from consumer electronics up to scientific research areas
- **Nitinol based components**
  for the healthcare market (minimal invasive surgery: e.g. stents)
- **Shape memory components and systems**
  like actuators and valves for consumer electronics, automotive and white goods industries
- **Functional composites and coated films**
  to protect goods for the packaging industry

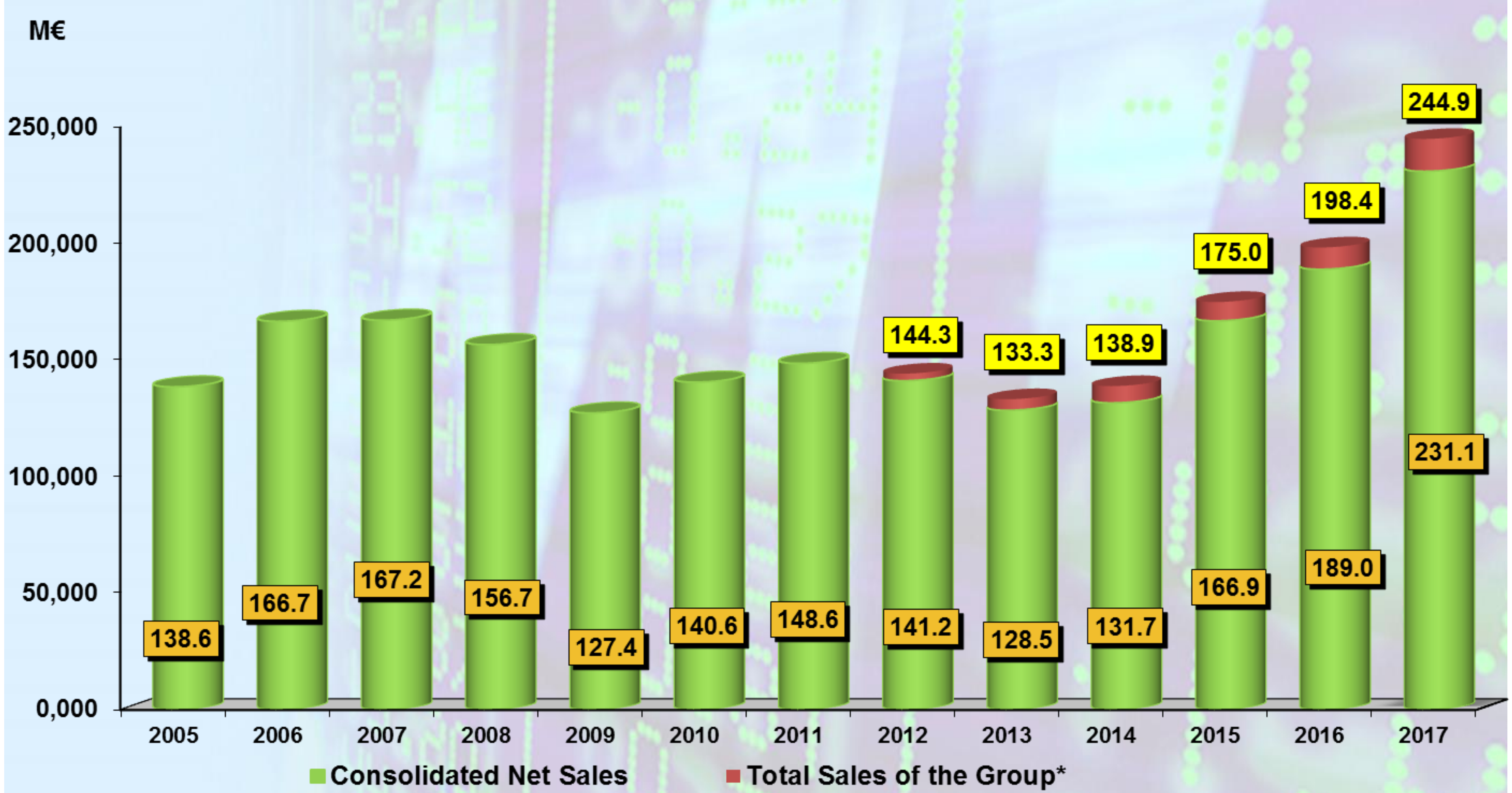
Global Presence



SAES Group is present in the world with eleven manufacturing facilities, distributed across Europe and United States, and has an active sales and technical service network on a global scale.

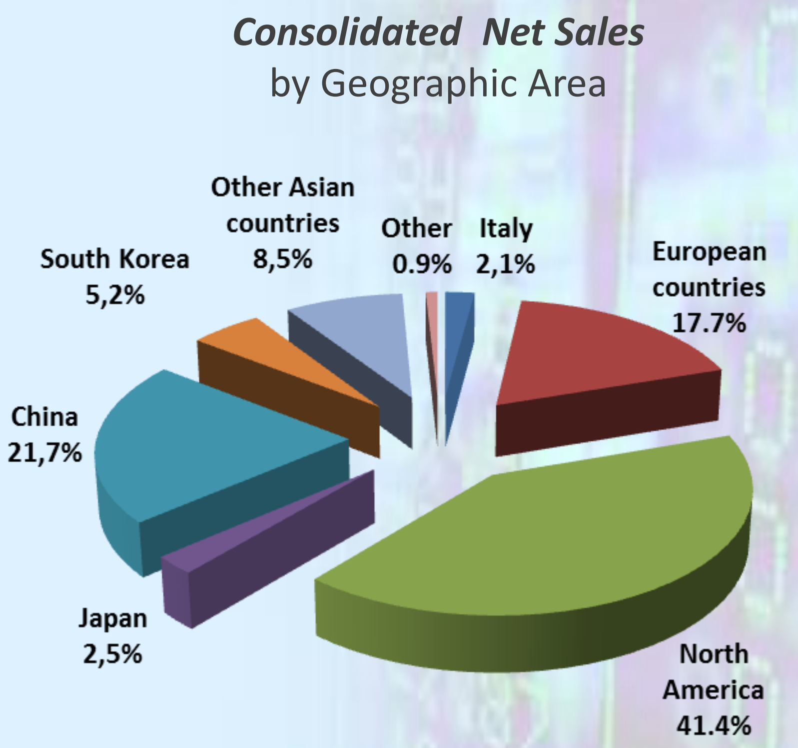
making innovation happen, together

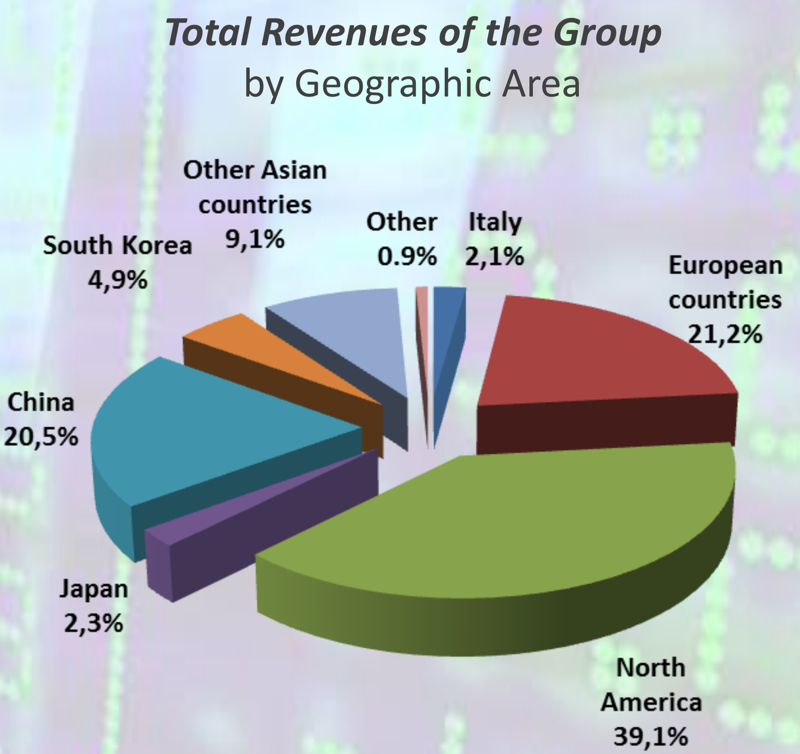
SAES Group Sales - 2017



* Achieved by incorporating the 50% joint venture Actuator Solutions, the 49% joint venture SAES RIAL Vacuum S.r.l. and the 33.79% joint venture Flexterra with the proportional method instead of the equity method

SAES Group Sales - 2017





Business Organization

INDUSTRIAL APPLICATIONS

- Getters & Dispensers
- Solutions for Vacuum Systems
- Sintered Components for Electronic Dev. & Lasers
- Systems for Gas Purification & Handling

SHAPE MEMORY ALLOYS

- Nitinol for Medical Devices
- SMA for Thermal & Electro Mechanical Devices

ADVANCED PACKAGING

- Solutions for advanced packaging

BUSINESS DEVELOPMENT

- Organic Solutions for Electronic Devices

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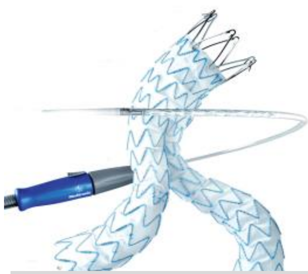
SHAPE MEMORY ALLOYS BU

About 32,8% of Consolidated Revenues 2017

Nitinol for Medical Devices - about 28,7%

This Business Area follows all SMA medical applications. NiTinol is used in a wide range of medical devices, particularly in the cardiovascular field. Its superelastic properties are ideal for the manufacture of devices used in non-invasive surgery such as catheters for navigating within the cardiovascular system and self-expanding devices (aortic and peripheral stents or cardiac valves).



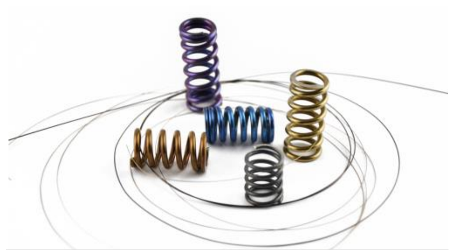
Stent Graphs

SMA for Thermal & Electro Mechanical Devices - about 4,1%

The shape memory alloy property is used in the production of various devices (valves, proportional valves, actuators, release systems, mini-actuators). This Business Area follows the use of SMA devices in the industry that is transversal to many application areas, including consumer electronics, automotive, home automation, and white industry.

Cardiac Valves

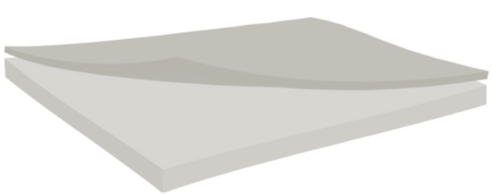
Guidewires & Catheters



Wires & Springs SmartFlex®

Actuators

ADVANCED PACKAGING BU



About 5,4% of Consolidated Revenues 2017

Solutions for Advanced Packaging

The SAES Group has recently expanded its business offer adding **flexible packaging materials**, focusing on the development of high performance polymer coatings for plastic films, with a particular focus on biocompatibility and low environmental impact. Unique expertise in this field is the result of SAES investment in the field of innovation and research of "hybrid" technologies that integrate getter materials into polymer matrices.

SAES developed an innovative packaging that can be used when its contents are environmentally sensitive. In fact, thanks to the **active coatings**, the packaging incorporates, in addition to the traditional protective functions, the ability to increase the life of the product or improve its features.

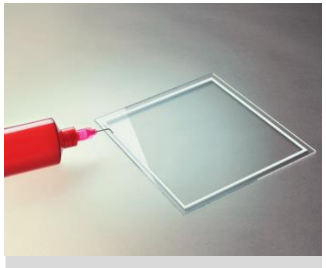
Fields of application include **food** such as fruit and vegetables, but also non-fresh products that require controlled storage, both in food and in food-related areas such as **home & personal care, nutraceuticals and the pharmaceutical industry**

About 0,7% of Consolidated Revenues 2017

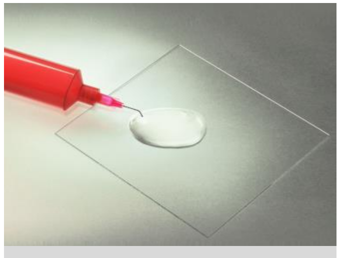
Organic Solutions for Electronic Devices

This area allows SAES to deploy its unmatched experience in the field of innovation in "hybrid" technologies (integrating getter materials into polymer matrices).

This unit deals with developments mainly related to applications in electronics and photonics, including display and photovoltaic sectors.
A special focus is dedicated to the **OLED** (Organic Light Emitting Diodes) industry, the ultimate innovation frontier in information **display** and **lighting**.
SAES products based on functional chemicals also enable **implantable medical devices** such as pacemakers and cochlear implants.

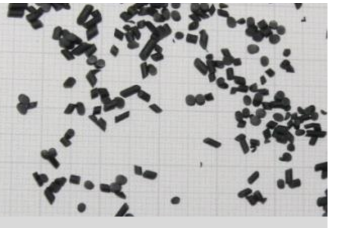


Active Barrier Sealants



Active Fillers

Dispensable Getter Composites



Hot Melt Getters

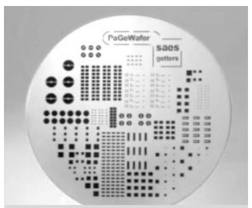
INDUSTRIAL APPLICATIONS BU

About 61,1% of Consolidated Revenues 2017

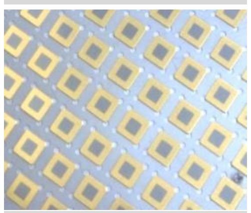
- **Getters , Metal Dispensers , Cathodes and NEG Pumps - about 24,6%**

These areas deal with sales of components and systems for:

- electronic and photonic devices,
- sensors for various market sectors: consumer electronics, security & defense, healthcare diagnostic, aerospace, industrial
- lamps,
- solutions for vacuum insulation (for cryogenic applications, for both domestic and high-temperature solar collectors, for thermos and for vacuum insulating panels for the white industry)
- solutions for vacuum systems utilized both in industrial and scientific applications like: analytical instruments, vacuum systems for research and particle accelerators



PageWafer®

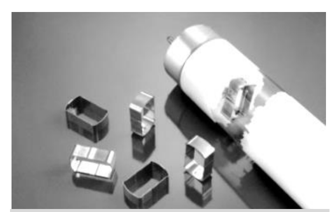


PageLid®

Alkali Metal Dispensers

Sintered Porous Getters

Smart Combo



Hg Dispensers
Total Quality Shield TQS®

Non Evaporable Getter Pumps

INDUSTRIAL APPLICATIONS BU

Systems for Gas Purification & Handling - about 36,5%

In the microelectronics market, SAES Group is active in the development and sale of advanced gas purification systems for the semiconductor industry and other industries using ultra-pure gas in their processes (Lithography, Display LCD & OLED, Fuel Cells, Fiber Optics).

Through our Company SAES Pure Gas, Inc., the group offers a complete range of purifiers for both process gases and special gases.

MegaTorr®

MicroTorr®

MonoTorr®

CollecTorr®

SAES Core Purification Technologies

Customized and shaped around end user requirements SAES develops Purification Solutions using:

- Ambient Temperature Adsorbent materials (Rare Gases, Nitrogen, CDA, Hydrogen, Specialty Gases)
- Heated Getter materials (Rare Gases, Nitrogen, Hydrogen)
- Heated Catalytic materials (Oxygen, CDA)
- Cryogenic Purification (Hydrogen)
- Palladium Membranes (Hydrogen)

Technologies for Hydrogen Purification

The most **common technologies for H_2 purification:**

- PSA (Pressure Swing Absorption)
- Membrane (non precious metal)
- Electrochemical purification and compression

- **Adsorber Purifiers**
- **Regenerable Adsorber Purifiers**
- **Getter Based Purifiers**
- **Palladium Purifiers**
- **Cryogenic Separation**

SAES Technologies for H_2 Purification

- Adsorber
- Regenerable Adsorber
- Getter and Cryogenic
- Palladium Membrane

Adsorber Technology

- Total flexibility in size and configuration
- Flow rates up to 2,000 slpm
- Pressure ratings up to 200 bar
- Low pressure drop
- Minimal cost of ownership
- Regenerable offline

- Automated Microprocessor Controller
- Continuous purification
- Compact
- Low power consumption
- System Alarms
- H_2 Leak Detection Sensor
- Vented Cabinet Purge

Heated Getter Purification

MonoTorr Purifiers (PS series)

Key Features (not on all models)

☐H_2O, O_2, CO, CO_2, H_2, **CH_4, N_2** removed to < 1 ppb

☐Life status sensor

☐Alarms for loss of power and pneumatics

☐Auto Bypass

☐Pneumatic in/out valves

☐Integral 0.003 µm metal filter

Maximum Flow: 200 sccm 5 slpm 75 slpm 150 slpm

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Pd Hydrogen Purifiers Product Range

- PS7-PD05-XX <50 slpm
  Small table-top unit for Laboratory/Research
- PS7-PD1-XX <660 slpm
  One Cell POU or Bulk Gas Purification
- PS7-PD2-XX <1,320 slpm
  Two Cells POU or Bulk Gas Purification

PS7-CR Benefits

- Lower cost of operation when compared to traditional heated getter purifiers.
- Higher flow capabilities when compared to heated getter or palladium membrane purifiers.
- Lower pressure drop when compared to heated getter purifiers.
- Lower inlet pressures needed when compared to palladium membrane purifiers.
- No consumable purification column.
- Can be fitted to operate in Class 1 Div.2 / Zone 2 environments.
- IC Ex certification available

Thank you for your attention

saes group

www.saesgroup.com

Flexible Hybrid separation system for H_2 recovery from NG Grids

HyGrid

Exploitation Workshop– 17-05-2018

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 700355.This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY

Duration: 3 years. Starting date: 01-May-2016

Contacts: F.Gallucci@tue.nl

Outline

- General Concept
- Target
- Layout
- Expected impact
- Participants
- Work package structure
- Time-line

General concept

HyGrid **aims** at developing of an advanced **high performance**, cost effective separation technology for **direct separation of hydrogen from natural gas networks.**

The system will be based on:

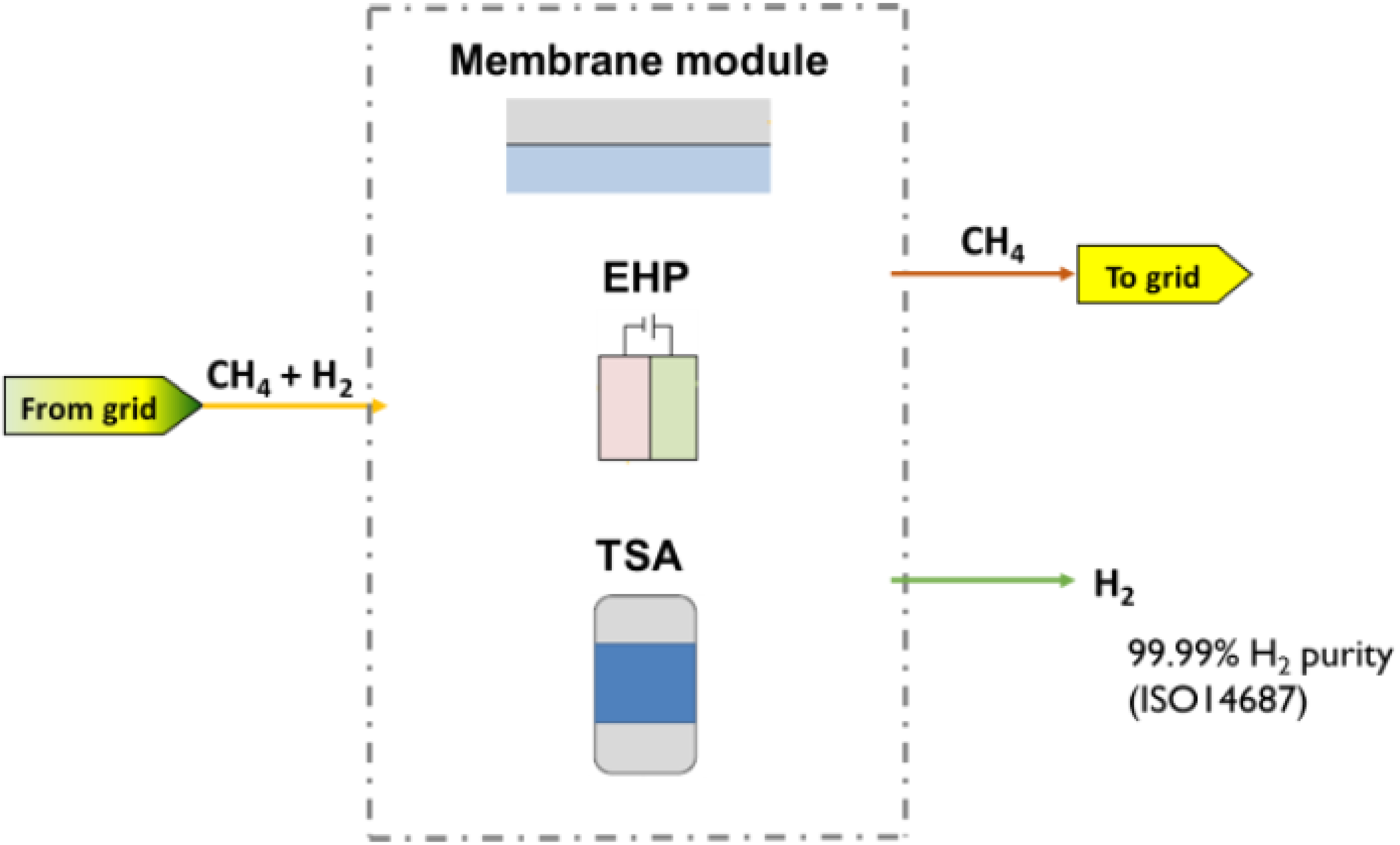
- Design, construction and testing of a **novel membrane based hybrid technology** for pure hydrogen production (ISO 14687) combining three technologies for hydrogen purification:
  - **Membrane separation technology:** is employed for removing H2 from the "low H_2 content" (e.g. 2-10 %)
  - **Electrochemical hydrogen separation** (EHP): optimal for the "very low H_2 content" (e.g. <2 %)
  - **Temperature swing adsorption** (TSA): to purify humidity produced in both systems upstream.

Target

- The project targets a pure hydrogen separation system with **power** and **cost** of **< 5 kWh/kg$_{H2}$** and **< 1.5 €/kg$_{H2}$** respectively.
- A pilot designed for **>25 kg/day** of hydrogen will be built and tested at industrially relevant conditions (TRL 5).

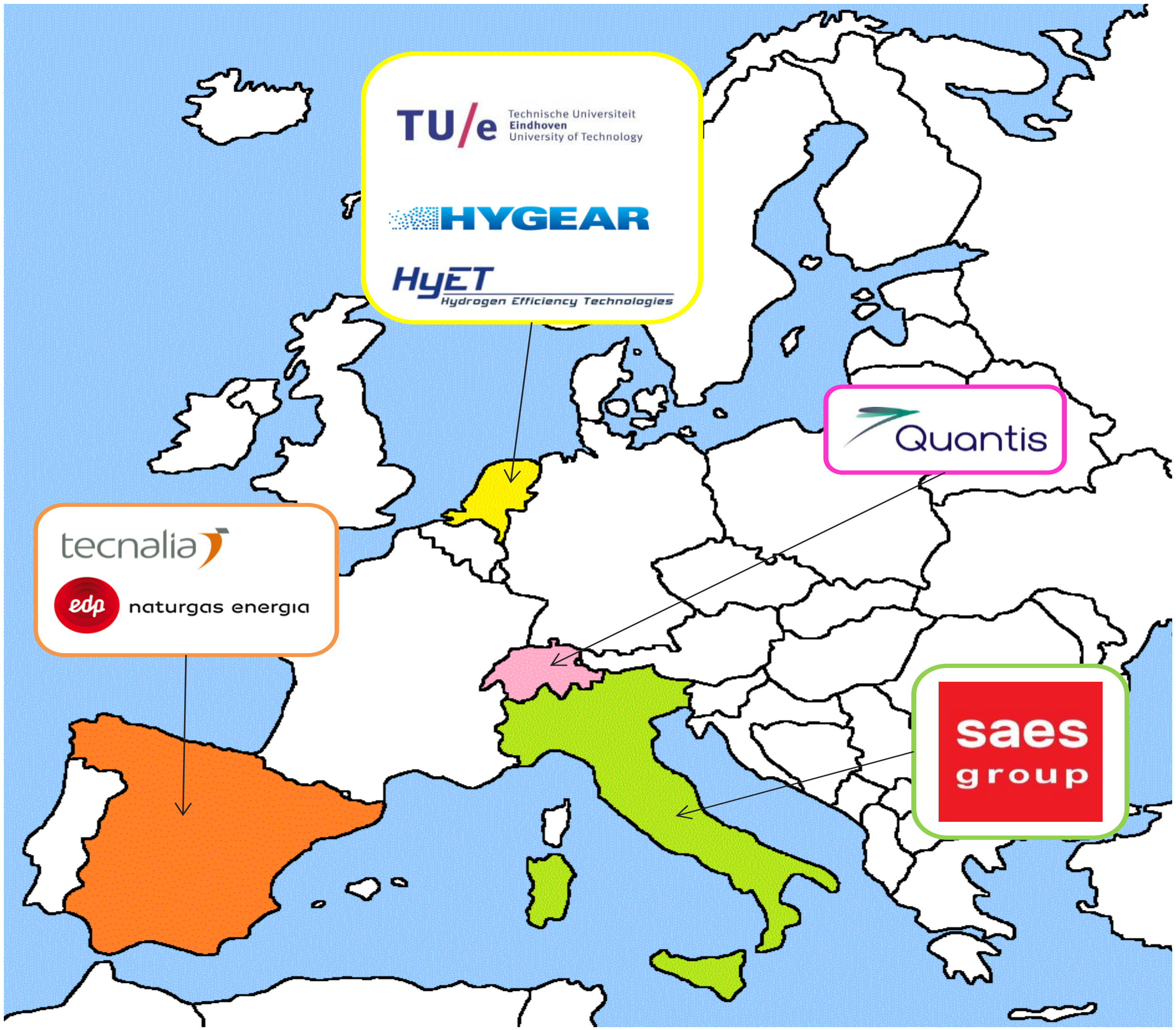
	P [bar]	T [°C]	H_2 production [kg/day]	H_2 cost [€/kg$_{H2}$]	Power consumption [kWh/kg$_{H2}$]	Payback time [years]	Lifetime [years]
HyGrid system	0.03-80	T<400	>25	<1.5	<5	< 6	>15

Layout of the HyGrid system

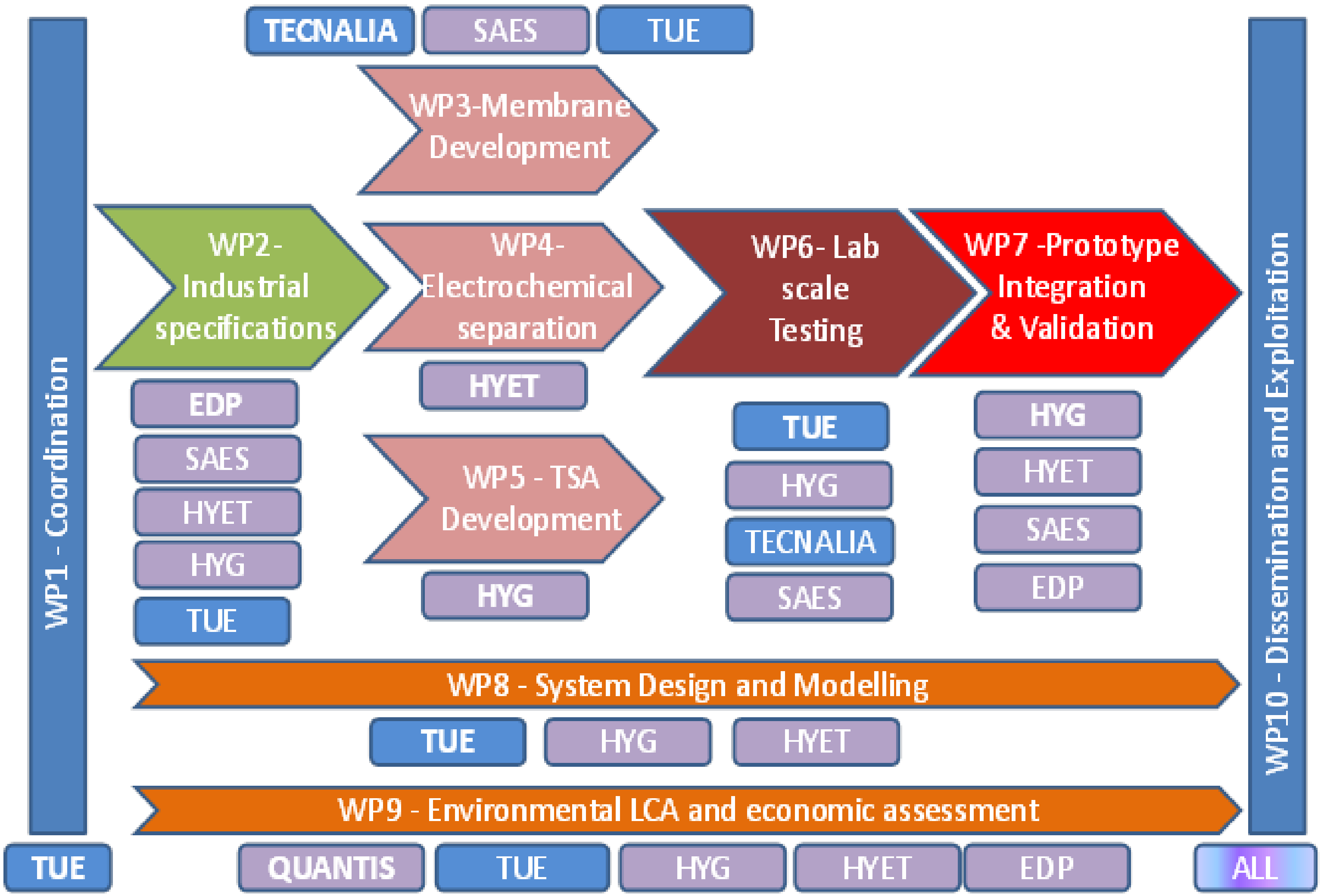


List of participants

Participant No *	Participant organisation name	Organization type	Country
1 (Coordinator)	Eindhoven University of Technology	RES	Netherlands
2	TECNALIA	RES	Spain
3	HyGear	SME	Netherlands
4	SAES	IND	Italy
5	Hydrogen Efficiency Technologies	SME	Netherlands
6	Quantis	SME	Switzerland
7	EDP Naturgas	IND	Spain


TU/e Technische Universiteit Eindhoven University of Technology
HYGEAR
HyET Hydrogen Efficiency Technologies
Quantis
tecnalia
edp naturgas energia
saes group

Work-packages



Participants role

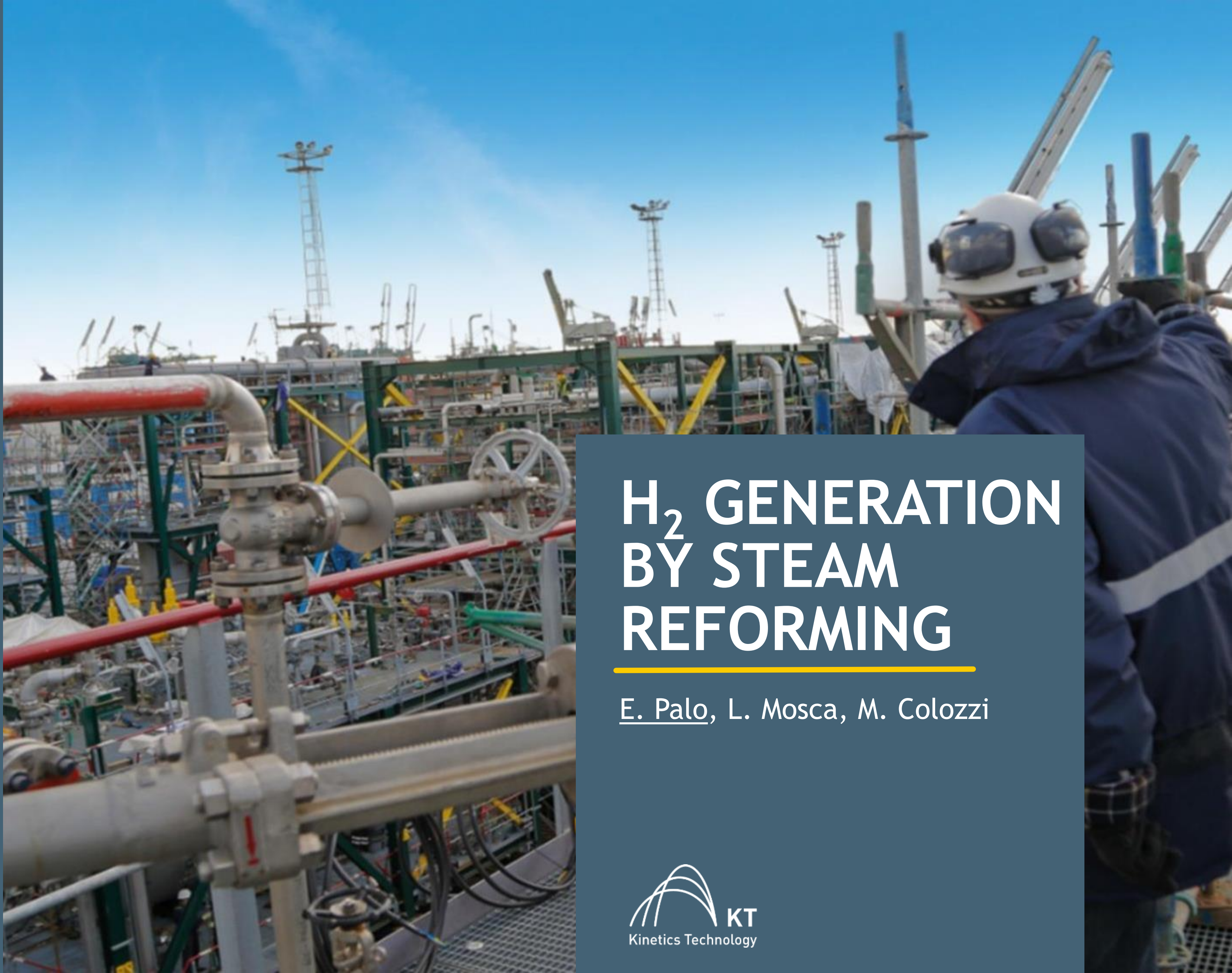
Participant	Main Role in HyGrid
TUE	Project Coordinator, lab scale testing & modelling, system modelling, energy analysis
TECNALIA	Leader of WP on membrane development, Dissemination Manager, membranes developer
HYG	Leader of WPs on prototype reactor, prototype developer
HYET	Leader of WP on electrochemical separation, Exploitation Manager
QUANTIS	Leader of WP on sustainability assessment (LCA and LCC)
SAES	Working on membrane testing and improved sealing technology for membranes
EDP	Leader on WP on industrial specification

Flexible Hybrid separation system for H2 recovery from NG Grids

HyGrid

Thank you for your attention

Contacts: F.Gallucci@tue.nl



H_2 GENERATION BY STEAM REFORMING

E. Palo, L. Mosca, M. Colozzi

KT Kinetics Technology

SUMMARY

1. H_2 production and use
2. H_2 in refinery
3. H_2 production via steam reforming
4. Economics
5. H_2 recovery
6. Conclusions

KT
Kinetics Technology

KT-KINETICS TECHNOLOGY AT A GLANCE

More than

40

years' experience

as a Process Engineering Contractor and in the development of new technologies for Oil & Gas industry

A leading expertise to implement

oil refining projects

+120

Hydrogen and Sulphur Recovery Unit Projects

completed in the last 10 years

WELL RECOGNIZED INTERNATIONAL PLAYER

in Licensing hydrogen technology and in licensing Sulphur Recovery and Tail Gas Treatment Technology

WORLD CLASS TRACK RECORD

in Large Gas Treatment Plants and Refinery Process Units

Development of **innovative technologies** and realization of **pilot plants**

H_2 PRODUCTION AND USE

- **Current hydrogen production is about 65 metric tons/year[1]**
- **The hydrogen market (merchant and captive) is currently of $115.25 billion USD and expected to grow to $154.74 billion USD in 2022[2]**

Production technologies[3]

NG STEAM REFORMING, 50%

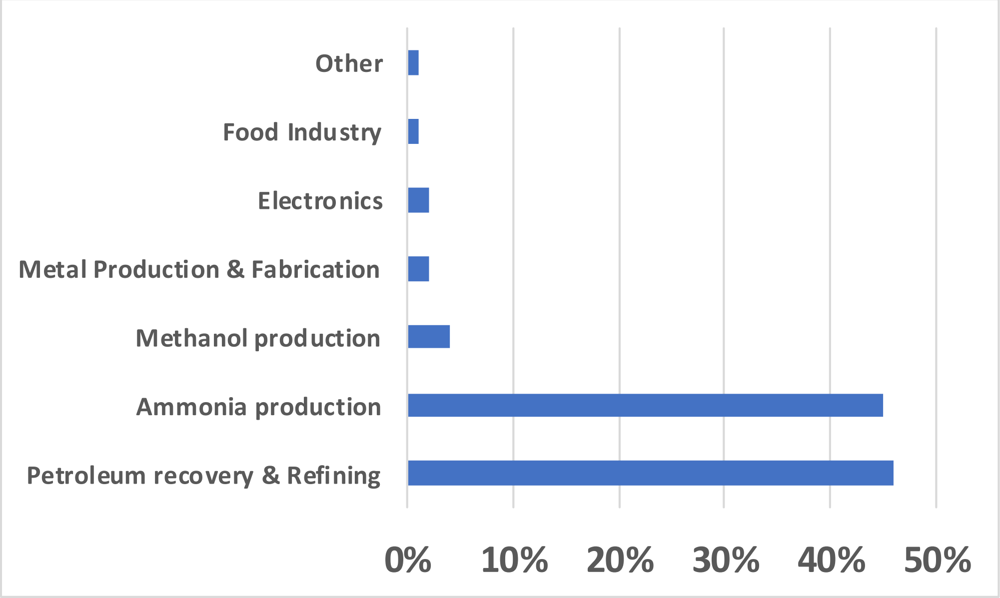
OIL/NAPHTA REFORMING FROM OFF GASES, 30%

COAL GASIFICATION, 18%

WATER ELECTROLYSIS, 3.9%

OTHER SOURCES, 0.1%

Applications[1]



[1] S. Satyapal, Hydrogen and Fuel Cells Overview, 2017
[2] M.-R. de Valladares, Global Trends and Outlook for Hydrogen, 2017
[3] C.M. Kalamaras, A.M. Efstathiou, Hydrogen Production Technologies: Current State and Future Developments, 2013

H_2 IN REFINERY 1/4

Demand and consumption

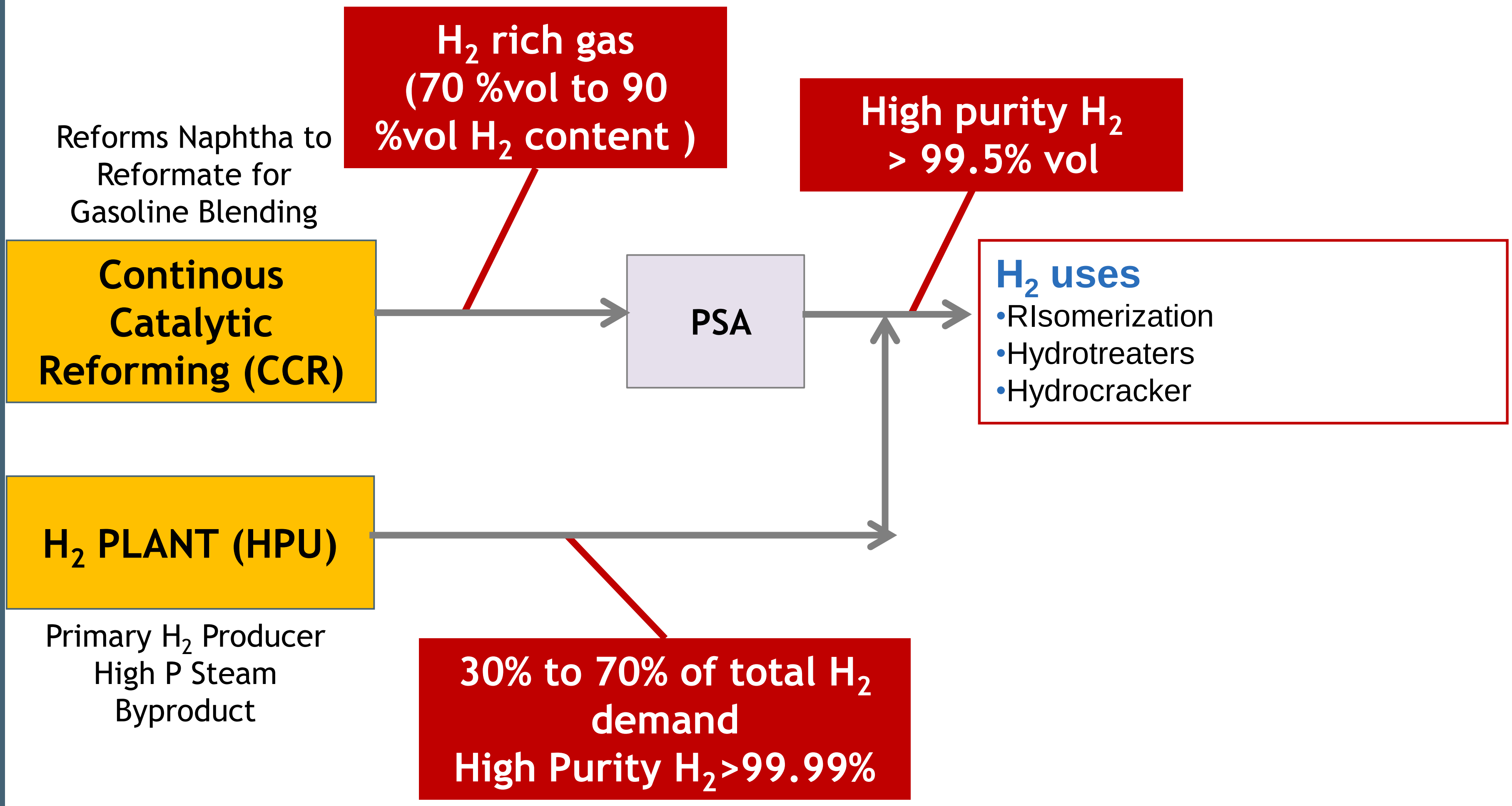
"Bottom of barrel" conversion (heavy) →	*Residue conversion*; *Hydrodesulphurization*
Yield improvement (lack of gasoil) →	*Hydrocracking*; *Hydrodesulphurization*
Meeting clean fuel spec's (environmental) →	*Hydrodesulphurization*

Typical consumption per unit type (Nm^3 of H_2 / tons of feed)

- ❑ ***Hydrodesulphurization*** → $10 > H_2cons > 150$
- ❑ ***Hydrocracking*** → $200 > H_2cons > 400$
- ❑ ***Isomerization*** → $30 > H_2cons > 50$
- ❑ ***Delayed coking*** → None
- ❑ ***Visbreacking*** → None
- ❑ ***Vacuum Residue HCK*** → $200 > H_2cons > 250$
- ❑ ***FCC*** → None

H_2 IN REFINERY 2/4

Network



H_2 IN REFINERY 4/4

Refinery Projects

REFINERY PROJECTS Planning/construction (2016-2021)	ADDED UNIT N°	ADDITIONAL HPU CAPACITY RANGE Nm^3/hr
UPGRADING PROJECTS in EXISTING REFINERIES		
HDK	11	13,000 ÷ 115,000
HDS / HDT	24	5,000 ÷ 85,000
DCU + HDT	14	8,000 ÷ 65,000
PROJECTS for NEW REFINERIES		
LOW CONVERSION	15	10,000 ÷ 90,000
DEEP CONVERSION	23	30,000 ÷ 250,000

KT's FORECAST BASED on WORLDWIDE CONSTRUCTION UPDATE O&GJ Nov. 2, 2015

H_2 PRODUCTION *via* STEAM REFORMING 1/5

Typical feed-stocks to SMR

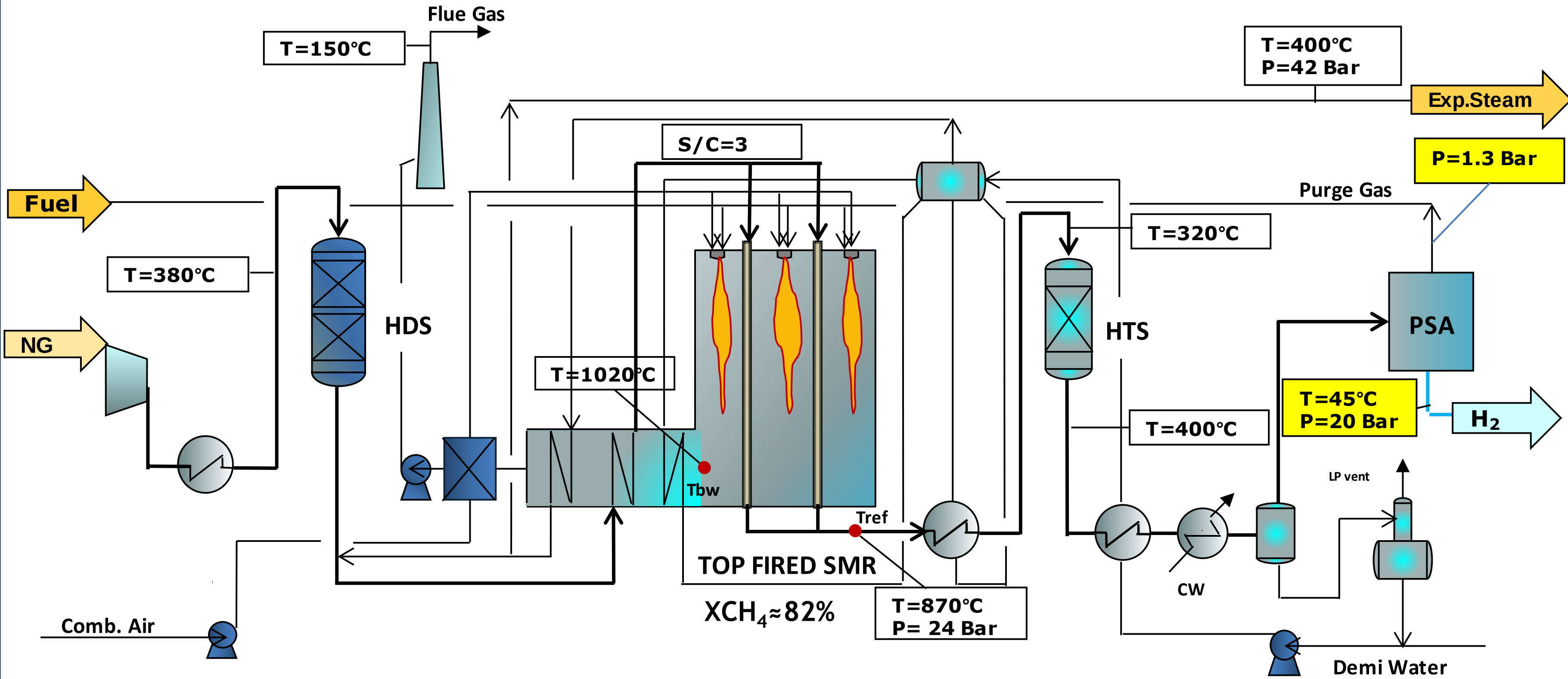
- Natural Gas
- Naphtha up to 220 °C FBP
- Refinery Off Gas (40%-60% max H2 content)
- Butane or LPG (typically in excess during summer months)

Steam system possible configurations

Steam export quality

- **"Segregated" or "dual steam segneration system"** to achieve the highest steam export quality. Two separate circuits, one for process steam and one for export steam generation: export steam quality is fully independent from process side but only dependent on the quality of supplied water from BL.
- **Single steam generation system** with **High pressure stripper** for condensate treatment, to further improve the quality of recovered condensate and export steam.
- **Single steam generation system** with condensate treatment in a **degasifier** by means of LP stripping steam.

H_2 PRODUCTION *via* STEAM REFORMING 2/5



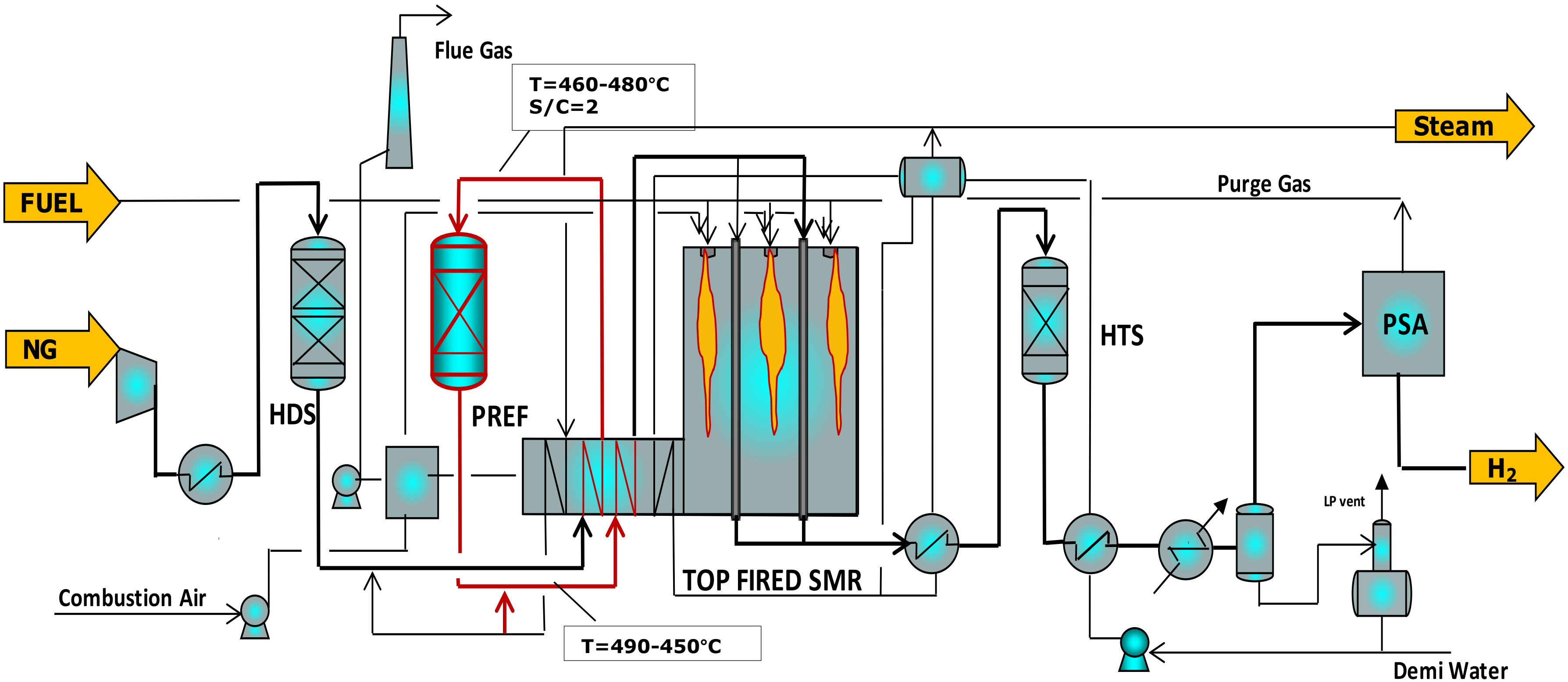
MAIN PROCESS REACTIONS

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \quad \Delta H^0_{298K} = +\,206\ kJ/mol$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \quad \Delta H^0_{298K} = -\,41\ kJ/mol$$

- Excess heat available for recovery
- Export steam credit increases the overall efficiency
- Typical energy efficiency: 80-85% (LHV Basis)
- Purge gas from PSA recovered and recycled at low P

H_2 PRODUCTION *via* STEAM REFORMING 3/5



Heavier hydrocarbons:

$C_nH_m + nH_2O = nCO + (n+m/2)H_2$ $\quad DH^0_{298K} = +1109$ kJ/mol (n-C_7H_{16})

$CO + 3H_2 = CH_4 + H_2O$ $\quad DH^0_{298K} = -206$ kJ/mol

$CO + H_2O = CO_2 + H_2$ $\quad DH^0_{298K} = -41$ kJ/mol

With Methane feedstock

$CH_4 + H_2O = CO + 3H_2$ $\quad DH^0_{298K} = +206$ kJ/mol

$CO + H_2O = CO_2 + H_2$ $\quad DH^0_{298K} = -41$ kJ/mol

- Minimum Export steam credit
- Typical energy efficiency: 75-80% (LHV Basis)
- Feed flexibility
- Reformer duty decrease
- Increase of capacity

H_2 PRODUCTION *via* STEAM REFORMING 4/5

H_2 PRODUCTION *via* STEAM REFORMING 5/5

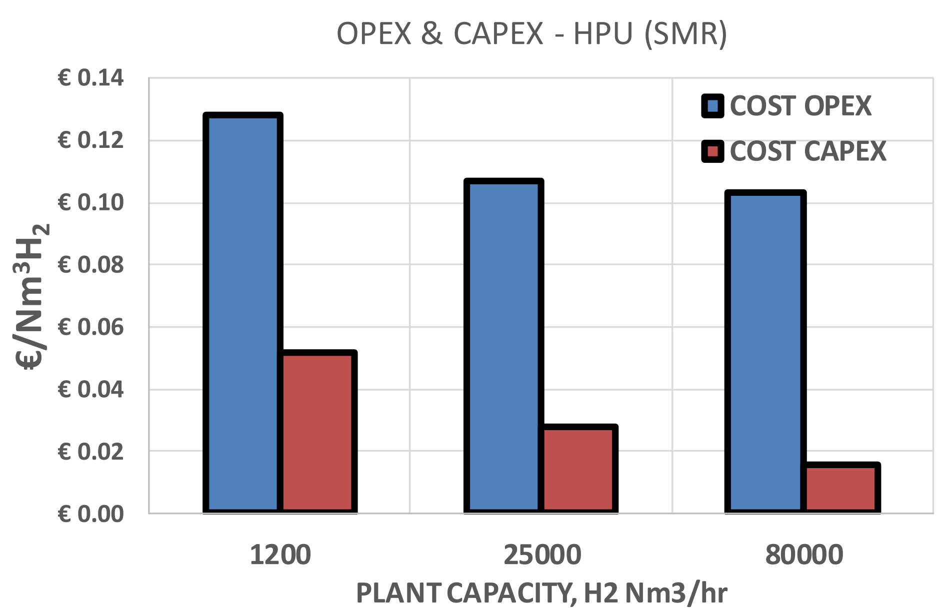
MIDOR/MIDTAP
Hydrogen plant (64,000 Nm^3/h)
Alessandria, Egitto

ECONOMICS 1/2

MAIN COMPONENTS

- Cost CAPEX (Plant equipments on EPC basis)
- Cost OPEX (feed, fuel, demi water, electric power, cooling water, LP steam import)
- Plant operation & maintenance

The weight of each component depends on plant capacity, plant location, local energy and feed cost, labour cost



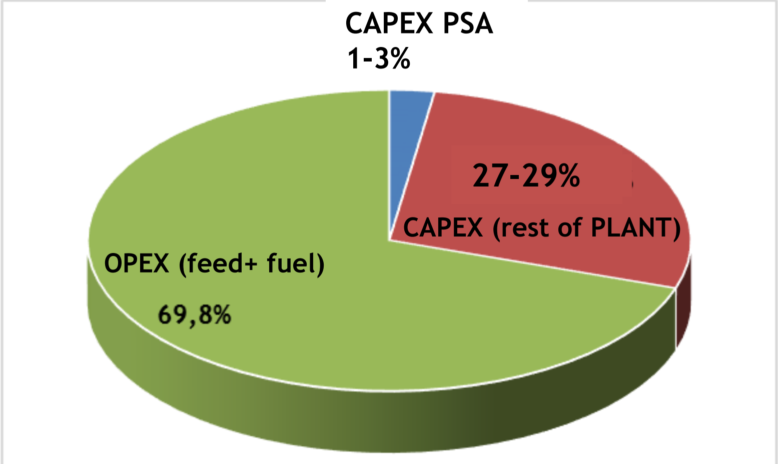
BASIC ASSUMPTIONS

- Plant life of 20 years
- Amortization with interest rate of 10%
- NG price 32Euro/MMkcal – 0.27Euro/Nm^{3}*

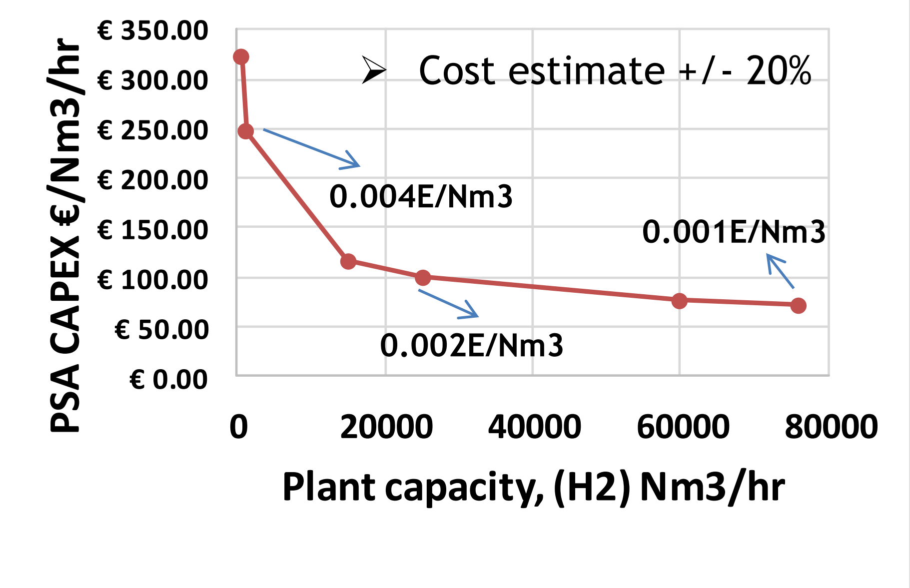
*http://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Development_of_natural_gas_prices_for_non-household_consumers,_EU-28,_2008-2017_(EUR_per_kWh).png

ECONOMICS 2/2

- Cost CAPEX HPU (on EPC basis)
- Cost CAPEX PSA (share)
- Cost OPEX (feed + fuel)



COST SPLITTING in SMR HPU



- In a conventional HPU, hydrogen separation cost via PSA is mainly CAPEX share

H_2 RECOVERY

From OFF-GAS

Main available technologies (*)

TECHNOLOGY	CRYOGENIC	MEMBRANE	PSA
Minimum H2 in feed [%]	15	15	50
Feed Pressure [Bar]	15-80	15-140	10-70
Hydrogen Recovery [%]	up to 98	up to 97	up to 90
Hydrogen Purity [%]	Max. 97	Max. 98	99-99,999
CO + CO2 removal	NO	NO	YES
Hydrogen product pressure	Close to Feed	Much lower than feed	Close to Feed

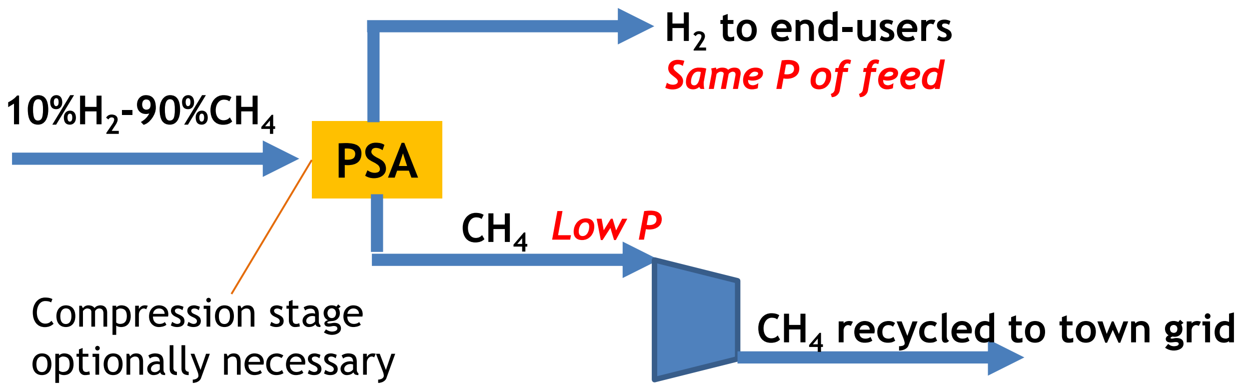
- Gas flow 3000 Nm^3/hr
- H_2= 81-85% vol
- P = 62 Barg
- T = 40°C
- recovery = 89 - 91 %
- purity = 98 %vol

Cost Estimate: 2280 k€ (CAPEX) +/-20%
Ammortization fee (20 years, 10% interest rate):
Membrane Hydrogen separation cost: 0,01 +/- 20% €/Nm3

(*) Z.Rabiei, Hydrogen management in refineries, 2012

H_2 RECOVERY

From TOWN GRID



- **To be evaluated performance (purity and recovery) of PSA with very low hydrogen concentration in the feed of PSA**
- **CAPEX of PSA might be very different from CAPEX calculated with HPU**
- **OPEX share should at least consider also the recompression of recycled CH_4**
- **Is PSA the most proper technology for hydrogen recovery from town grid?**

CONCLUSIONS

- Hydrogen production currently mostly addresses refinery demand
- Hydrogen in refinery mostly produced by steam reforming from hydrocarbons
- Different schemes are available for Hydrogen Production Unit, with Hydrogen Separation typically performed with Pressure Swing Adsorption (PSA)
- Hydrogen production cost greatly affected by feed+fuel price and plant capacity
- In refinery HPU, hydrogen separation with PSA mainly CAPEX based and affected by plant capacity
- Hydrogen recovery from town grid with PSA would require at least additional steps of recompression and relevant costs

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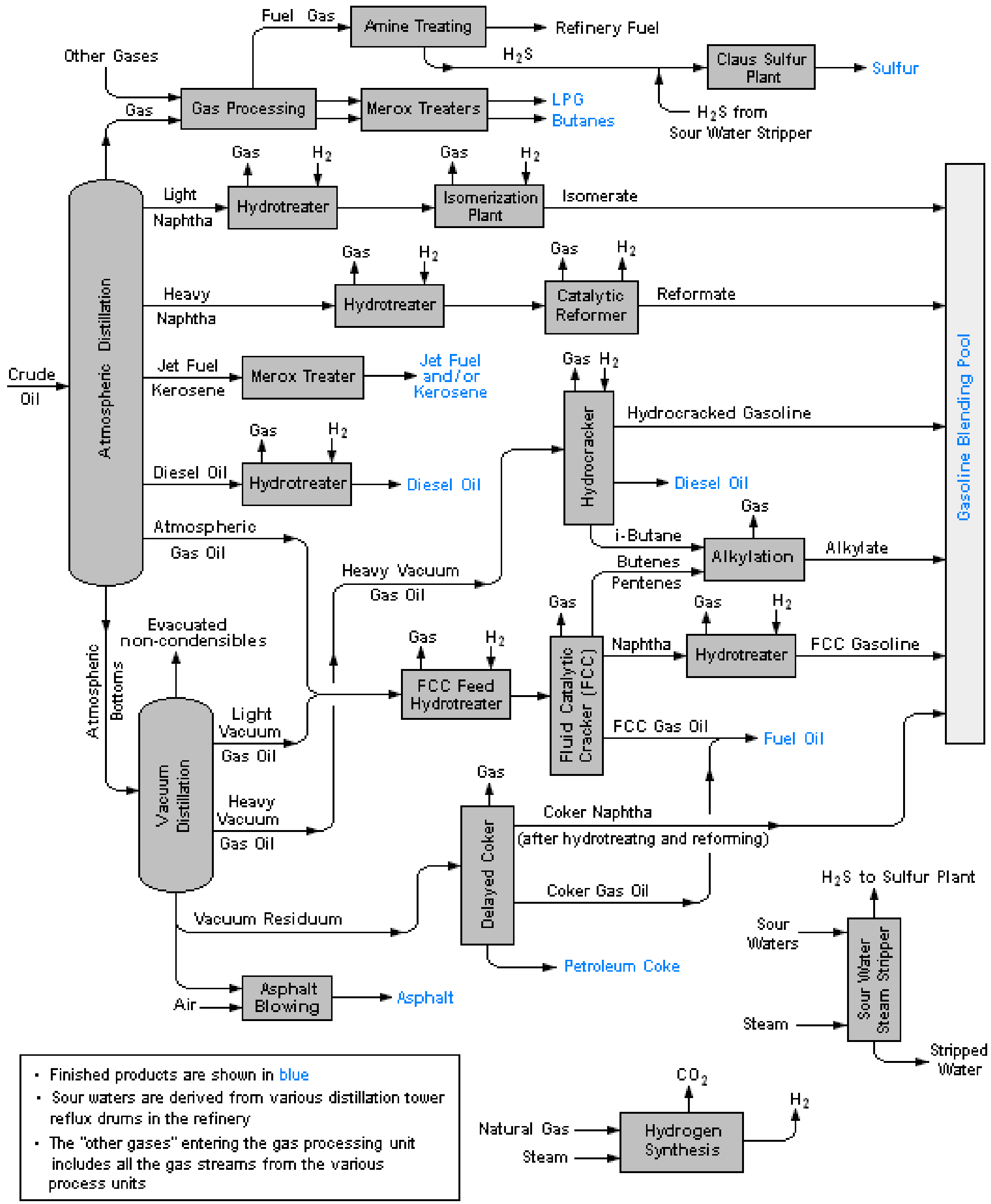

Fuel Gas
Amine Treating
Refinery Fuel
Other Gases
H2S
Claus Sulfur Plant
Sulfur
Gas
Gas Processing
Merox Treaters
LPG
Butanes
H2S from Sour Water Stripper
Gas
H2
Gas
H2
Light Naphtha
Hydrotreater
Isomerization Plant
Isomerate
Gas
H2
Gas
H2
Heavy Naphtha
Hydrotreater
Catalytic Reformer
Reformate
Crude Oil
Atmospheric Distillation
Jet Fuel Kerosene
Merox Treater
Jet Fuel and/or Kerosene
Gas H2
Hydrocracker
Hydrocracked Gasoline
Gasoline Blending Pool
Gas
H2
Diesel Oil
Hydrotreater
Diesel Oil
Diesel Oil
Gas
Atmospheric Gas Oil
i-Butane
Alkylation
Alkylate
Heavy Vacuum Gas Oil
Butenes
Pentenes
Evacuated non-condensibles
Gas
Gas
H2
Gas
H2
Naphtha
Hydrotreater
FCC Gasoline
Atmospheric Bottoms
FCC Feed Hydrotreater
Fluid Catalytic Cracker (FCC)
Light Vacuum Gas Oil
FCC Gas Oil
Fuel Oil
Vacuum Distillation
Gas
Heavy Vacuum Gas Oil
Coker Naphtha
(after hydrotreatng and reforming)
Delayed Coker
H2S to Sulfur Plant
Coker Gas Oil
Vacuum Residuum
Sour Waters
Sour Water Steam Stripper
Petroleum Coke
Asphalt Blowing
Asphalt
Air
Steam
Stripped Water
• Finished products are shown in blue
• Sour waters are derived from various distillation tower reflux drums in the refinery
• The "other gases" entering the gas processing unit includes all the gas streams from the various process units
CO2
H2
Natural Gas
Steam
Hydrogen Synthesis

H_2 IN REFINERY 3/4

Refinery Projects

REFINERY PROJECTS planning/construction 2015-2020	North America	S&C America	Africa	Europe	Russia & CIS	Middle East	Asia & Pacific	TOTAL
NEW REFINERIES	-	10	5	-	1	10	12	38
EXPANSION/UPGRADING	10	16	3	14	4	4	18	69
TOTAL	10	26	8	14	5	14	30	107
ADDED OPERATIONS								
HDK	4	1		4	2			11
HDS		9		5			4	18
HDT	1	2				1	2	6
DCU	3	4		1	2		4	14
Total	8	16		10	2	1	10	49

Data from the WORLDWIDE CONSTRUCTION UPDATE O&GJ Nov. 2, 2015

KT

Kinetics Technology

HYDROGENICS
SHIFT POWER | ENERGIZE YOUR WORLD

HYGRID WORKSHOP – LAINATE (IT)

Guy VERKOEYEN
Hydrogenics Europe N.V.
Area Sales Manager EMEA

17th May 2018

Agenda

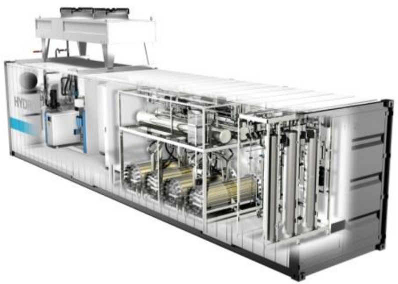
1. **Hydrogenics**
2. Water electrolysis
3. Fuels cells
4. Renewable Hydrogen
5. Conclusions

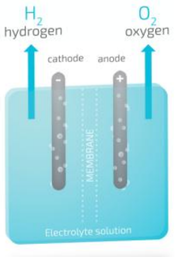
Introduction video

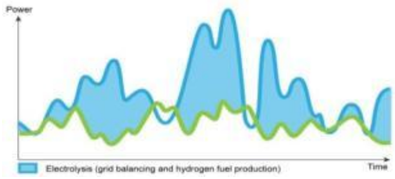
https://www.youtube.com/watch?v=KKr4nKPrzHg

Electrolysers: Power → Hydrogen
Fuel cells: Hydrogen → Power (+ heat)

HYDROGENICS Technologies



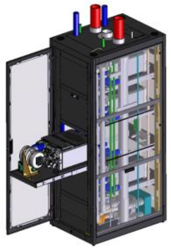




Electrolysis

- Industrial applications
- Hydrogen refueling stations
- Power-to-X & grid balancing

WATER (H_2O) + **POWER** (+ HEAT) — **Electrolysis** → / ← **Fuel cell** — **HYDROGEN (H_2)** + OXYGEN (O_2) (+ HEAT)



Fuel cells

- Back-up power
- Stationary power
- Mobile power

Our History: Over 60 Years of Experience

1948
The Electrolyser Corporation, a manufacturer of *Atmospheric Alkaline Electrolyzers* is incorporated in Toronto, Canada

1987
Vandenborre Hydrogen Systems, a manufacturer of *Pressurized Alkaline Electrolyzers* is founded in Belgium

1995
Hydrogenics is founded

2000
Hydrogenics goes public

The Electrolyser Corporation renamed "Stuart Energy" after going public

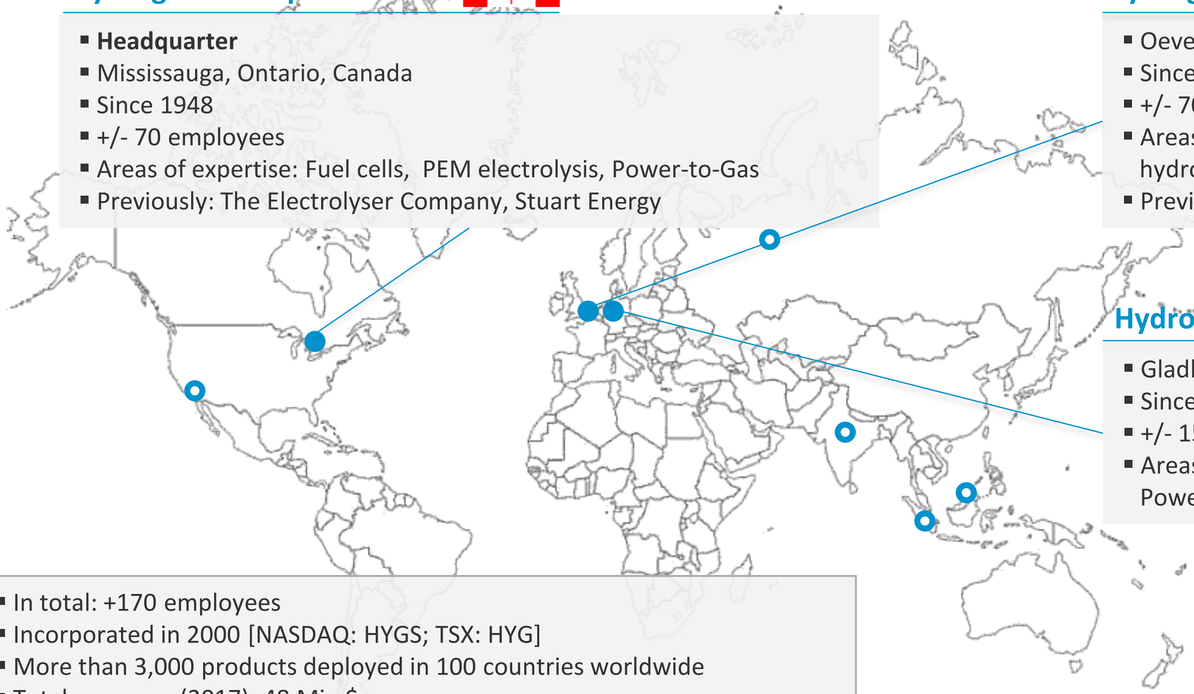
2002
Hydrogenics acquires ENKAT GmbH and begins operations in Germany

2003
Stuart Energy acquires Vandenborre

2005
Hydrogenics acquires Stuart Energy to become the only fuel cell and electrolyzer company in the industry

2016
Hydrogenics is the global leader in fuel cell and hydrogen technology solutions

Hydrogenics, a 100% global hydrogen company



Hydrogenics Corporation

- **Headquarter**
- Mississauga, Ontario, Canada
- Since 1948
- +/- 70 employees
- Areas of expertise: Fuel cells, PEM electrolysis, Power-to-Gas
- Previously: The Electrolyser Company, Stuart Energy

Hydrogenics Europe

- Oevel, Belgium
- Since 1987
- +/- 70 employees
- Areas of expertise: pressurized alkaline electrolysis, hydrogen refueling stations, Power-to-Gas
- Previously: Vandenborre Hydrogen Systems

Hydrogenics Gmbh

- Gladbeck, Germany
- Since 2002
- +/- 15 employees
- Areas of expertise: Fuel cells, mobility projects, Power-to-Gas

- In total: +170 employees
- Incorporated in 2000 [NASDAQ: HYGS; TSX: HYG]
- More than 3,000 products deployed in 100 countries worldwide
- Total revenues (2017): 48 Mio $
- Over 65 years of electrolysis leadership

● Production facility

○ Sales office

Agenda

1. Hydrogenics

2. **Water electrolysis**

Water electrolysis
H_2O + electricity → $H_2 + ½ O_2$

Pressurized ALKALINE vs Proton Exchange Membrane (PEM)

3. Renewable Hydrogen

4. Fuels cells

5. Conclusions

World hydrogen market

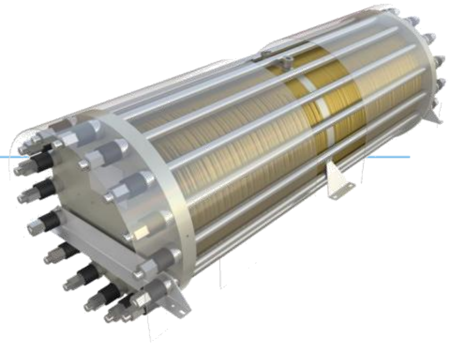
But most of the hydrogen produced today is not CO_2-free (from gas, oil, coal)

If produced from renewable power via electrolysis, hydrogen is fully renewable and CO_2-free.

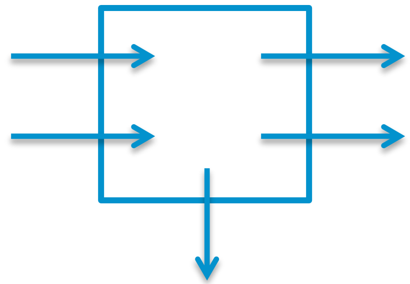
Renewable hydrogen has the potential to decarbonize a large range of applications

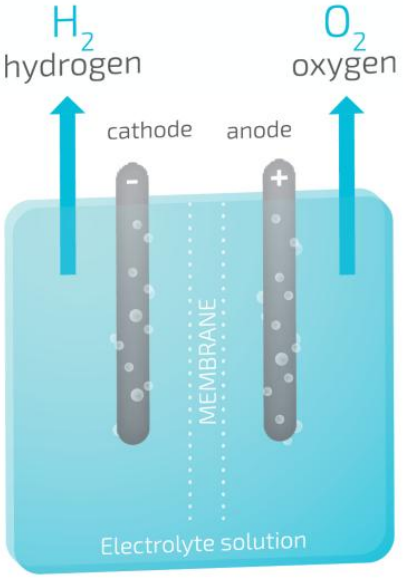
Data source: The Hydrogen Economy, M. Ball 2009 & Esprit Associates 2014

Water electrolysis | Fundamentals



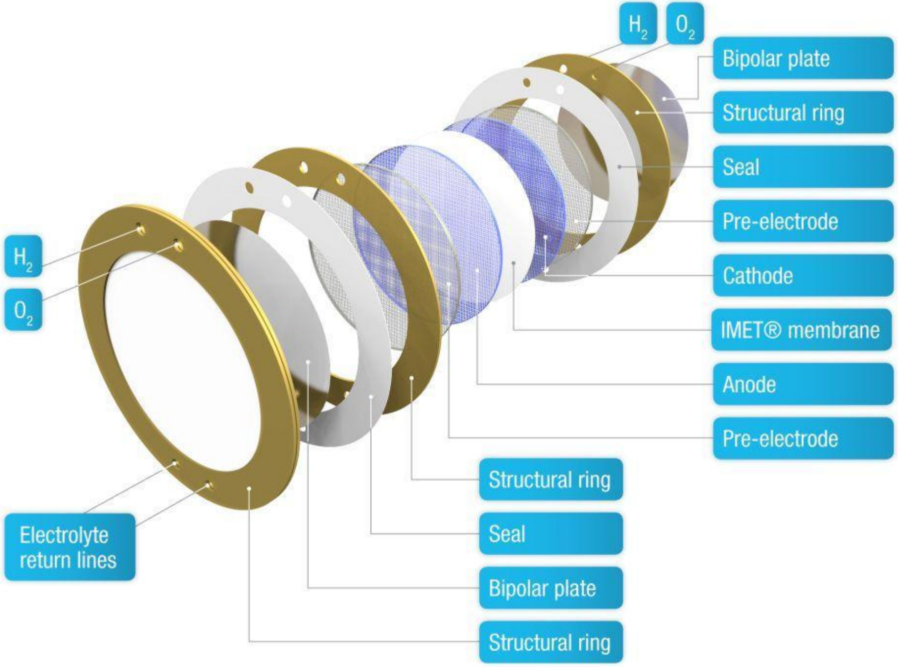
- Electrochemical reaction that splits water into Hydrogen and Oxygen, using electricity.
  It is a 100% emission free and carbon-free process
  - Cathode : $4\ H_2 0 + 4\ e^- \Rightarrow 2\ H_2 + 4\ OH^-$
  - Anode : $4\ OH^- \Rightarrow 0_2 + 2\ H_2 0 + 4\ e^-$
  - Overall : $4\ H_2 0 \Rightarrow 4\ H_2 + 2\ 0_2$



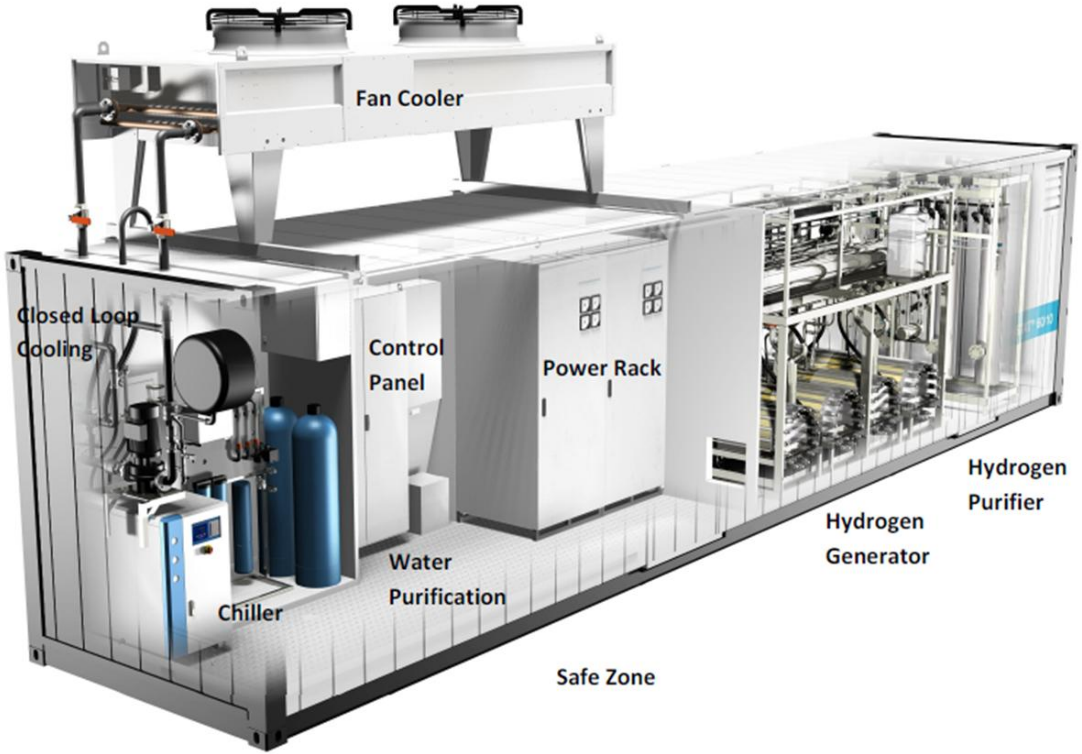


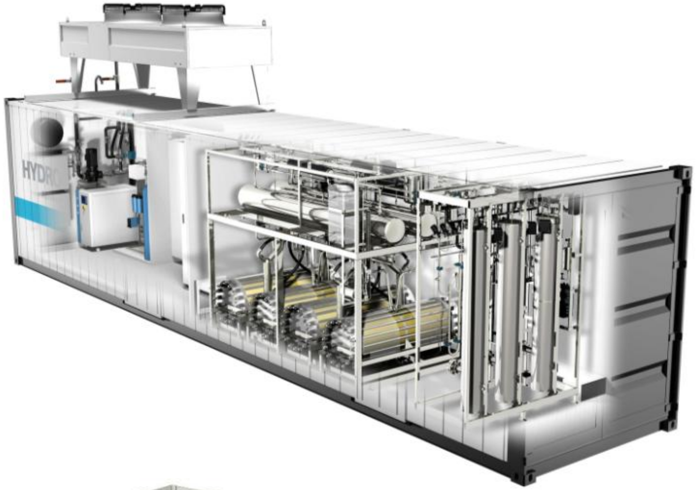
Hydrogenics HySTAT™ Alkaline Stack

- Gas production: H_2 (cathode) and O_2 (anode)
- Series of cells (electrodes and membranes) assembled in a bipolar design
- Electrodes = Gas production
- Membranes = Gas separation allowing ionic conductivity (OH-)
- Cells are assembled electrically in series, hydraulically in parallel.

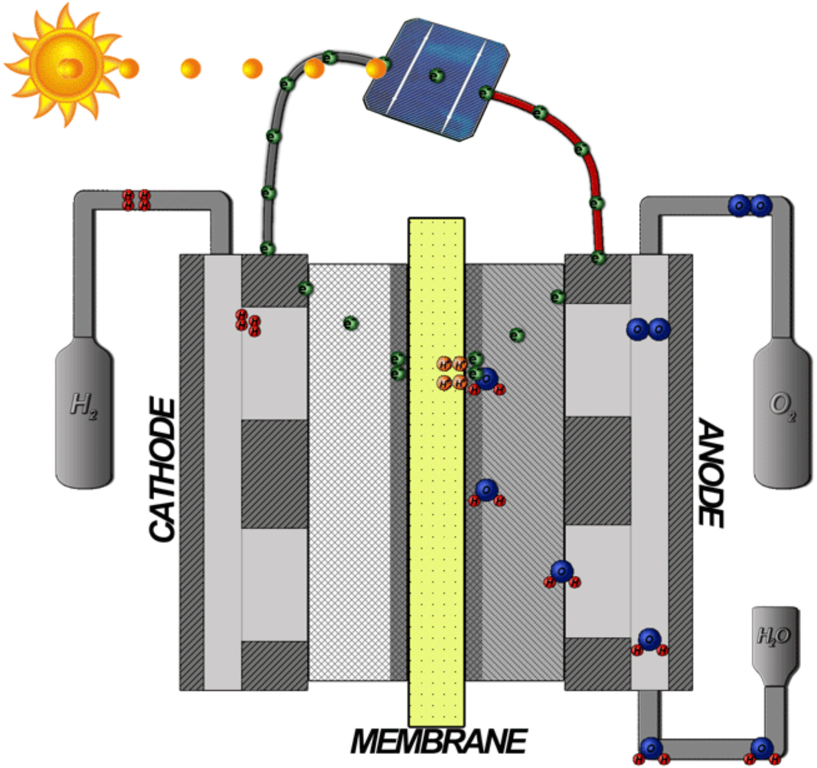


HySTAT™ 60 - alkaline electrolyser

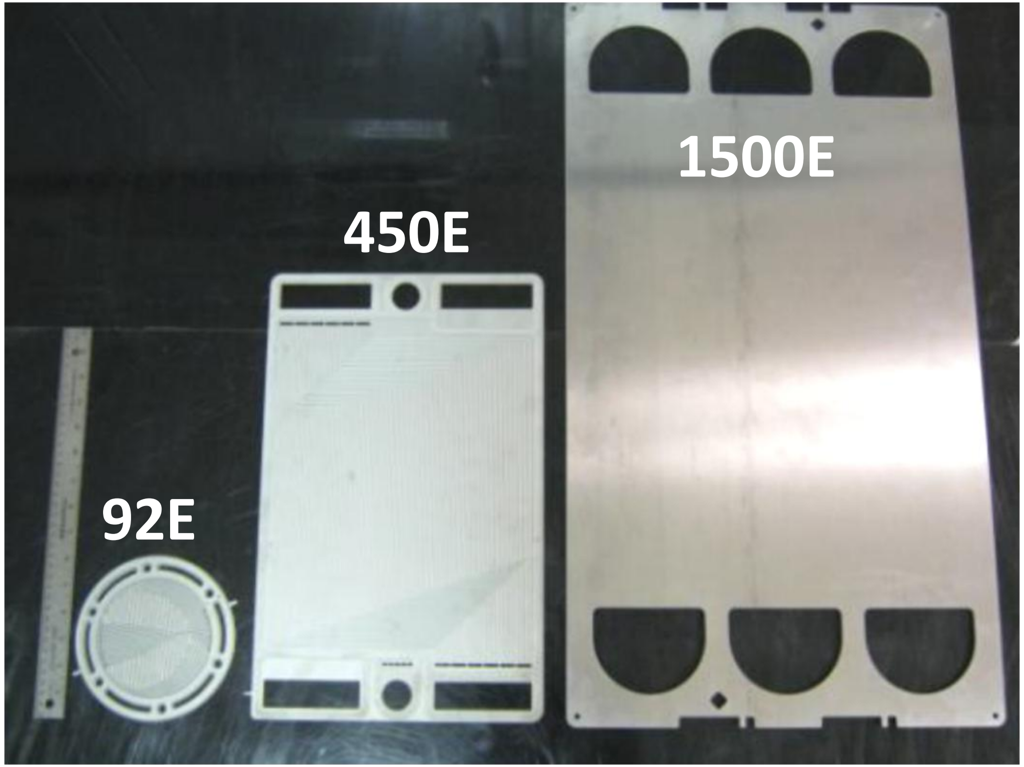




Proton Exchange Membrane (PEM) Electrolysis
How does it work ?



PEM, 2012 : **LET'S GO FOR IT**



New benchmark in PEM electrolysis HyLYZER®-600
3 MW cell stack from Hydrogenics

1

MW Scale Electrolyzer Stack

1.5MW industry benchmark

2

Reduction of Plant Capital Costs

Achieved target system cost

Power Input: 3.0 MW
Hydrogen Output: 620 Nm^3/h
Design Pressure: 40 bar

3

Stack Efficiency Improvements

Leading industry performance

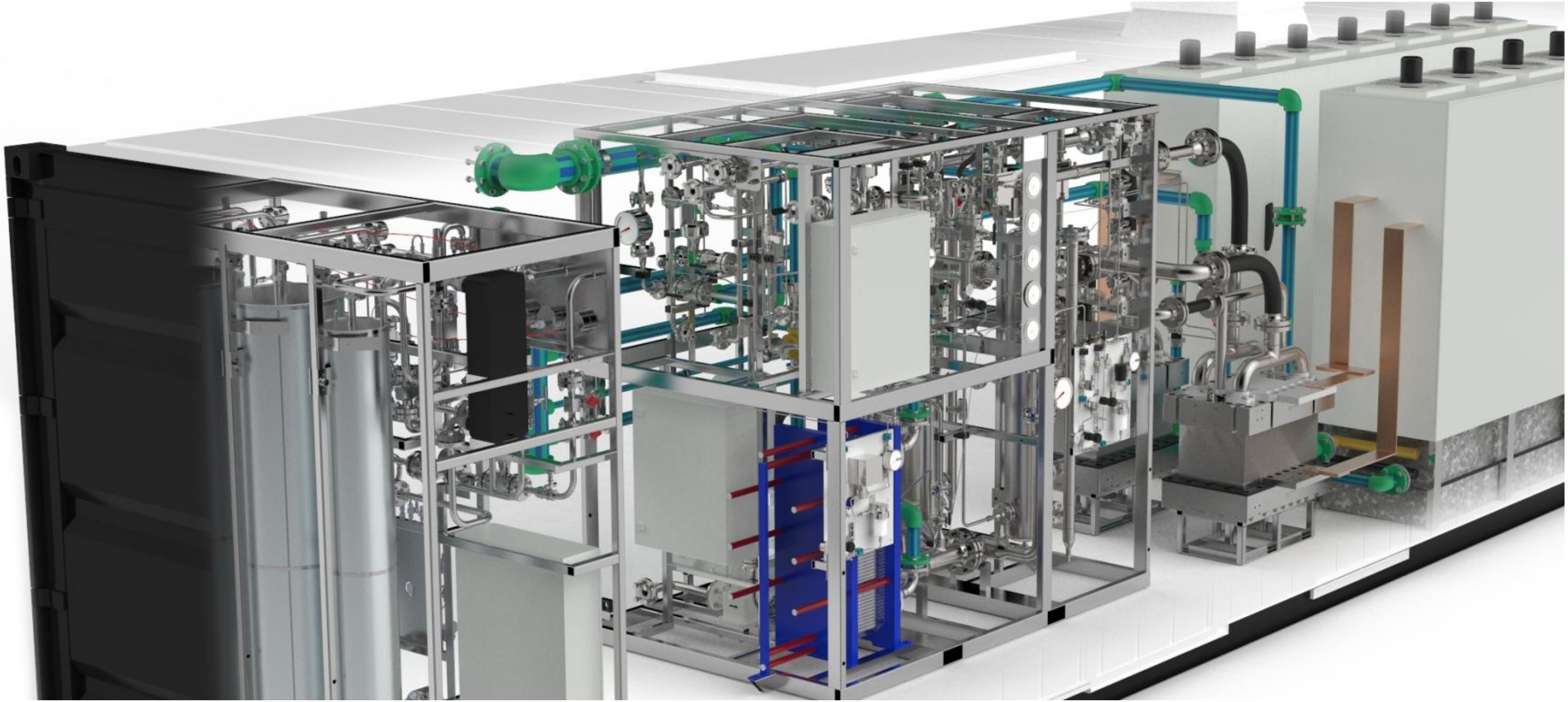
4

Fast Response and Dynamic Operation

Key IPR established

Power Input: 1.5 MW
Hydrogen Output: 310 Nm^3/h
Design Pressure: 40 bar

..Compact



Alkaline & PEM electrolysis | Product's line

	Alkaline			PEM (Proton Exchange Membrane)		



	HySTAT®-15-10/30	HySTAT®-60-10	HySTAT®-100-10	HyLYZER® -100-30	HyLYZER® -400-30	HyLYZER® -3,000-30
Output pressure	10 barg – 27 barg			30 barg		
Number of cell stacks	1	4	6	1	2	10
Nominal hydrogen flow	15 Nm³/h	60 Nm³/h	100 Nm³/h	100 Nm³/h	400 Nm³/h	3,000 Nm³/h
Nominal input power	80 kW	300 kW	500 kW	500 kW	2 MW	15 MW
AC power consumption (utilities included, at nominal capacity)	5.0-5.4 kWh/Nm³			5.0-5.4 kWh/Nm³		
Hydrogen flow range	40-100%	10-100%	5-100%	1-100%		
Hydrogen purity	99.998% O_2 < 2 ppm, N_2 < 12 ppm (higher purities optional)			99.998% O_2 < 2 ppm, N_2 < 12 ppm (higher purities optional)		
Tap water consumption	<1.7 liters / Nm³ H_2			<1.4 liters / Nm³ H_2		
Footprint	20 ft container	40 ft container	40 ft container	40 ft container	40 ft + 20 ft container	600 m² (indoor)

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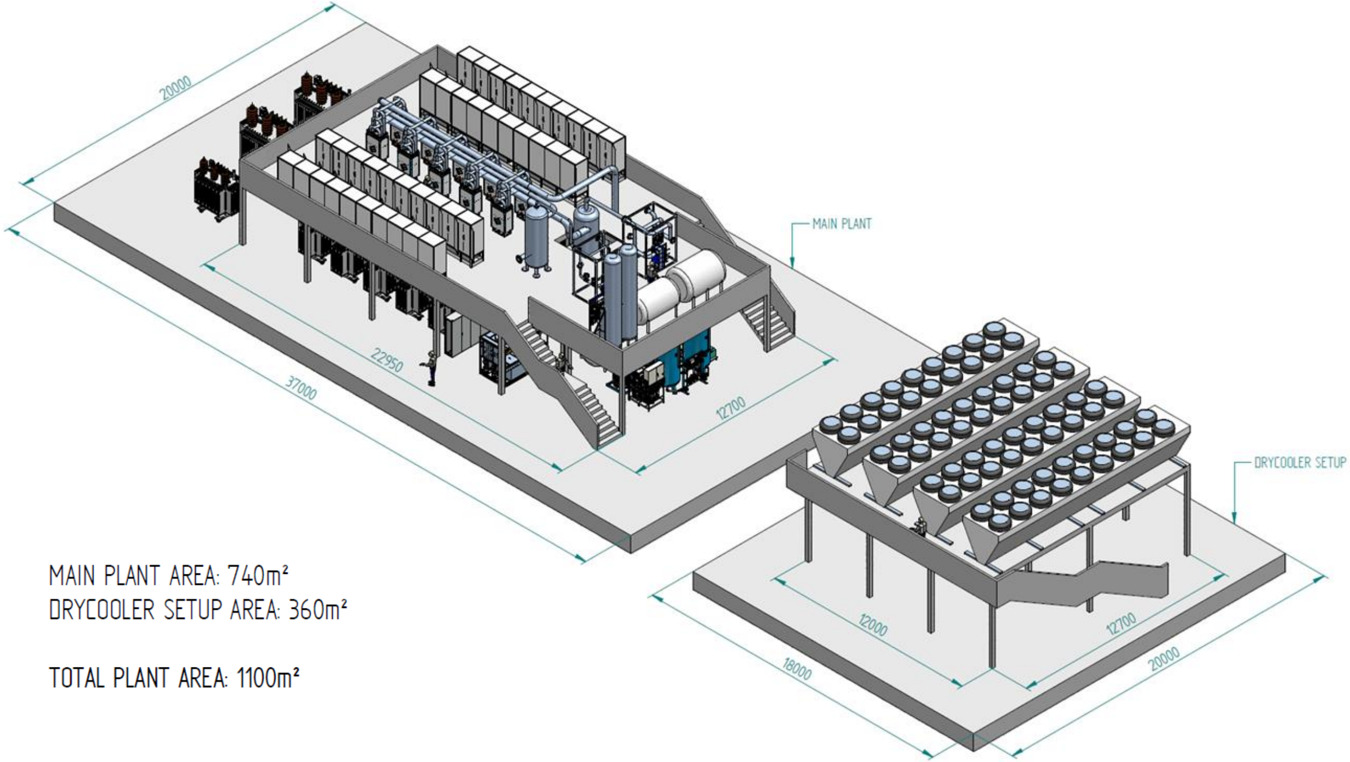
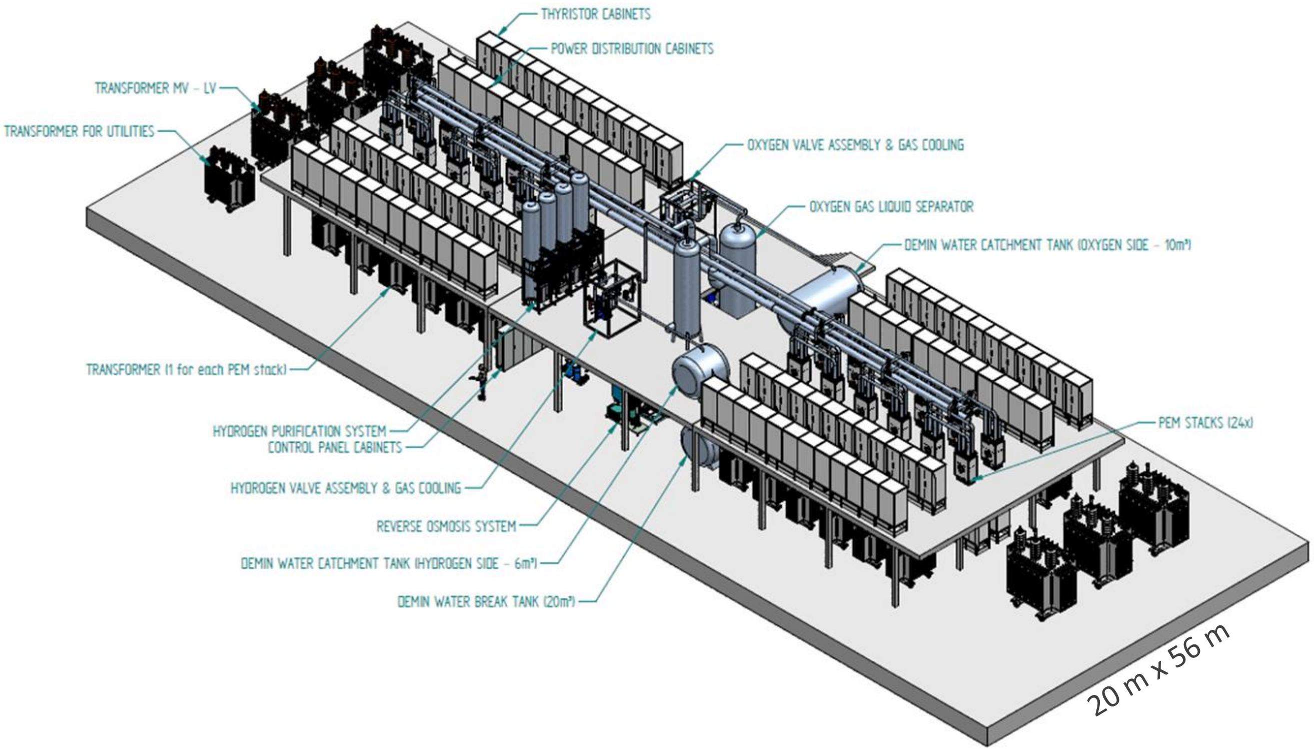
Rendering of a 20 MW PEM electrolysis plant
The smallest footprint on the market !



MAIN PLANT AREA: 740m²
DRYCOOLER SETUP AREA: 360m²

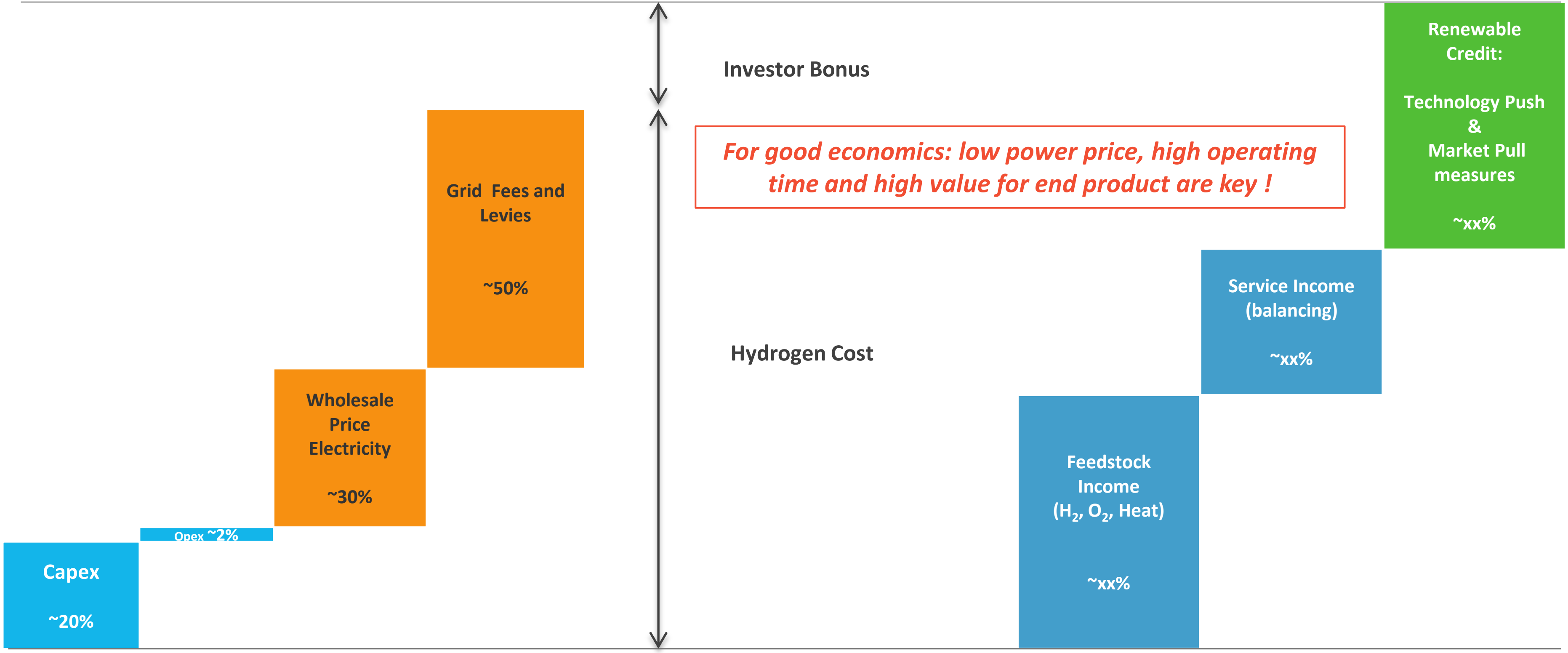
TOTAL PLANT AREA: 1100m²

Rendering of a 60 MW PEM electrolysis plant
The smallest footprint on the market !



PtG: Business Case Drivers

For more information on the economics, consult the Power-to-Gas Roadmap for Flanders: www.power-to-gas.be/roadmap-study

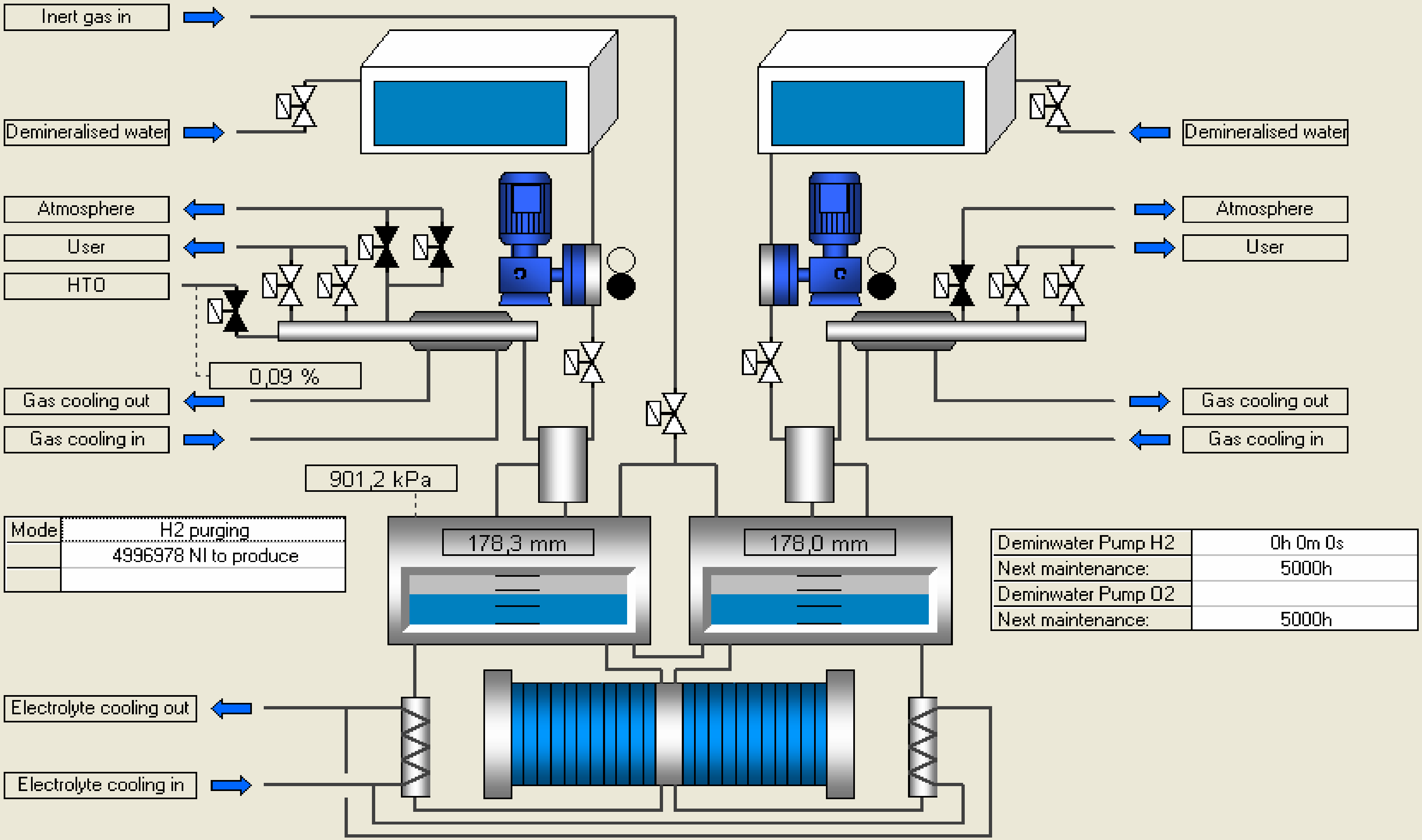


Electrolysers | Fast reacting devices

- A matter of power electronics
- 'Power' operated rather than 'Pressure' operated
- **Balance renewables** (wind and solar) **and provide Grid Balancing Services**

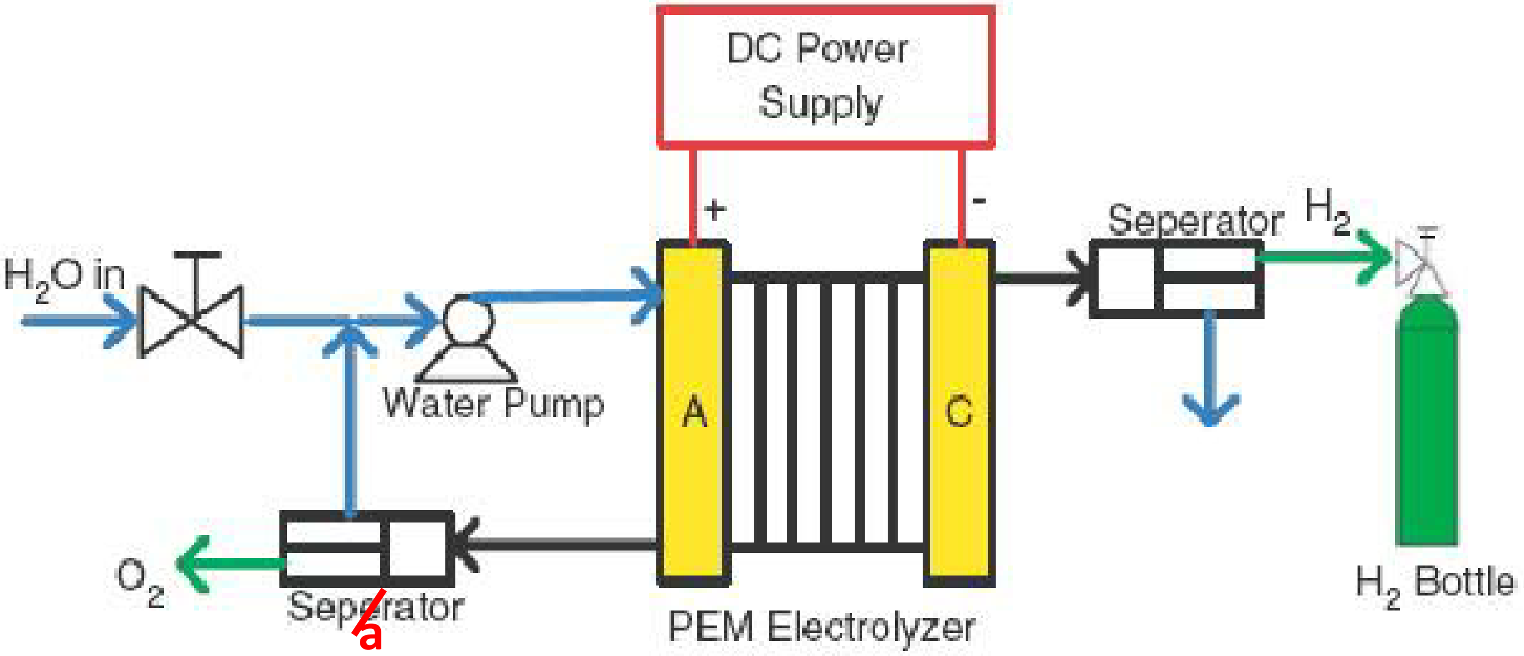
	Alkaline	PEM
Response signal (from pressurized stand-by to 100%)	< 3 sec	< 3 sec
Response signal (Operating system = HOT)	<1 sec	<1 sec

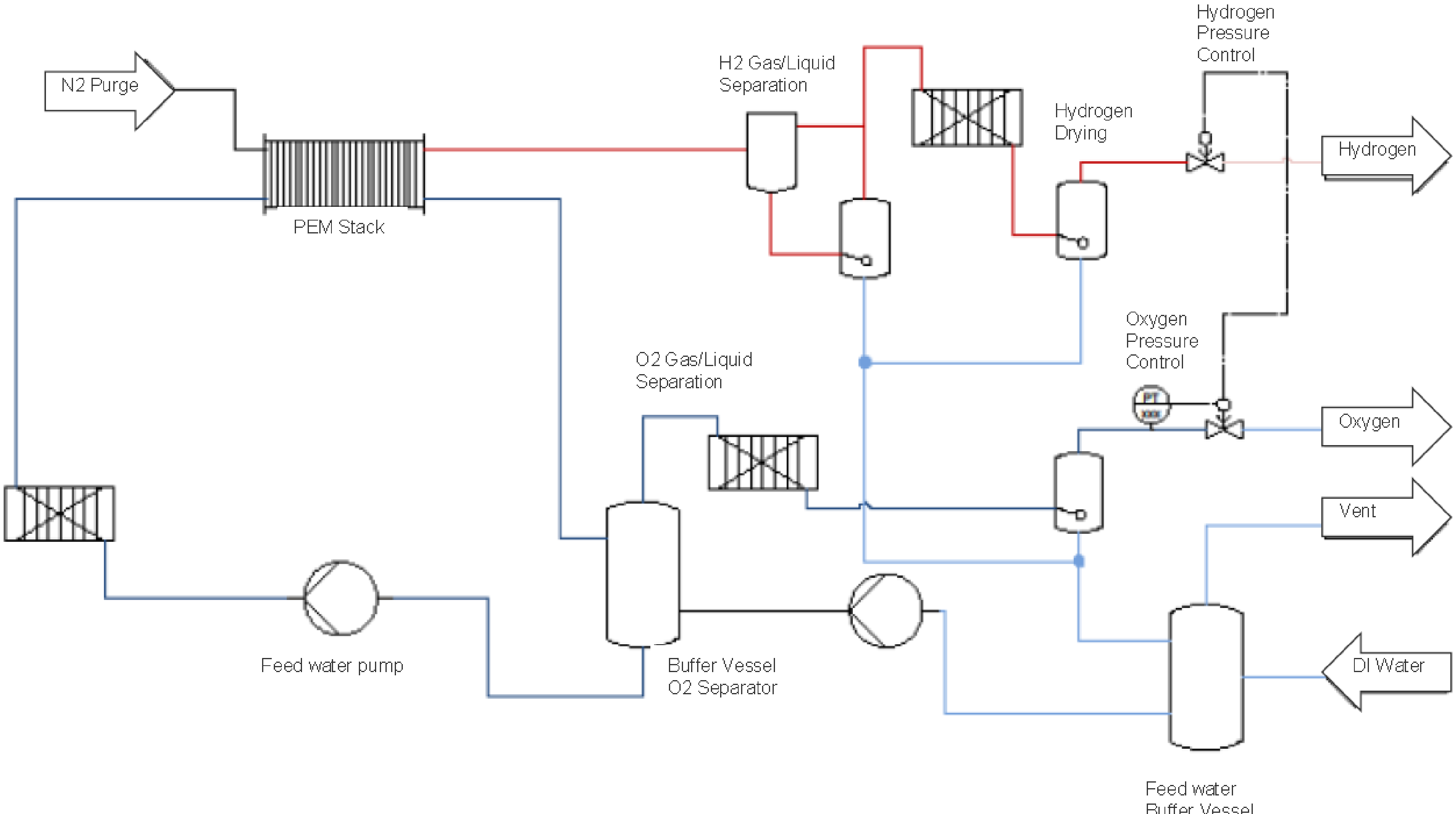
Example: 1.5 MW PEM Electrolyser, WindGas Reitbrook, Hamburg



Inert gas in
Demineralised water
Atmosphere
User
HTO
0,09 %
Gas cooling out
Gas cooling in
901,2 kPa
Mode
H2 purging
4996978 Nl to produce
178,3 mm
178,0 mm
Demineralised water
Atmosphere
User
Gas cooling out
Gas cooling in
Deminwater Pump H2
0h 0m 0s
Next maintenance:
5000h
Deminwater Pump 02
Next maintenance:
5000h
Electrolyte cooling out
Electrolyte cooling in

PEM water electrolysis – 'only circulating water'





N2 Purge
PEM Stack
H2 Gas/Liquid Separation
Hydrogen Drying
Hydrogen Pressure Control
Hydrogen
O2 Gas/Liquid Separation
Oxygen Pressure Control
Oxygen
Vent
Feed water pump
Buffer Vessel O2 Separator
DI Water
Feed water Buffer Vessel

PEM versus alkaline

	Alkaline (HySTAT®)	PEM (HyLYZER®)
Maximum H2 flow out of one stack	15 Nm³/h (one cell stack size)	2 or 30 or 600 Nm³/h (3 cell stack sizes)
Cell surface to reach 1 Nm³/h H2	0,6 m²	0,125 m²
Operating range	40-100% (opt. 10-100%)	5-120%
Specific consumption Containerized solution @ Nominal output (100%) ***OpEx***	5,3 kWh/Nm³	5,3 kWh/Nm³
H2 Gas purity after purification	99,998%, option 99,9995%	99,998%, option 99,9995%
Pressure	10 bar - option 27 bar	30 bar
Investment cost 100Nm³/h (0,5 MW)	0.9 M€ (1x40ft)	1.2 M€ (1x 40ft, 1x20ft)
Investment cost 200Nm³/h (1 MW)	1.75 M€ (2x 40ft)	1.75 M€ (1x40ft, 1x 20ft)
Investment cost 400Nm³/h (2 MW)	3.2 M€ (4x 40ft)	2.5 M€ (2x 40ft)
Investment cost 600Nm³/h (3 MW)	4.5 M€ (6x 40ft)	3.3 M€ (2x 40ft)
Operational cost Service/Maintenance	Low	Very Low
Lifetime of stack	60.000 h in field	Estimated 80.000 h (lab test)
Required water quality	< 5 µS/cm	< 1 µS/cm
References Hydrogenics	+500	15
Type of application	TRL9	TRL8

Conclusion: PEM vs. Alkaline

Why PEM ?

- Compactness – smaller footprint than Alkaline (for >1MW installations) – Up to 3MW in 2x 40ft container
- High Direct Output Pressure (30barg)
- Absence of caustic media
  - Less wear on Process Components
  - Low Maintenance costs
  - Opportunity to lower costs of Process
- High Gas Quality (5.0 after HPS)
- Lower investment cost for larger systems (>2MW)
- Wide operating range
- Higher efficiency at low load
- Overload allowed – up to 20% extra.
  CapEx for OpEx

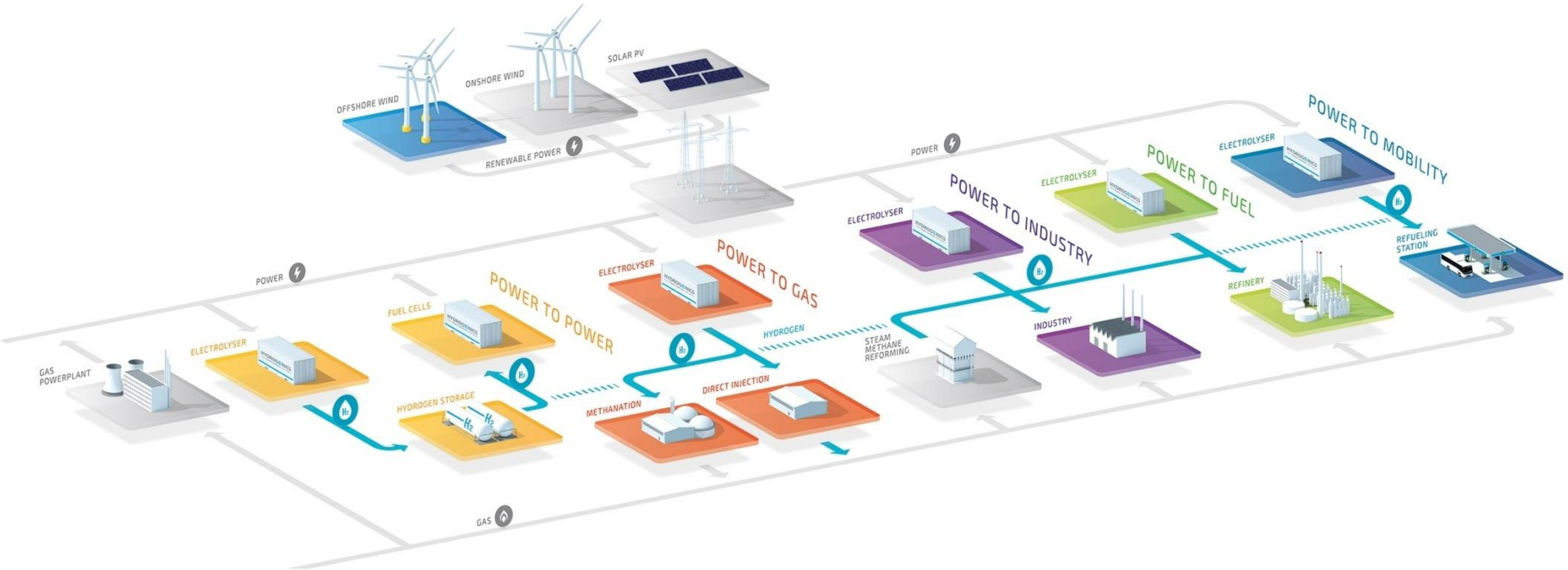
Why Pressurized Alkaline ?

- Mature technology and well established
- Many industrial references over the past century
- Small Footprint (compared to Alkaline Atmospheric Electrolyzers)
- Proven high cell stack lifetime and high reliability – availabilities of 99% and beyond measured
- Well established with many (industrial) field references
- Lower investment cost for smaller systems
- Smaller building blocks for large systems => Inherent Redundancy, but higher OpEx.
- High Gas Quality (5.0 after HPS)
- Direct Output Pressure (10 bar or 27bar)

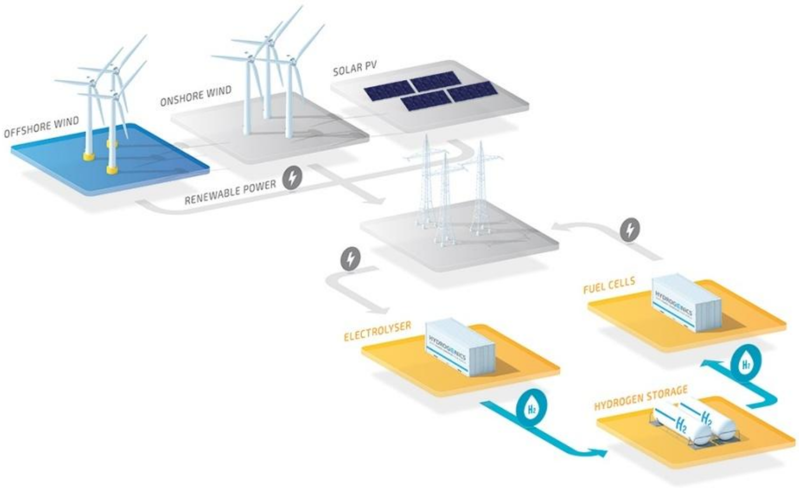
Agenda

1. Hydrogenics
2. Water electrolysis
3. **Renewable Hydrogen**
4. Fuel Cells
5. Conclusions

Renewable Hydrogen



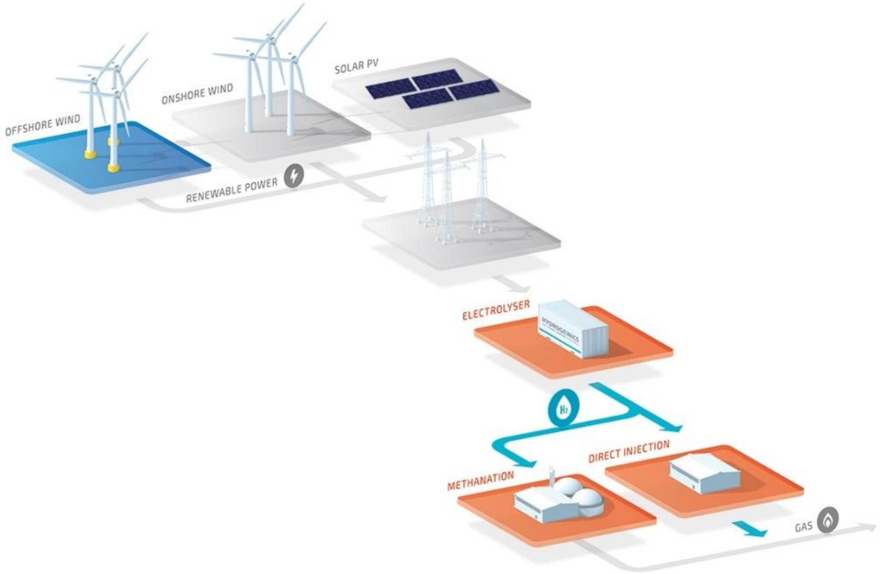
Power-to-Power | For Electrical Energy Storage



- Conversion of excess power in hydrogen via an **electrolyser**
- **Storage of hydrogen** in gas bottles, tanks or underground
- Repowering of the hydrogen through a **fuel cell**
- **Ideal for long-term energy storage** (remote locations, telecom, off-grid systems)

[1] Wind-Hydrogen, Glencore Raglan Mine, Canada: 350 kW electrolyser + 120 kW fuel cell
[2] WIND-projekt, Mecklenburg-Vorpommern, Germany: 1 MW electrolyser + 150 kW hydrogen combustion engine

Power-to-Gas



- Direct injection of hydrogen in gas grid (2%-10%$_{vol}$)
- Injection of Synthetic Natural Gas (SNG) after a methanation step : $H_2 + CO_2 \rightarrow CH_4 + H_2O$

[1] UNIPER's power-to-gas facility, Falkenhagen, Germany: 2 MW electrolyser
[2] BioCat project, Avedøre, Denmark: 1 MW electrolyser

WindGas Falkenhagen, Germany (2013)
Direct injection of hydrogen in natural gas grid (transportation)

2 MW
Direct injection
Alkaline

- **OBJECTIVES**
  - 1st demo project worldwide to inject hydrogen in the high-pressure transmission natural gas pipeline at 55bar (ONTRAS) with a max concentration of 2%vol
  - Optimize operational concept (fluctuating power from wind vs. changing gas feed).
  - Gain experience in technology, cost and business aspects.
- **SOLUTION**
  - 6 x HySTAT®-60-10 with all peripherals in 20Ft. housings to produce 360 Nm³/h hydrogen (power: 2 MW)
  - A 40 Ft container including 2 compressors to compress the hydrogen to 55barg.
- **PARTNERS:**
  - UNIPER Energy Storage GmbH (ex-EON)
- **More information:** www.uniper.energy

Photo credits: Uniper Energy Storage GmbH

Power-to-Gas

WindGas Reitbrook (Hamburg), Germany (2015)

Direct injection of hydrogen in natural gas grid (distribution)

1,5 MW
Direct injection
PEM

- **OBJECTIVES**
  - Development of 1,5 MW PEM Electrolysis Stack and System
  - Validate PEM technology in operational environment
  - Gain experience in technology and cost.
  - Feed hydrogen into the medium-pressure distribution natural gas pipeline at 30 bar without compression.

- **SOLUTION**
  - 1x HyLYZER®-285-30 PEM electrolyser with all peripherals in 40ft. housings for max 285 Nm³/h H_2 at 30 bar (Power: 1.5 MW)

- **PARTNERS:**

uniper | SolviCore Fuel Cell Technologies | Bundesministerium für Verkehr und digitale Infrastruktur | NOW Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie | nip Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie

HYDROGENICS SHIFT POWER | ENERGIZE YOUR WORLD | DLR | Fraunhofer ISE

- **More information:** www.windgas-hamburg.com

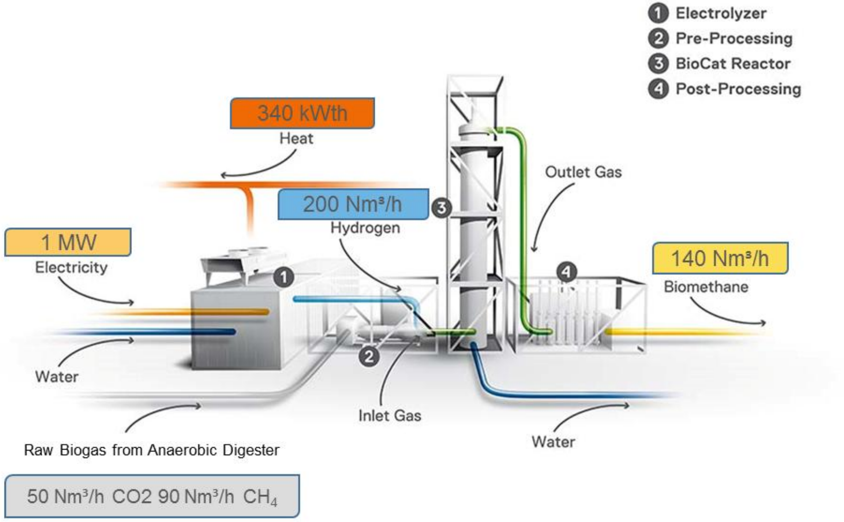
Photo credits: Uniper Energy Storage GmbH

BioCat, Avedøre, Denmark (2016)
Biological methanation and SNG injection in distribution gas grid

1 MW
Alkaline
Reduced
footprint

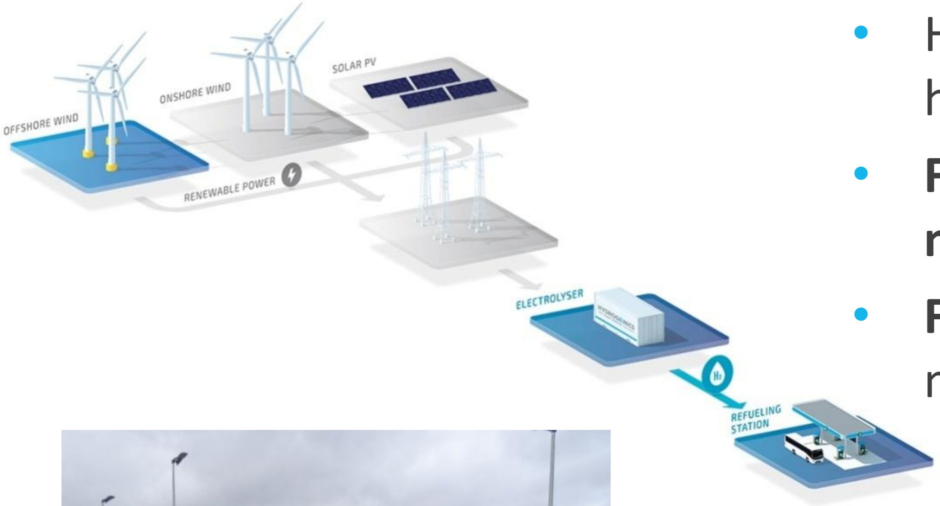
BioCatProject
POWER-TO-GAS VIA BIOLOGICAL CATALYSIS

www.biocat-project.com



Electrochaea
Audi Vorsprung durch Technik
BIOFOS
FORSK EL
HYDROGENICS SHIFT POWER | ENERGIZE YOUR WORLD
HMN GASHANDEL
INSERO BUSINESS SERVICES
NEAS ENERGY

Power-to-Mobility



- Hydrogen refueling stations with onsite hydrogen production
- **For cars (700 bar),** a refueling takes **3-5 min** for a driving range of **400-500 km**
- **For buses (350 bar),** a refueling takes 10 min for a driving range of 350 km

ACHES 350/700 bar hydrogen refueling station, Aberdeen (UK)

Example: Toyota MIRAI

Hydrogen refueling stations
> 50 references with onsite hydrogen production


Shell, Santa Monica, USA

Aberdeen Hydrogen Bus Project, Scotland, UK, 2015

Stockholm, Sweden, 2005


Oslo, Norway, 2012


Vattenfall, Hamburg, Germany, 2012


Barcelona, Spain, 2005

ACHES HRS
(Aberdeen City Hydrogen Energy Storage hydrogen refueling station)

ACHES – general overview
350 bar / 700 bar

COMPRESSOR STATION

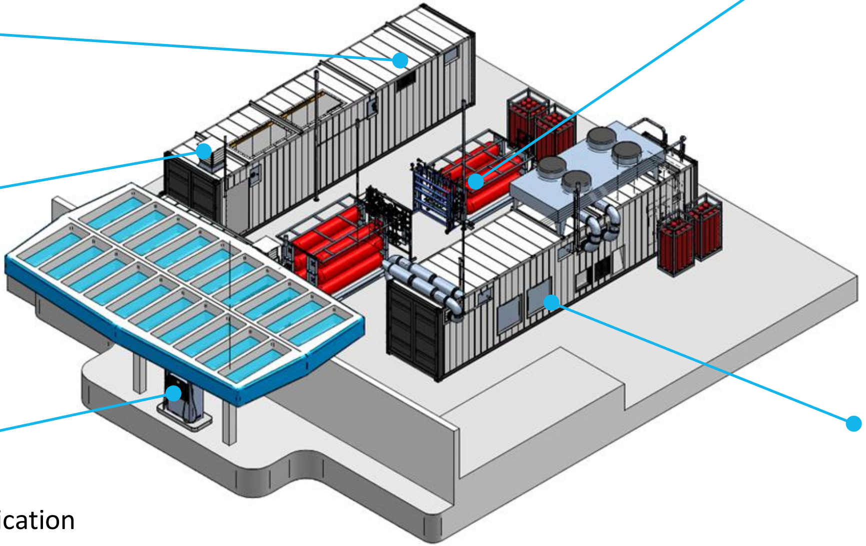
Compressor : reciprocating piston
Drive train : hydraulic
450 bar : 3 stages
900 bar : 2 stages
Housing : 40 FT HC ISO container

HYDROGEN COOLING

350 bar H2: -20°C
700 bar H2: -40°C
Housing : 20 FT HC ISO container

DUAL HOSE HYDROGEN DISPENSER

Manufacturer : Hydrogenics
Fueling protocol : SAE J2601 – IR communication
Nozzle : WHE TK17 fast fill
Card reader : Tokheim SlimDialog (RFID)
350 bar H2: for bus and utility vehicles Refueling time : <10 min
700 bar H2: for cars Refueling time : <3 min



HYDROGEN STORAGE

For 350 bar refueling
Capacity: 100 kg
Storage pressure : 450 bar
Maximum pressure : 500 bar
Cascade : 3-bank

For 700 bar refueling
Capacity : 50 kg Storage pressure : 900 bar
Maximum pressure : 1.050 bar
Cascade : 4-bank

WATER ELECTROLYSER

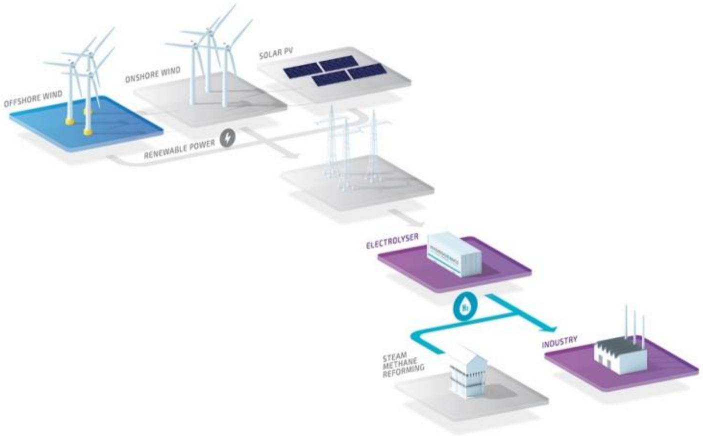
Model : HySTAT®-60-10
H_2 Capacity : 130 kg/day
H_2 Pressure : 10 barg
H_2 Quality : > 99,999%
Operating range : 40-100%
Efficiency : < 5,2 kWh_e/Nm^3
Housing : 40 FT HC ISO container

Don Quichote, Halle, Belgium (2015-2018)
Hydrogen from wind to power fuel cell forklifts

Hydrogen Refueling Station > **forklifts**

- **OBJECTIVES**
  - Located at one of the warehouse of Colruyt, one of the biggest Belgian retail company
  - Hydrogen is used to fill fork lift trucks
- **SOLUTION**
  - 30 Nm³/h alkaline + 30 Nm³/h PEM electrolysers
  - 50 kg 350 bar storage + dispenser
  - 100 kW Fuel Cell
- **SUPPORT**
  - 1st part funded by InterReg project (Waterstofregio Vlaanderen Zuid-Nederland)
  - 2nd part funded FCH-JU
- **More information:** www.don-quichote.eu

Power-to-Industry



- Hydrogen is used massively in the **industry : ammonia (fertilizers), refineries, steel, float glass, semi-conductors, oil and fat, power plants.**
- 1 ton of renewable hydrogen avoids the emission of +/- 10 tons of CO_2

Main industries consuming hydrogen

- 50%: chemical industry (ammonia, methanol)
- 43%: oil refineries
- 6%: float glass, steel and semi-conductors
- 1%: power plants, oil hydrogenation and mobility

Total consumption 2014 = 571 bcm H_2

Data source: The Hydrogen Economy, M. Ball 2009 & Esprit Associates 2014

Power-to-Industry

HyBalance, Hobro, Denmark (construction in 2017)
Industrial hydrogen and delivery to hydrogen refueling stations

1.2 MW
PEM
Dual stack

- **OBJECTIVES**
  - Validate the highly dynamic PEM electrolysis technology in a real industrial environment and provide grid balancing services on the Danish power market
  - Validate innovative hydrogen delivery processes for fueling stations at high pressure

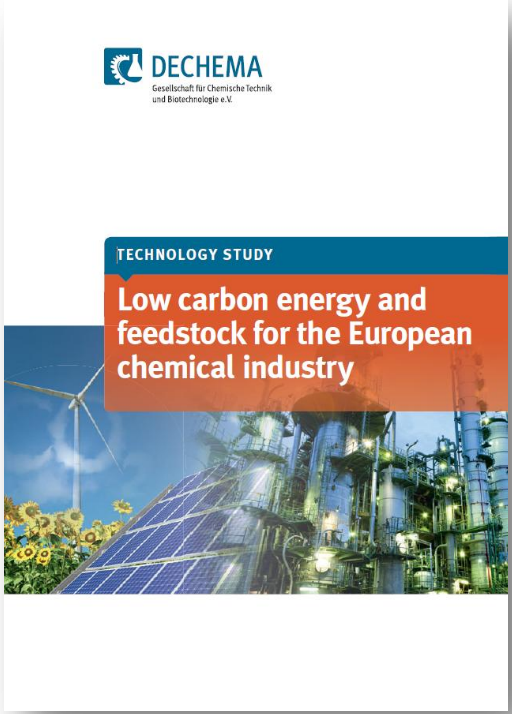
- **SOLUTION**
  - 1x HyLYZER®-230-30 (PEM, dual cell stack design) with all peripherals to produce 230 Nm³/h H_2 (power: 1,2 MW)

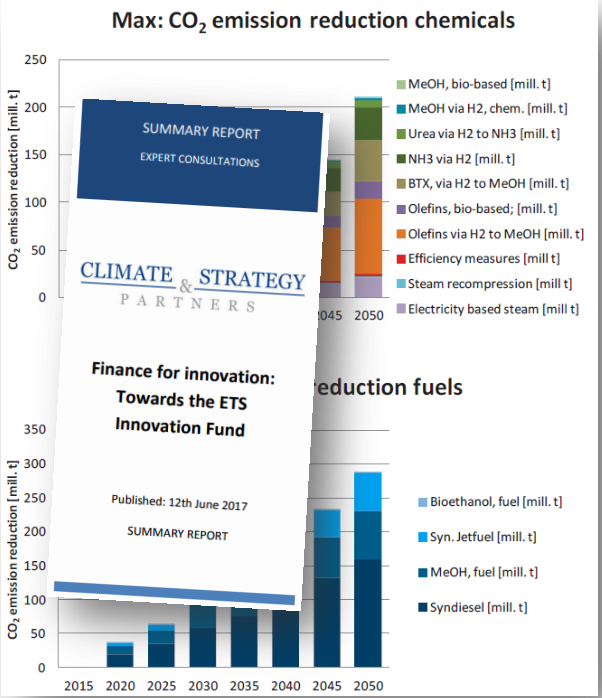
- **PARTNERS:**
  - This project receives financial support FCH-JU (GA No 671384) and ForskEL program, administered by Energinet.dk.

AIR LIQUIDE · HYDROGENICS · HYDROGEN VALLEY · NEAS ENERGY · ludwig bölkow systemtechnik · FCH · FORSK EL

- **More information:** www.hybalance.eu

Huge decarbonisation potential via Renewable H_2 in EU industry: chemistry, refineries, steel….





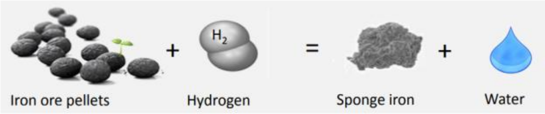
http://www.cefic.org/Documents/RESOURCES/Reports-and-Brochure/DECHEMA-Report-Low-carbon-energy-and-feedstock-for-the-chemical-industry.pdf

Industry across Europe is responsible for more than half of all carbon dioxide, particulate matter and other key pollutants emitted into the air, according to updated industrial pollution country profiles published today by the European Environment Agency (EEA).

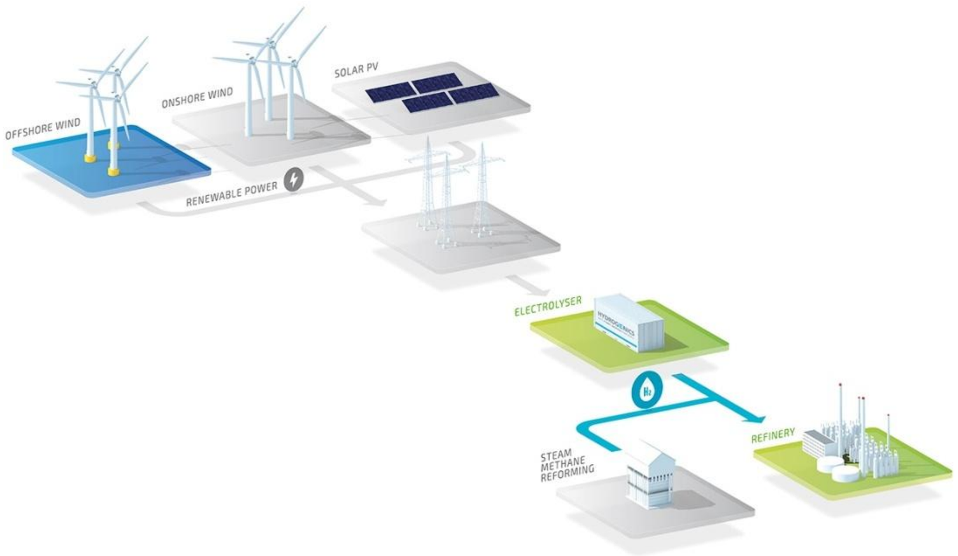
6 Dec 2017

European Environment Agency

CO2-emission free iron making



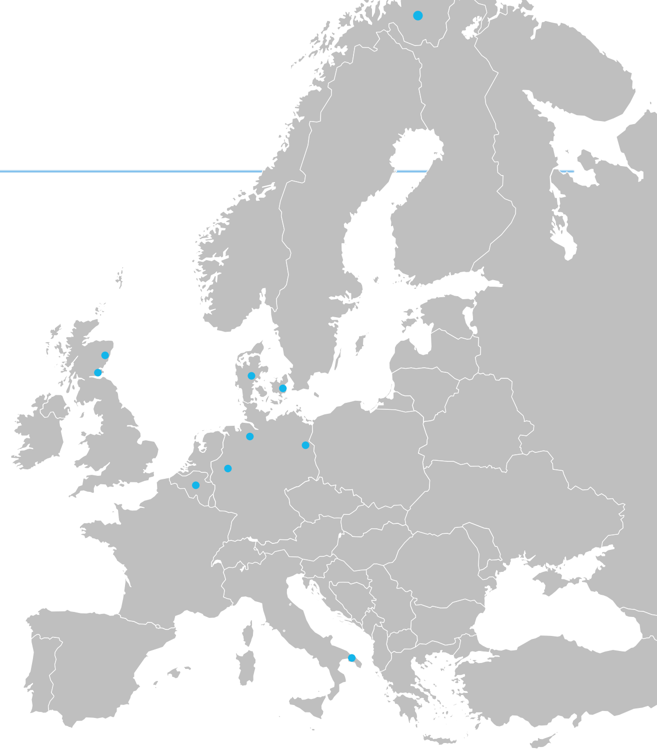
Power-to-Fuel



- Renewable hydrogen for **refineries** for the desulfurization of the fuels (massive CO_2 savings)
- Synthesis of renewable **methanol**: $H_2 + CO_2 \rightarrow CH_3OH + H_2O$
- Possible introduction in EU Renewable Energy and Fuel Quality Directives (Upstream Emmission Reductions)

[Renewable] hydrogen
Selection of recent demonstration projects

Country	Project	Size	Year	Electrolyser technology	Power	Gas	Industry	Mobility	Fuel
Norway	Haeols	5MW	2019	PEM	•				
Germany	WindGas Brunsbuttel	2.4 MW	2017	PEM		•			
Thailand	EGAT	1.2 MW + 500 kW FC	2017	PEM	•				
Canada	Embridge P2G	2 MW	2017	PEM		•			
Germany	MefCO2	1 MW	2017	PEM					•
Denmark	HyBalance	1.2 MW	2017	PEM			•	•	
UK	Levenmouth	370 kW + 100 kW FC	2016	Alkaline + PEM	•			•	
Denmark	BioCat	1 MW	2016	Alkaline		•			
Italy	Ingrid	1 MW	2016	Alkaline	•	•	•		
UK	Aberdeen	1 MW	2016	Alkaline				•	
Germany	WindGas Reitbrook	1.5 MW	2015	PEM		•			
Belgium	DonQuichote	150 kW	2015	Alkaline + PEM	•			•	
Germany	WindGas Falkenhagen	2 MW	2014	Alkaline		•			



Main conclusions from these projects:

1. Hydrogen **technologies work fine** and deliver according to expectations.
2. There is still room for further technical improvement but **no technology breakthrough is expected**.
3. There is a important potential for further **cost reduction**: going from project manufacturing to product manufacturing
4. Energy **regulatory framework is no suited** for these applications and **business operation** of these projects **remains very challenging**

Agenda

1. Hydrogenics
2. Water electrolysis
3. Renewable Hydrogen
4. **Fuels cells**
5. Conclusions

Fuel Cell

$H_2 + ½ O_2 \rightarrow H_2O$ + electricity

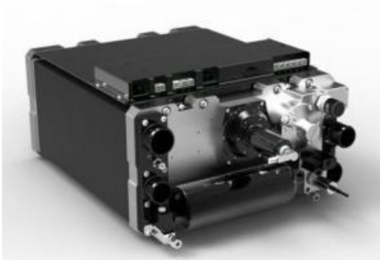
Fuel cells solutions: from power modules for turnkey systems

PEM Single Cell

- MEA - Membrane Electrolyte Assembly
- Bipolar plates
- Gas Diffusion layer
- Gaskets

Integrators, OEMs

Fuel Cell Power Module



Cell stack

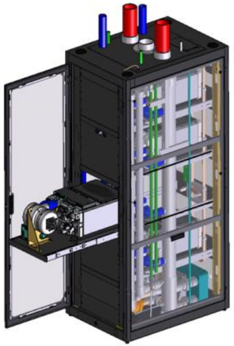
- Multiple cells layered
- End plates
- Tie rods
- Spring washers
- Bus bar interfaces
- Fuel cell voltage monitor

Balance-of-Plant

- Fuel management
- Air management
- Water management
- Coolant pump and control
- Control hardware and software

OEMs, Fleet Owners

Fuel Cell System



- Power conditioning
- Hybrid energy storage
- Hybrid control hardware and software
- Cooling or heat exchanger (or CHP)
- H2 storage

KOLON Water & Energy, South Korea (2015)
Repowering of by-product hydrogen from chemical industry

1 MW
Stationary
Fuel cell

- **OBJECTIVES**
  - Process Plant with by-product hydrogen
  - Korean government provides incentives (feed-in) for power produced from hydrogen
- **SOLUTION**
  - >1 MW HyPM-R based on HyPM-R120 fuel cell racks
  - Grid feed inverters, outdoor containers
  - Joint venture power purchase agreement (PPA)
  - 20 year Service agreement
  - Commissioned October 2015
  - 2x40ft containers
- **More information:** http://www.hydrogenics.com/about-the-company/news-updates/2014/06/23/hydrogenics-signs-agreement-to-create-kolon-hydrogenics-joint-venture-for-power-generation-in-south-korea

Fuel cells for mobility applications
Many references


Canary Islands, Spain


FZ FORMULAZERO


Toronto Canada


Konstanz, Germany


TACOM/General Motors


H2Fly, DLR, Germany


Riversimple, UK


Basel, Switzerland


Los Angeles, CA

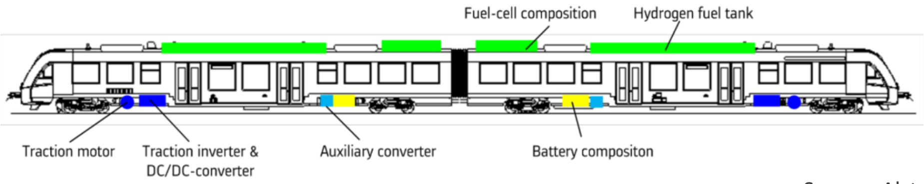

Berlin, Germany


ALSTOM, Germany


Los Angeles, CA, USA

Alstom Transport | Zero-emission (hydrogen) train | Coradia iLint

- ~50% of rail network in Germany is not electrified (operated with diesel)
- More stringent regulation (exhaust emission, noise) and expected price increase for diesel
- LOI from 4 German States to buy min 40 zero emission passenger trains (2014)
- 1st train (2016) with hydrogen fuel cell
- Commercial service expected by 2020



Source: Alstom

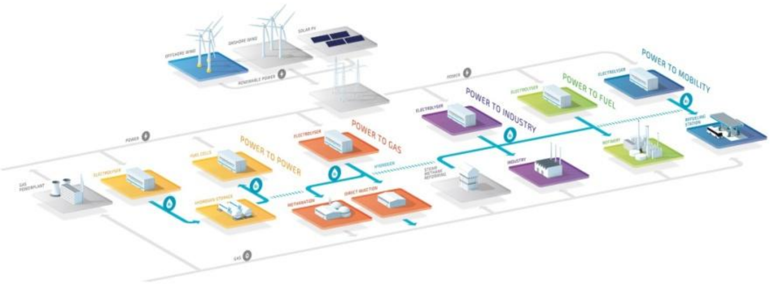
Agenda

1. Hydrogenics
2. Water electrolysis
3. Renewable Hydrogen
4. Fuel Cells
5. **Conclusions**

Key messages

- Hydrogen and Fuel Cell **technologies are** mature and **ready**
- Massive **cost reduction** potential : from project to product manufacturing & product up scaling
- Massive **CO_2 reduction** potential: power, gas, transport and industry

- **But markets are not ready !**
- We need:
  1. Green hydrogen certification mechanism
  2. Premium value for end product / application
  3. Access to renewable electricity at low cost
  4. Grid connection to deliver balancing services



Thank you for your attention

We're Ready.

Guy Verkoeyen | Area Sales manager
Hydrogenics Europe NV – OnSite Generation
Mobile: +32 477 411 411 | Email: gverkoeyen@hydrogenics.com

The challenge of distributing Hydrogen into the natural gas network

Dr Angel Mª Gutierrez
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This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 700355.This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY

May 17th, 2018

Summary

- Introduction
- Hydrogen in natural gas infrastructure
- H2NG
- Renewable hydrogen value chain
- Metrology
- Origin and Certification for H_2 – Monitoring
- System Safety Aspects
- Hydrogen Compatibility of Materials
- Grid operators
- Gas infrastructure equipment and devices
- Grid integrity and operation

Introduction

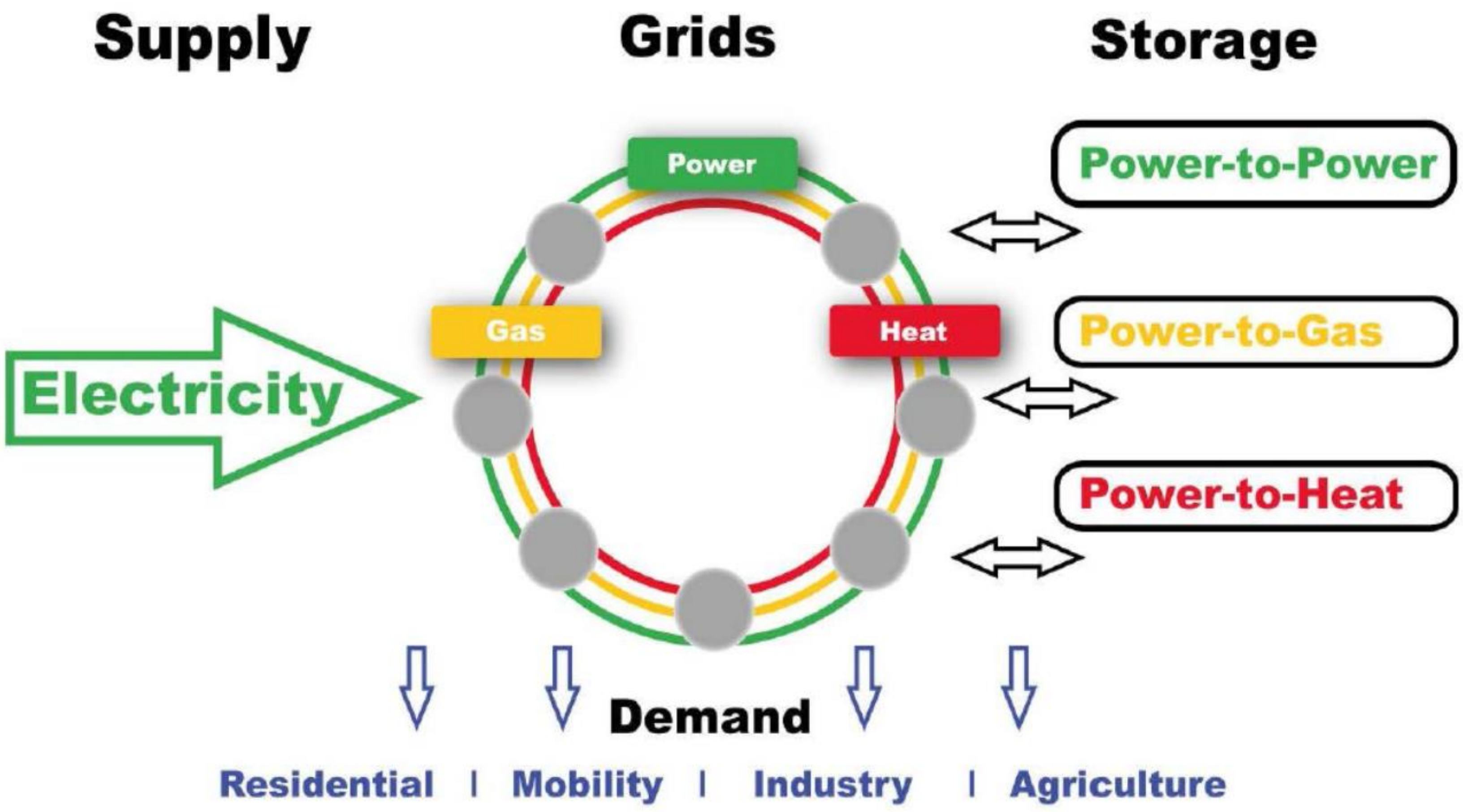
- In the current annual EU Work Programme, the following was stated:

  "Assuring interoperability between grids for the increase of renewable energies in the power mix in order to enhance the capacity of the existing infrastructures to absorb green energy resources while not increasing the cost for users."

  The CEN and CENELEC committees, especially the CEN-CENELEC/TC 6 'Hydrogen in energy systems', CEN/TC 234 'Gas infrastructure' and CEN and CENELEC TCs related to the H_2 end use, were established to face the challenge as identified by the Commission as priority for Standarisation.

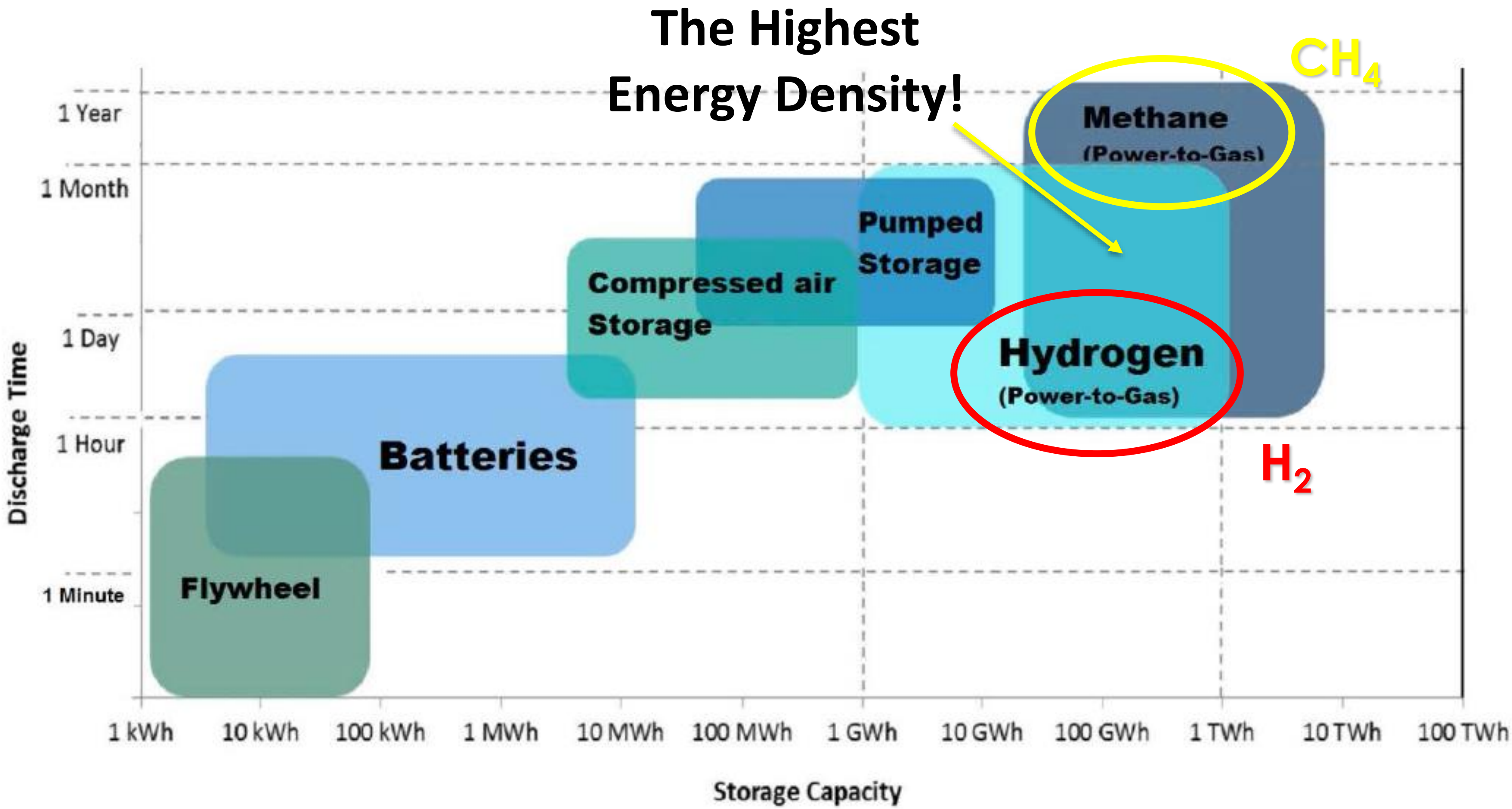
  There is a need to create a new market for the product '**Green Hydrogen**'.

Integration of Energy Systems



Source: *EC STAFF WORKING DOCUMENT Energy Storage – the role of electricity. Brussels, 01 Feb 2017*

Storage Energy Technologies



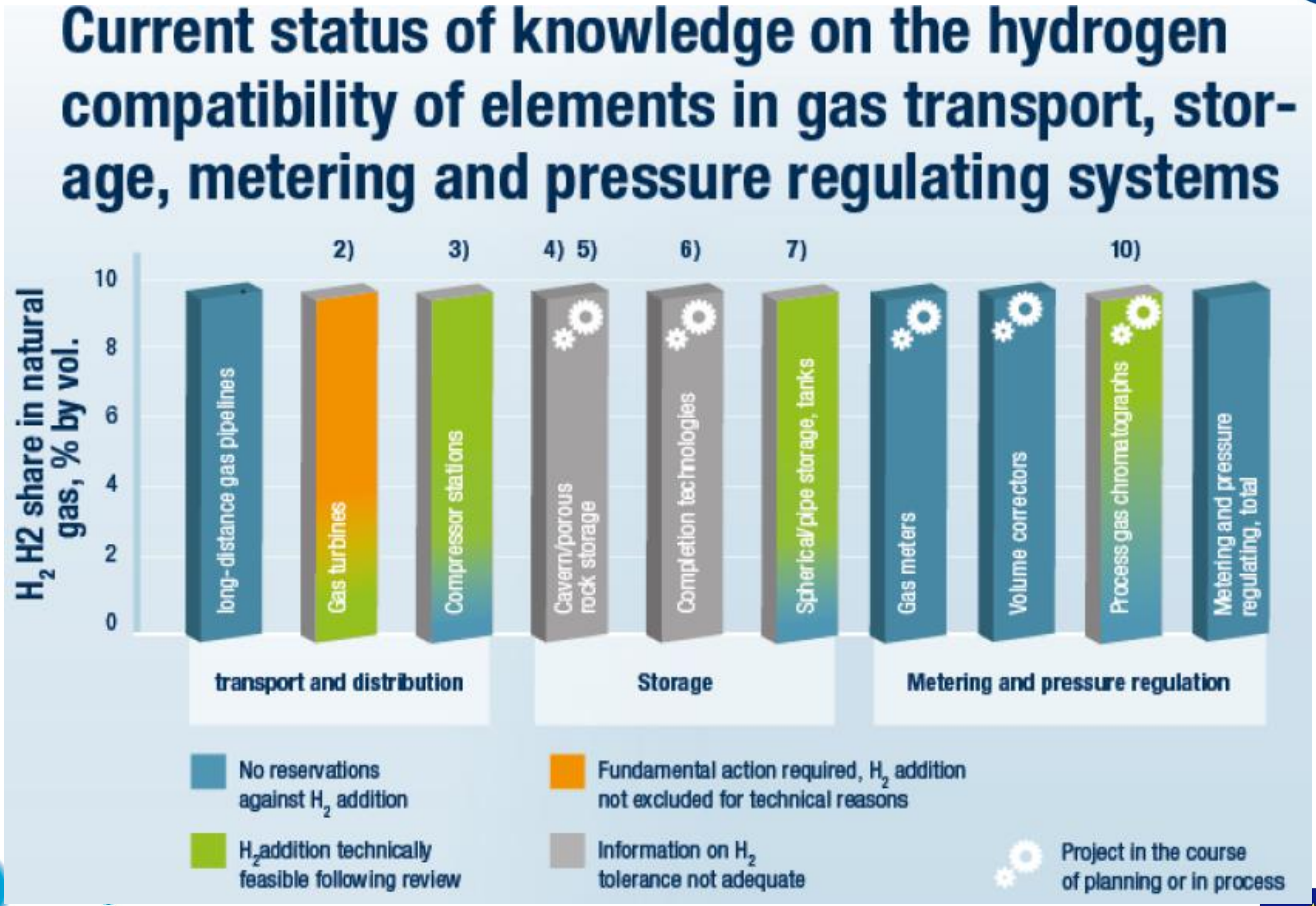
Source: *EC STAFF WORKING DOCUMENT Energy Storage – the role of electricity. Brussels, 01 Feb 2017*

Hydrogen in natural gas infrastructure

- There are two ways to distribute H_2 in the natural gas grids:
  - Processing of hydrogen and conversion in methane (methanation, SNG)
  - **Admixture of molecular hydrogen to natural gas up to an admissible concentration (H2NG)**

- For this aim, the following is needed to be taken into account :
  - Interconnection standards to allow physical connection and communication between electrolysers and the control of the gas grid
  - Operational conditions for Hydrogen injection in the gas grid (pre-mix, pressure, temperature and quality among others)

Hydrogen in natural gas infrastructure



H2NG

- Injecting hydrogen into the natural gas network can contribute significantly to solving the problem of transporting and storing surplus electricity generated from renewable resources.
- The following is required as a first proposal:
  - An H_2 concentration accepted by all stakeholders, allowing higher H2 concentrations in regional grids and
  - Developing the infrastructure with the objective to accept higher concentrations in future steps

- Depending on the location of the Power-to-Gas plant, hydrogen could be injected either into the transmission or distribution grid which have very different gas flow rates.
- Pre-mixing stations may be required in order to not exceed the concentration limits.

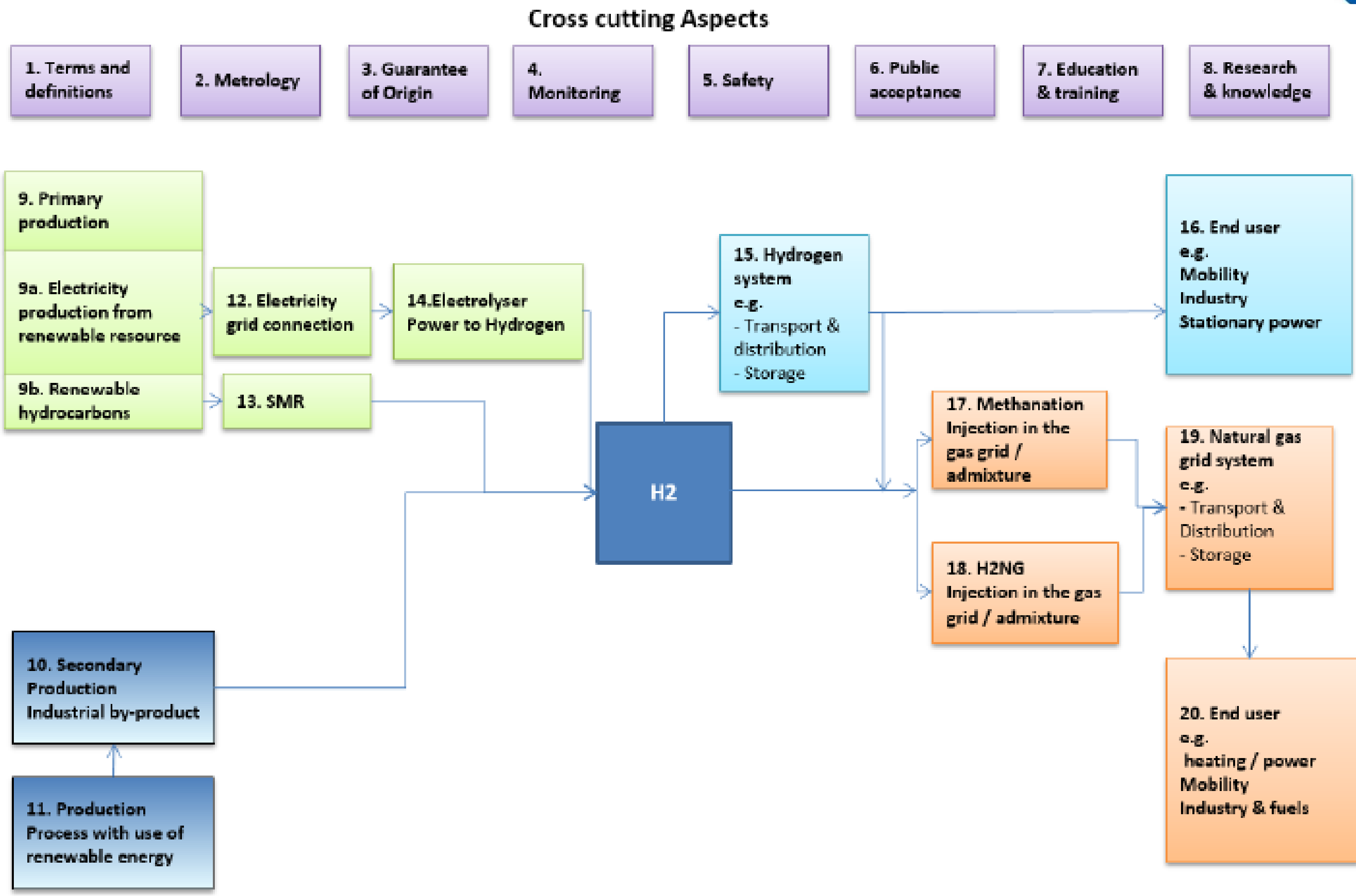
H2NG

- Regarding hydrogen, **it is not possible at present to specify a limiting value which would generally be valid <u>in all areas of the European gas infrastructure</u>.**

- One reason for this situation is that for the time being there is no common understanding for an admissible hydrogen concentration due to a lack of knowledge. Therefore, the EN16726 Gas infrastructure —Quality of Gas— Group H does not yet offer requirements on hydrogen.

- The distribution grid also uses a greater variety of materials such as plastic pipelines and thus a differentiation was made between the grids where necessary. An assessment was performed to **identify the key issues related to different hydrogen concentration limits of 2% vol., 5% vol. and 10% vol.,** taking into account the results of prior research.

Renewable hydrogen value chain



Renewable hydrogen value chain

- With regard to the points 9, 10, 11, 12, 13 and 16 of the hydrogen value chain, no standardisation related actions are foreseen
- Consequently, early attention to the following points is required:
  - Development of an unambiguous terminology
  - System Safety Aspects need continued focus
  - Clarification of the legal status of Power to Gas
  - Guarantee of origin and Certification for H_2
  - Implementation of FQD* at national level
  - Clarification of IED* with respect to electrolysers
  - Training and education frameworks

*FQD: Fuel Quality Directive
*IED: Industrial Emissions Directive

Metrology

- Metrology is mainly used in relation to Hydrogen quality and purity or to H2NG measurement.
- It is of high relevance regarding the safe use of the end-use applications.
- It is also required to know what the impact of pressures and flows is to ensure a continuous supply of gas to the end users and for billing purposes.
- Research actions:
  - Modelling the mixing behaviour
  - Development of measurement devices or software

Origin and Certification for H_2 – Monitoring

- In order to develop the Green Hydrogen market, a **tracking system ensuring the quality of hydrogen** is necessary.
- *Standardisation action*:
  - EN standard(s) supporting the deployment of a Guarantees of Origin scheme for Green Hydrogen
- Concerning monitoring, the development of sensors are needed to enable the detection of potential leaks specifically of H2NG and for measurements of gross calorific value or Wobbe index of the blending as well as the hydrogen concentration.

System Safety Aspects

- Further research is required into the gas properties of H2NG in order to determine appropriate safety measures.

- Research actions:
  - More details are needed on safety relevant properties: **the upper and lower explosion limit (LEL, UEL)**, the ignition energy and **auto-ignition temperature for hydrogen/methane mixtures in the range 0 to 20% vol. H_2** as function of temperature and pressure.

  - Research into ignition of hydrogen and H2NG by mechanically generated sources, electrostatic and corona discharge at different concentrations.

Hydrogen Compatibility of Materials

- To ensure safety and reliability of H2NG installations, the interaction of hydrogen with many types of materials should be known across a wide range of hydrogen concentrations, temperatures and pressures.

- Pre-normative actions:
  - List of materials compatible with H2NG systems
  - Testing procedures such as the fatigue life test and also a permeability test
  - Accelerated fatigue testing and investigation of welds

Grid operators

- Gas grid operators, when receiving a request to connect a PtG plant should analyse the current status and any potential effect in their grid to determine **the maximum volume of hydrogen the network is capable of accommodating**.

- The effect of hydrogen on all components of the gas grid infrastructure and the gas system including underground storage needs to be assessed.

Gas infrastructure equipment & devices

- In mid-term attention is required to the following topics:
  - Adaptation of gas analysis instruments and methods: the addition of H_2 influences to the properties of the gas, such as compressibility, viscosity, density and heat capacity.
  - The effect on volume measurement, gas composition analysis, metering and measurement of calorific value, especially for billing purposes should be assessed.
  - In order to quantify the delivered amount of energy, the calorific value and other properties of the gas have to be measured.
  - The presence of two combustible gases (methane and hydrogen) and a lack of oxygen precludes the use of common sensor types.
  - The first devices that are able to measure up to 5% vol H_2 in natural gas are available and subject to national certification processes in some countries.

Gas infrastructure equipment & devices

- Mid-term attention is required to the following topics:

<u>Pressure regulators and valves, seals and connections</u>:

- At present the available knowledge does not indicate difficulties for low hydrogen concentration (below 10% vol) and further research is needed.
- The soft sealing used in pressure regulators, valves and slam-shut valves (SSV) should be considered. These devices have a major influence on safety and therefore the effect of hydrogen, also at concentrations above 10% vol., has to be determined.

<u>Compressor stations:</u>

- For low concentrations of hydrogen (below 5% vol) the effects are expected to be minor but further investigations should be performed.

Grid integrity and operation

- Hydrogen concentrations up to 10% vol:
  - Experimental proof is needed to show that embrittlement and fatigue effects do not occur below 10% vol. hydrogen in natural gas for all materials used in the grid especially if further imperfections are present.

- Flow behaviour
  - Improved modelling of the mixing behaviour is needed to better understand the flow behaviour of gas mixtures and to identify areas where due to imperfect mixing of higher H_2-concentrations can occur.
  - Additional development of hydraulic software for modelling gas flows/pressures is needed, in order to meet billing requirements.

Flexible Hybrid separation system for H2 recovery from NG Grids

HyGrid

Thank you for your kind attention

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nortegas

Flexible Hybrid separation system for H2 recovery from NG Grids
HyGrid

Exploitation Workshop
Hydrogen separation using membranes

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 700355.This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY

Duration: 3 years. Starting date: 01-May-2016

Contacts: F.Gallucci@tue.nl

Objectives

Development of cost effective tubular supported membranes for the recovery of hydrogen from low concentration streams (2% -10%) in the whole range of pressures of the Natural Gas Network. Two different types of membranes will be developed as well as the final membrane module:

- **Pd-based membranes** for the medium to the lowest Natural Gas Grid pressures with improved flux and selectivity.
- **Carbon Molecular Sieve membranes** for the high pressure range.
- Membrane **module for the prototype**.

Summary of the presentation

SAES — G.Macchi

Selection of ceramic supports (in coordination with Tecnalia)

Development of membrane sealing technology

Characterization of membranes and sealing

Tecnalia — D.A. Pacheco Tanaka

Preparation of Pd-Ag membranes

Preparation of carbon membranes

Characterization of membranes and sealing

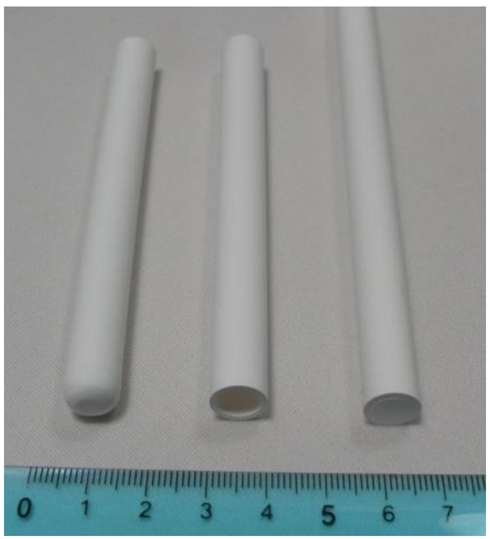
Selection of ceramic supports

Symmetric support

- main body and surface: 0.2 µm pore size
- thicker near the brazing area
- advantage: easier manufacturing
- lenght: 10 cm, 42 cm

Asymmetric support

- surface: 0.1 µm pore size
- main body: 2-3 µm pore size
- advantages: low pressure drop
  high permeation



code	RT N_2 permeance (mol Pa^{-1} s^{-1} m^{-2})
10/7 o-o	2.10×10^{-6}
10/8 o-o	2.78×10^{-6}
10/8 f-o	2.69×10^{-6}
10/4 o-o*	12.8×10^{-6}
10/7 o-o*	36.1×10^{-6}
14/7 f-o*	12×10^{-6}†

substrate	H_2 permeance (mol Pa^{-1} s^{-1} m^{-2})	
	w/ Pd layer	w/o Pd layer
10/7	1.0×10^{-6}	5.1×10^{-6}
10/7*	4.0×10^{-6}	40×10^{-6}
10/8	2.4×10^{-6}	6.5×10^{-6}
10/9	0.8×10^{-6}‡	14.2×10^{-6}
14/7*	2.0×10^{-6}†	-

data obtained in SAES laboratories

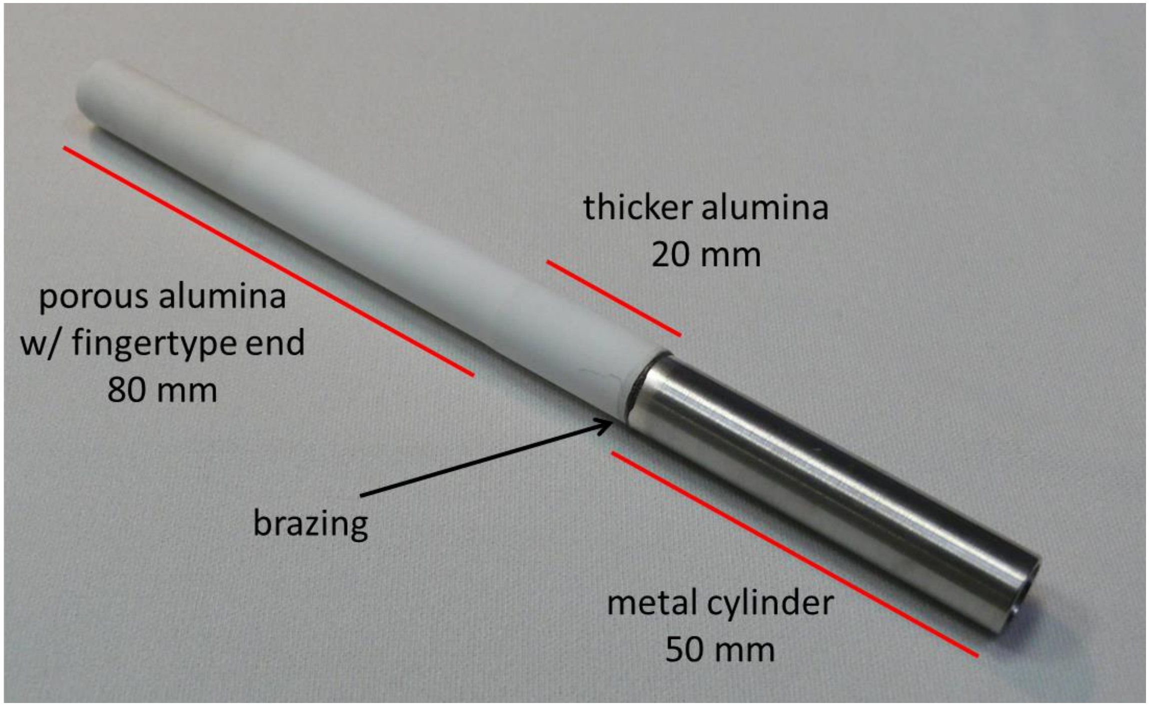
†: provided by Tecnalia ; ‡: provided by TU/e

- 10/9 symmetric supports have permeance figures suitable to match HyGrid needs and thus a reliable option to 10/7 asymmetric samples
- choice of support also depending on sealing/connection technology requirements

Development of sealing technology

- several symmetric and asymmetric porous tubes were sealed

- the best results were obtained by brazing a metal cylinder with the same outside diameter of the symmetric alumina tube



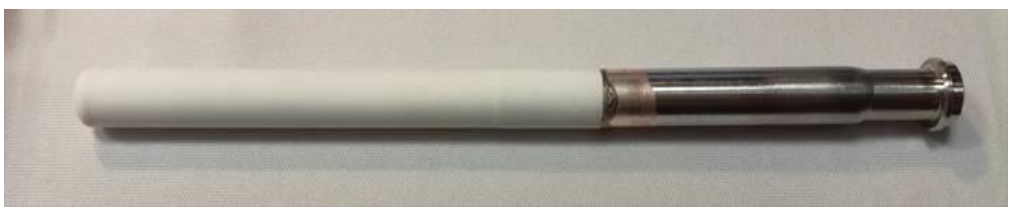
- trials with asymmetric tubes have not been succesfull:
  leaking in the brazing region
  detachment between the dense metal tube and porous alumina

Development of sealing technology

Critical issues in brazing supports on metal:

- alumina is porous and thus mechanically more fragile than dense alumina
- the brazing process must not modify the porosity of alumina so it cannot exceed temperatures in the range of 1000° C
- the surface of alumina must remain perfectly clean and without defects at the end of the brazing process
- the alumina and the area of transition to other materials must be perfectly smooth to allow the deposition of a thin Pd film without cracks.

A few samples has been prepared: they have successfully passed the bubble test



- graphite ferrules (compression type connection) as candidate alternatives

Characterization of membranes

- H_2 permeance and leak-rate

membrane	H_2 permeance (mol Pa^{-1} s^{-1} m^{-2})	He leak rate (mbar l s^{-1})	
brazed porous ceramic A	1.8×10^{-6}	7.0×10^{-2}	*n.a.*
brazed porous ceramic B	2.7×10^{-6}	3.0×10^{-3}	7.3×10^{-5}
porous ceramic w/ graphite	1.2×10^{-6}	8.0×10^{-3}	4.0×10^{-8}
self-standing	0.5×10^{-6}	4.8×10^{-8}	$< 10^{-9}$

H_2 permeance at 400° C ; He leak-rate under 0.5 barg He ; He leak-rate in static conditions
data obtained in SAES laboratories

- selectivity as pure gas flowrate ratio and N_2 inlet/outlet ratio

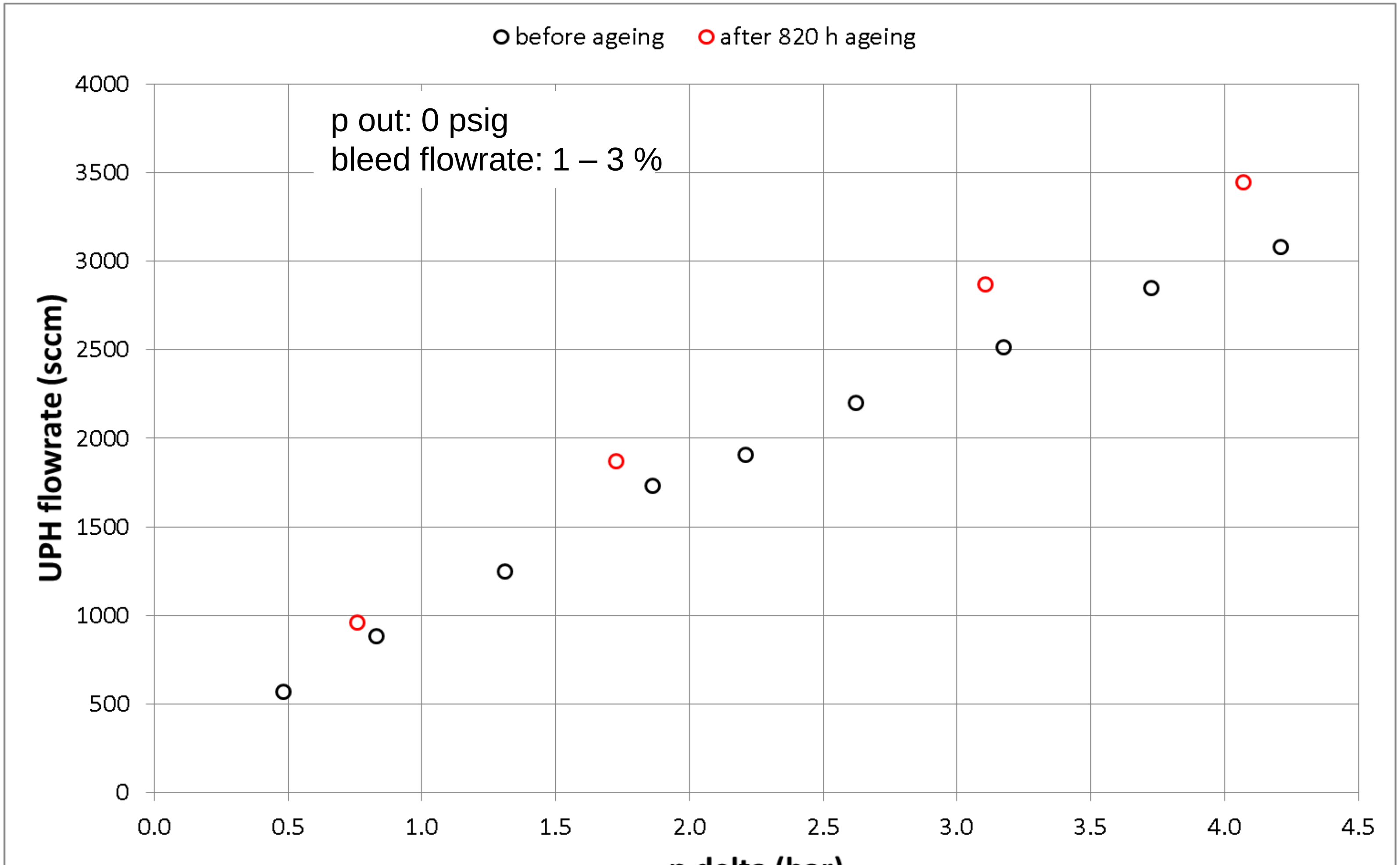
membrane	N_2 flowrate RT (sccm)	N_2 flowrate 400°C (sccm)	H_2 flowrate 400°C (sccm)	H_2:N_2 ratio
brazed porous ceramic A	*n.a.*	*n.a.*	2280*	-
brazed porous ceramic B	1.76	1.11	2600	2350
porous ceramic w/ graphite	0.6	0.15	1720	11500
self-standing	*<l.o.d.*	*<l.o.d.*	300	>30000

Flowrate at 3.0 bar pressure drop. *: calculated from permeance value.
data obtained in SAES laboratories

Characterization of membranes

ASYMMETRIC SUPPORT W/ GRAPHITE CONNECTIONS

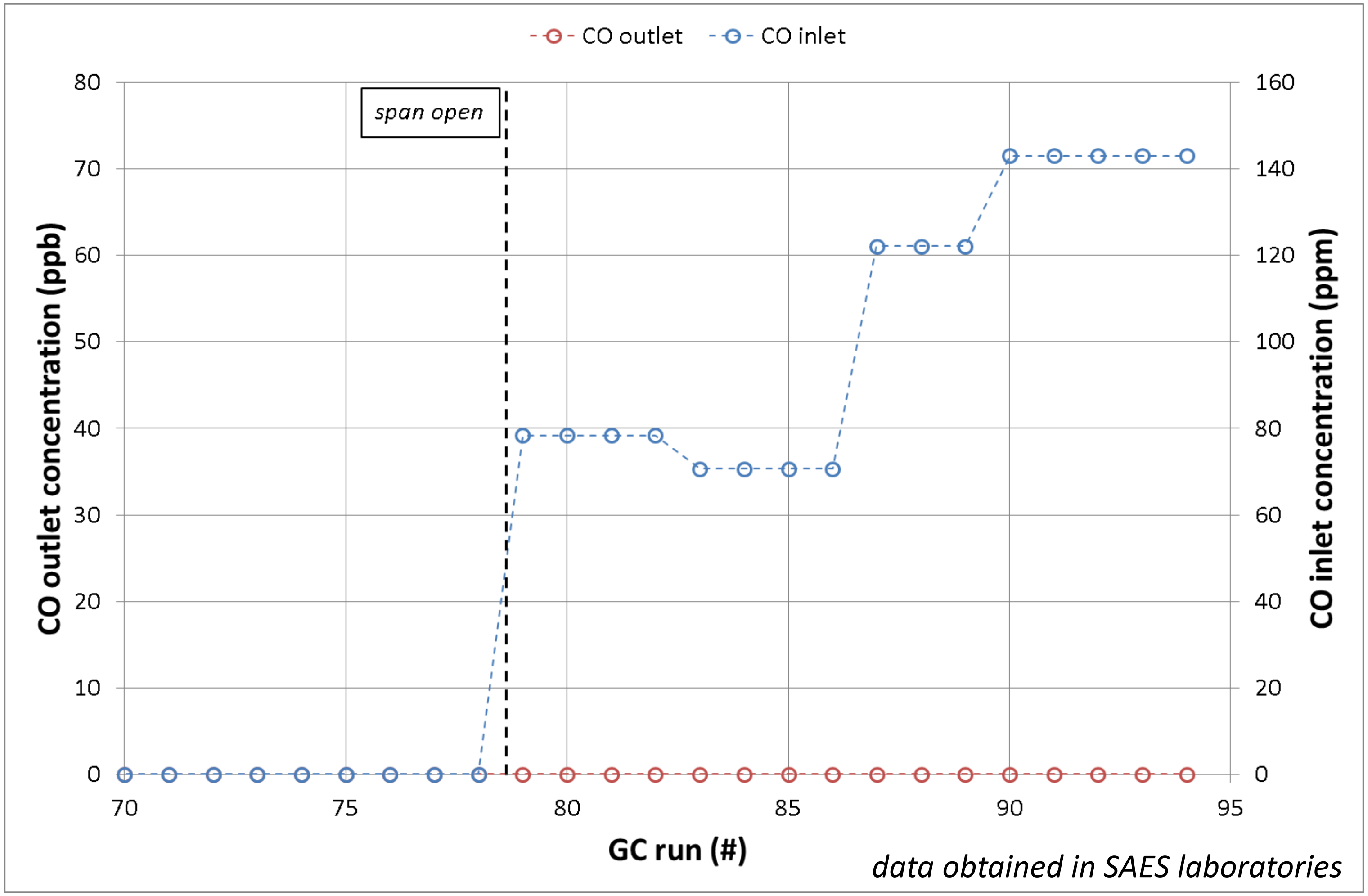
- flowrate performance vs. p – ageing effect: 8-10% increase and improved *n* fit



data obtained in SAES laboratories

Characterization of membranes

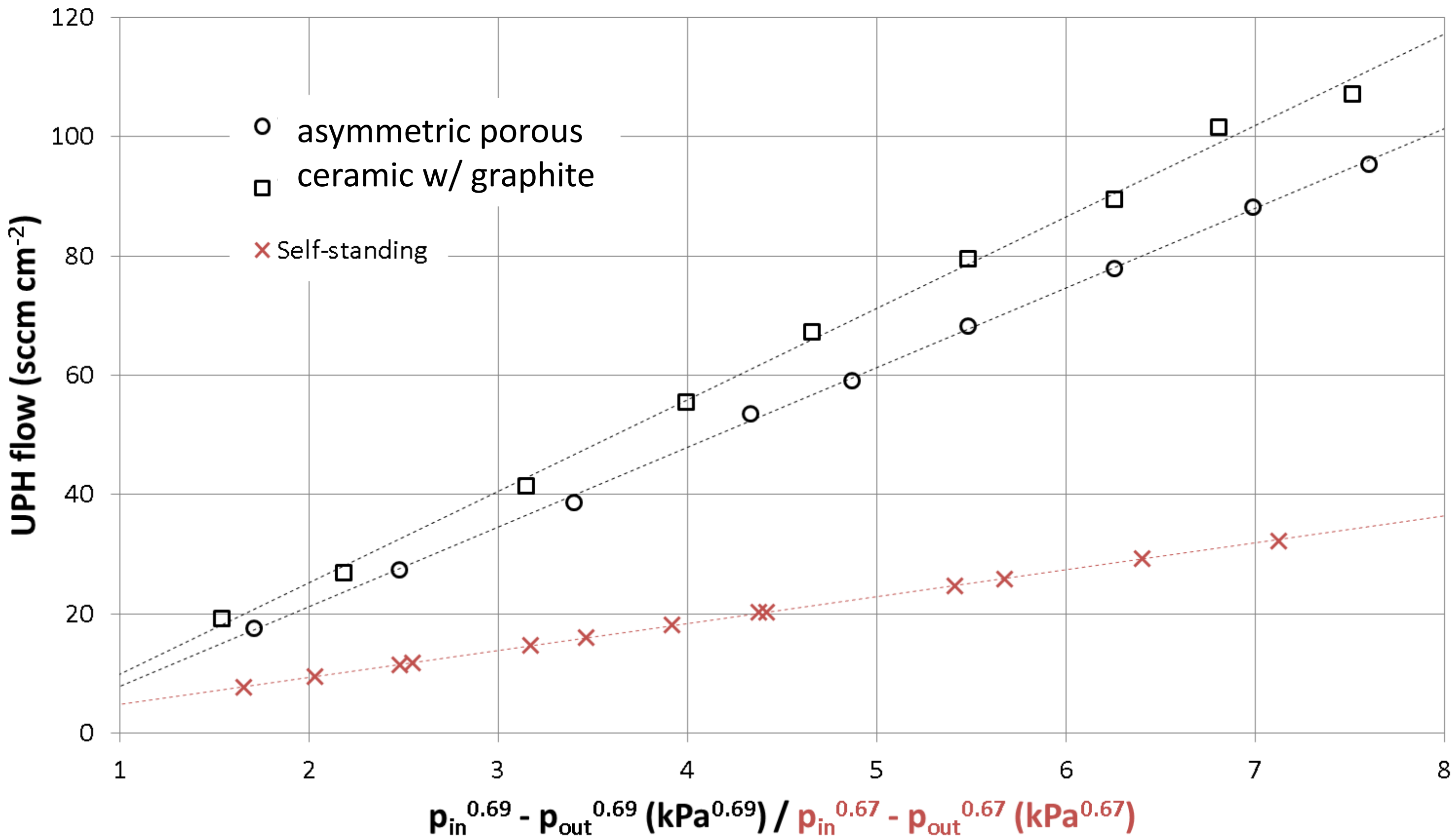
SELF-STANDING PD MEMBRANE



- at best of GC analysis, removal efficiency is ideal (∞)

Characterization of sealed membranes

Asymmetric support w/ graphite connections vs. self-standing membranes

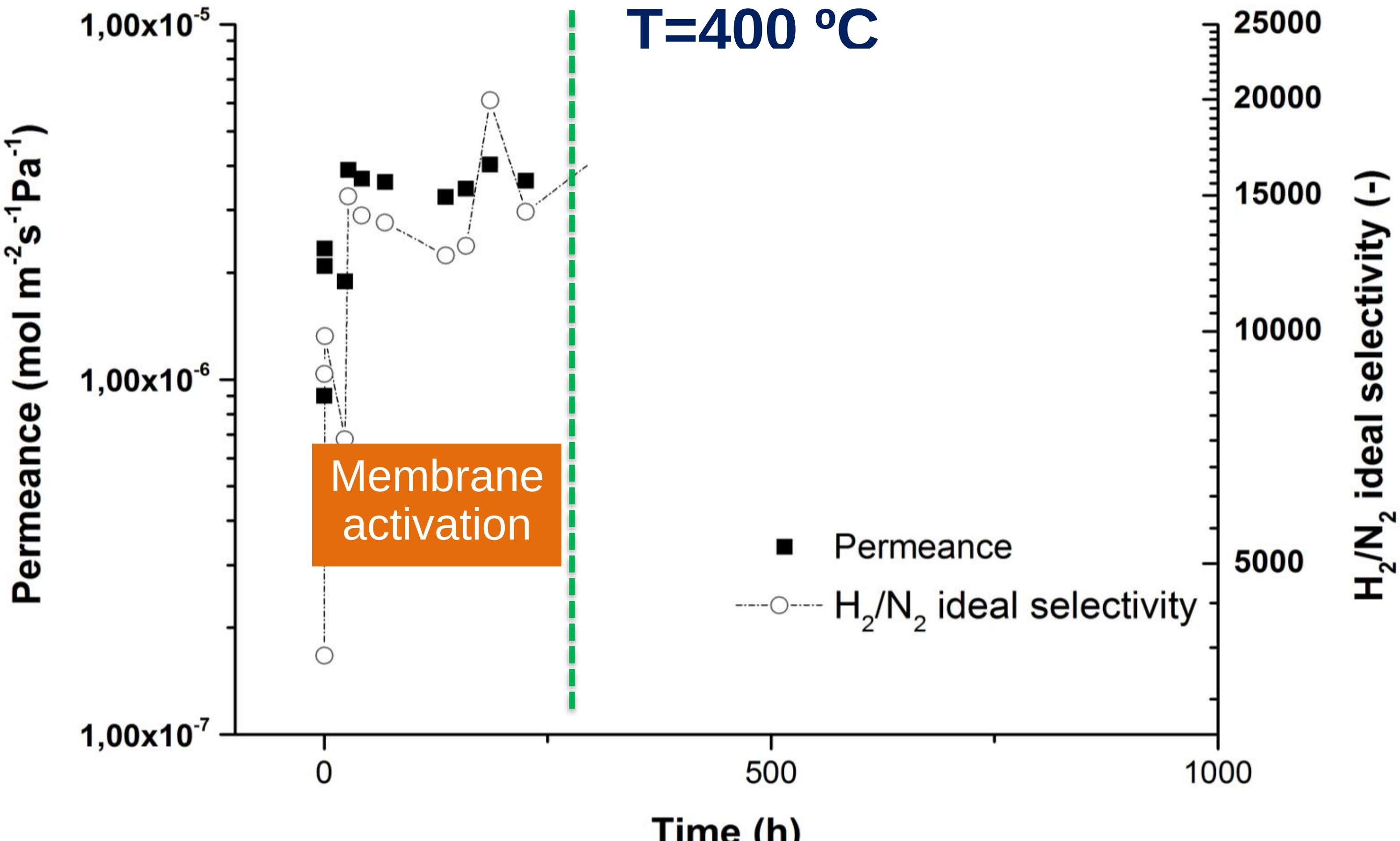


data obtained in SAES laboratories

self-standing:	n 0.67	17.6 cm^2	0.23 x 10^{-6} mol Pa^{-1} s^{-1} m^{-2}
ceramic # 1:	n 0.69	32.3 cm^2	1.55 x 10^{-6} mol Pa^{-1} s^{-1} m^{-2}
ceramic # 2:	n 0.69	34.2 cm^2	1.81 x 10^{-6} mol Pa^{-1} s^{-1} m^{-2}

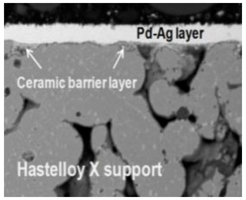
Supported PdAg membranes

Ceramic supported Pd-based (3-4 μm thick) membrane 10/7 Support



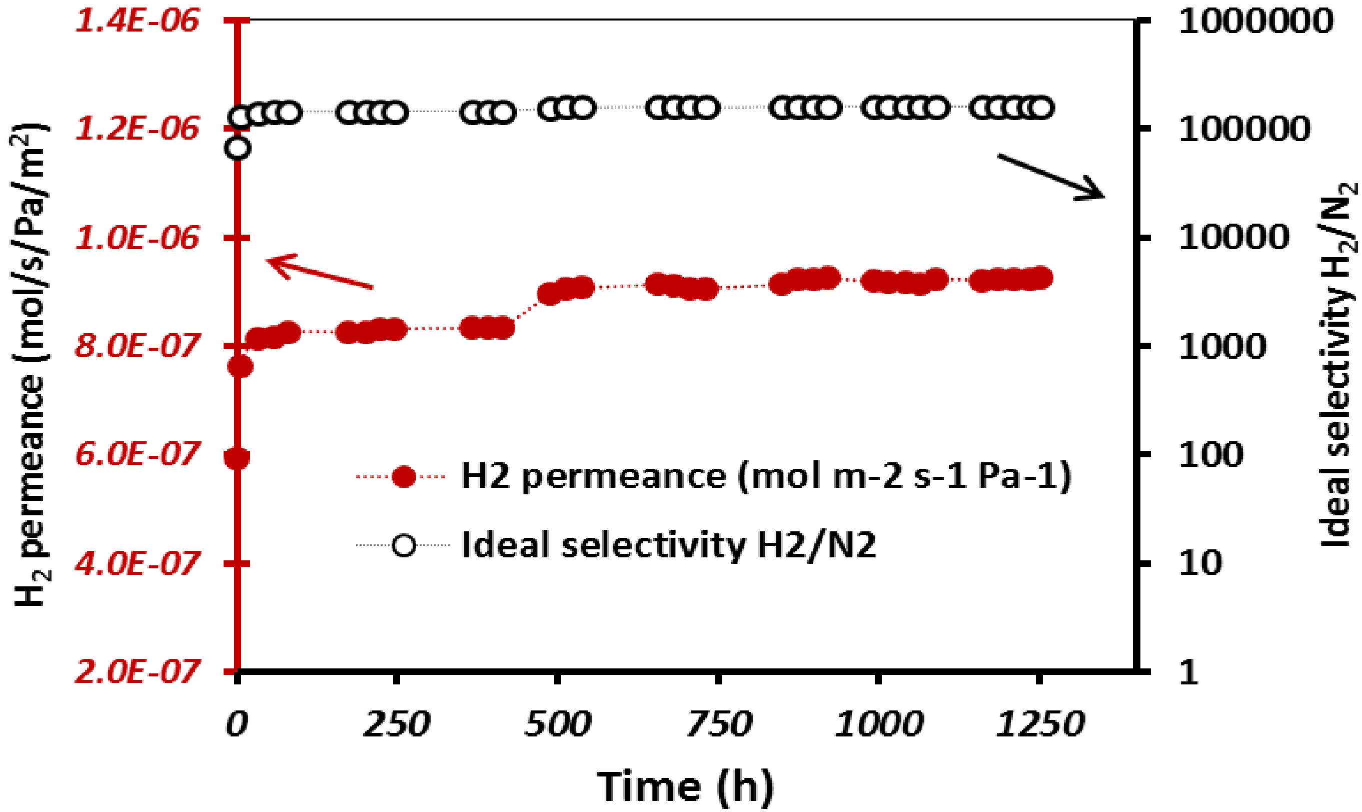
Helmi et al., Molecules 21 (2016) 376

Metallic supported Pd-Ag membranes



(5 µm thick)

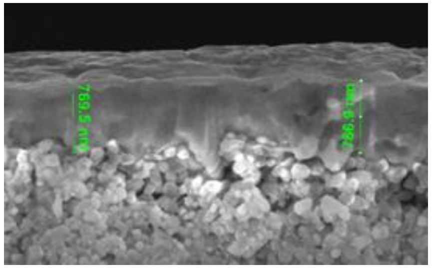
Long term permeation test at 400 ° C



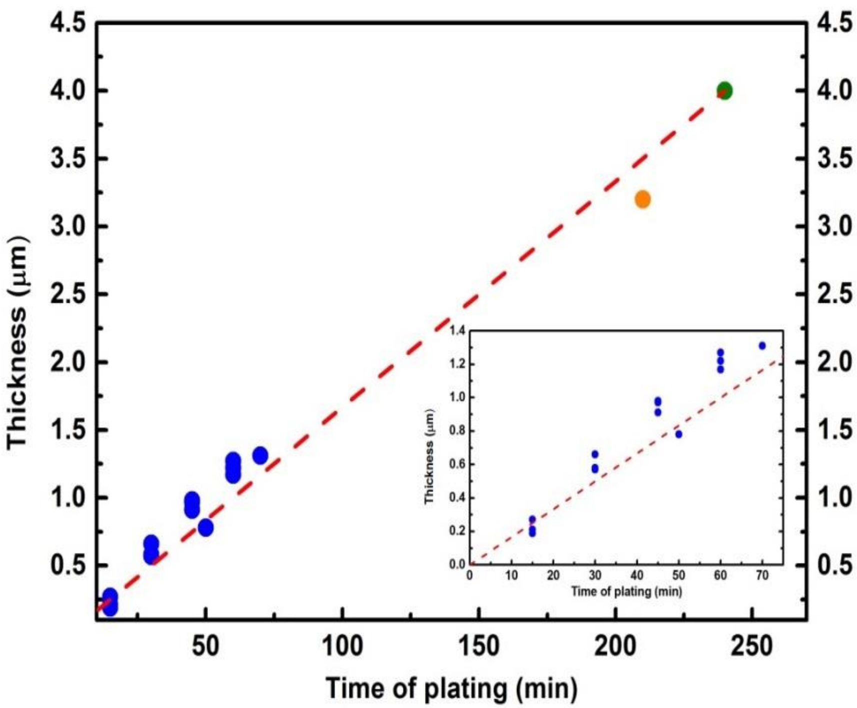
- H_2 permeance 400 ºC: **0.9 x 10^{-6} mol m^{-2} s^{-1} Pa^{-1}**
- H_2/N_2 ideal selectivity 400 ºC: **>150,000 for >1200 h**

Medrano et al., Int. J. Hydrogen Energy 41 (2016) 8706-8718

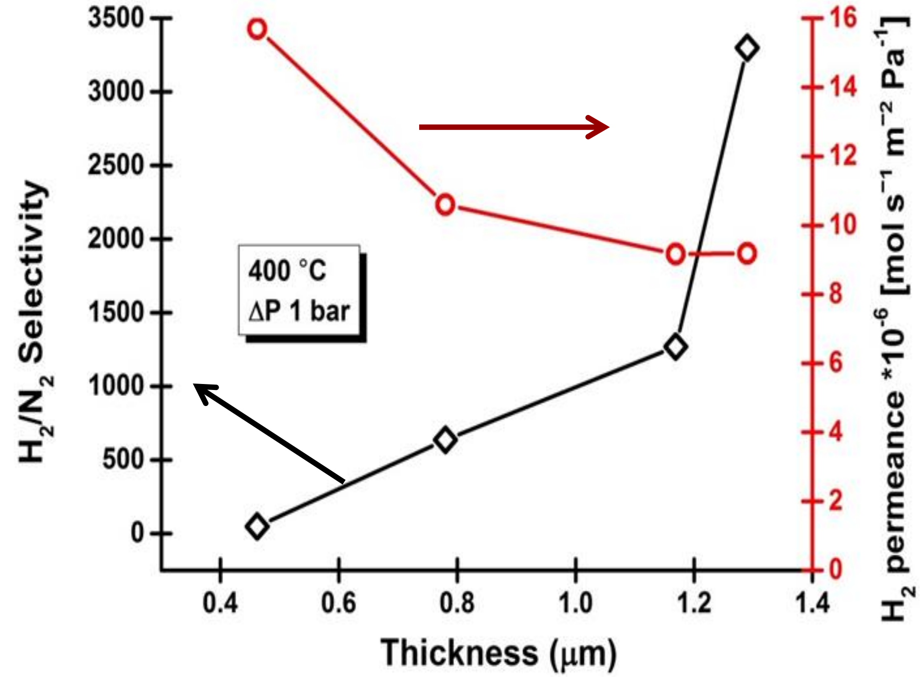
Ultra-thin Pd-Ag membranes ≈ 1µm



Thickness vs plating time

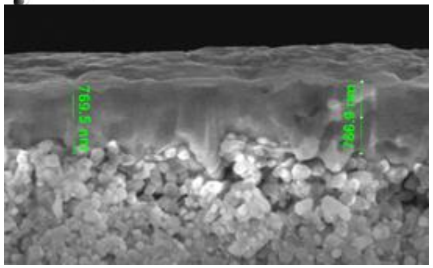


H_2/N_2 selectivity and H_2 permeance vs thickness



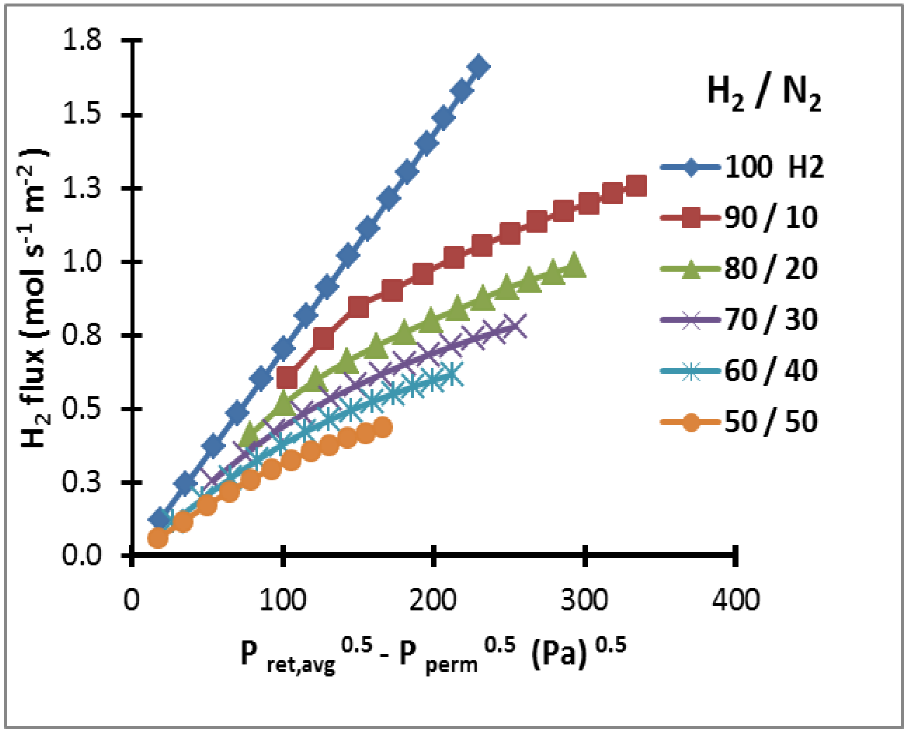
Melendez et al., Journal of Membr. Sci. 528 (2017) 12–23

H2 flux at various gas mixtures and pressures at 400° C



Membrane thickness 1.30 um

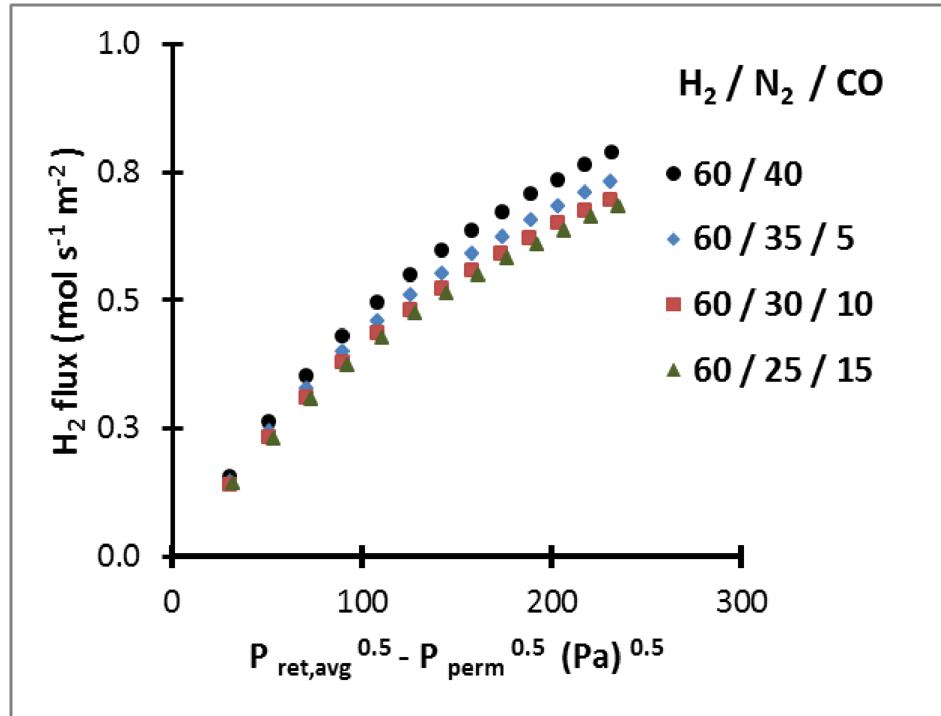
Effect of dilution H_2 and N_2



Effect of CO

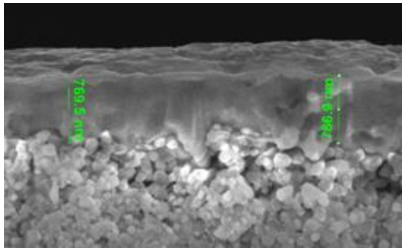
At H_2 /N_2 60/40

Replacing some N_2 with CO



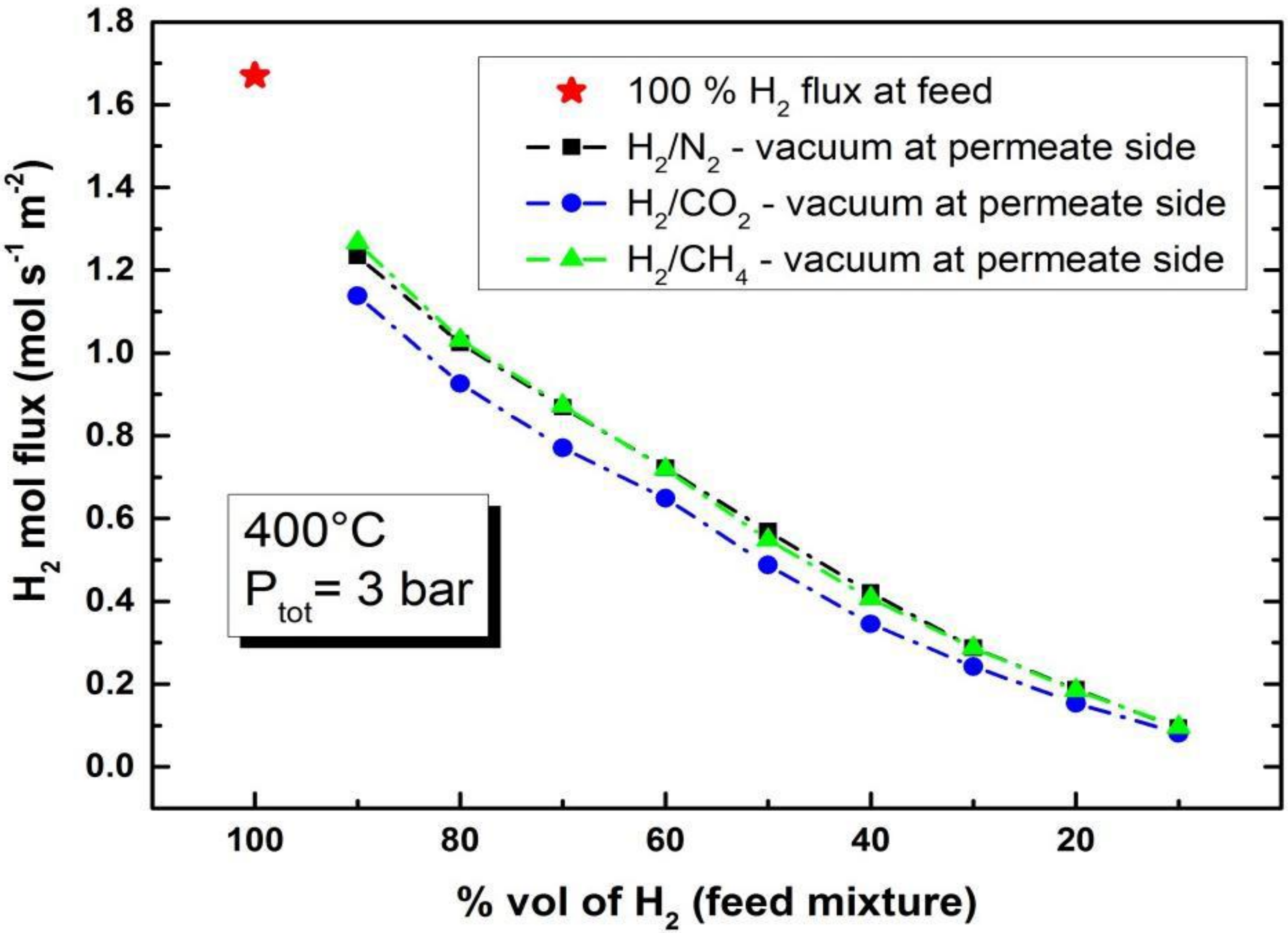
Melendez et al., Journal of Membr. Sci. 528 (2017) 12–23

H2 flux at various gas mixtures and pressures at 400° C



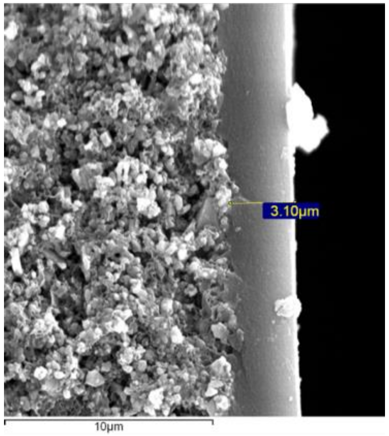
Thickness 1.30 um

3 bar total pressure, vacuum at the permeate



Melendez et al., Journal of Membr. Sci. 528 (2017) 12–23

Carbon Molecular Sieves Membranes (CMSM)



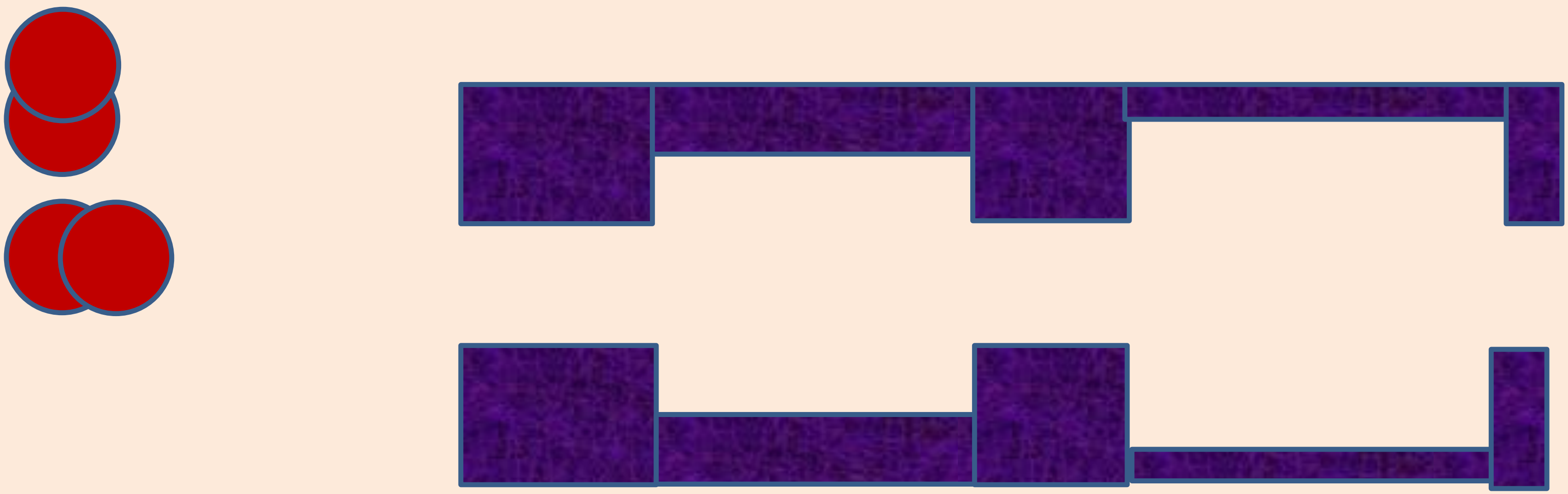
Molecular sieves membranes

Zeolite membranes

- Difficult to obtain crack-free
- Intercrystallite voids affecting selectivity

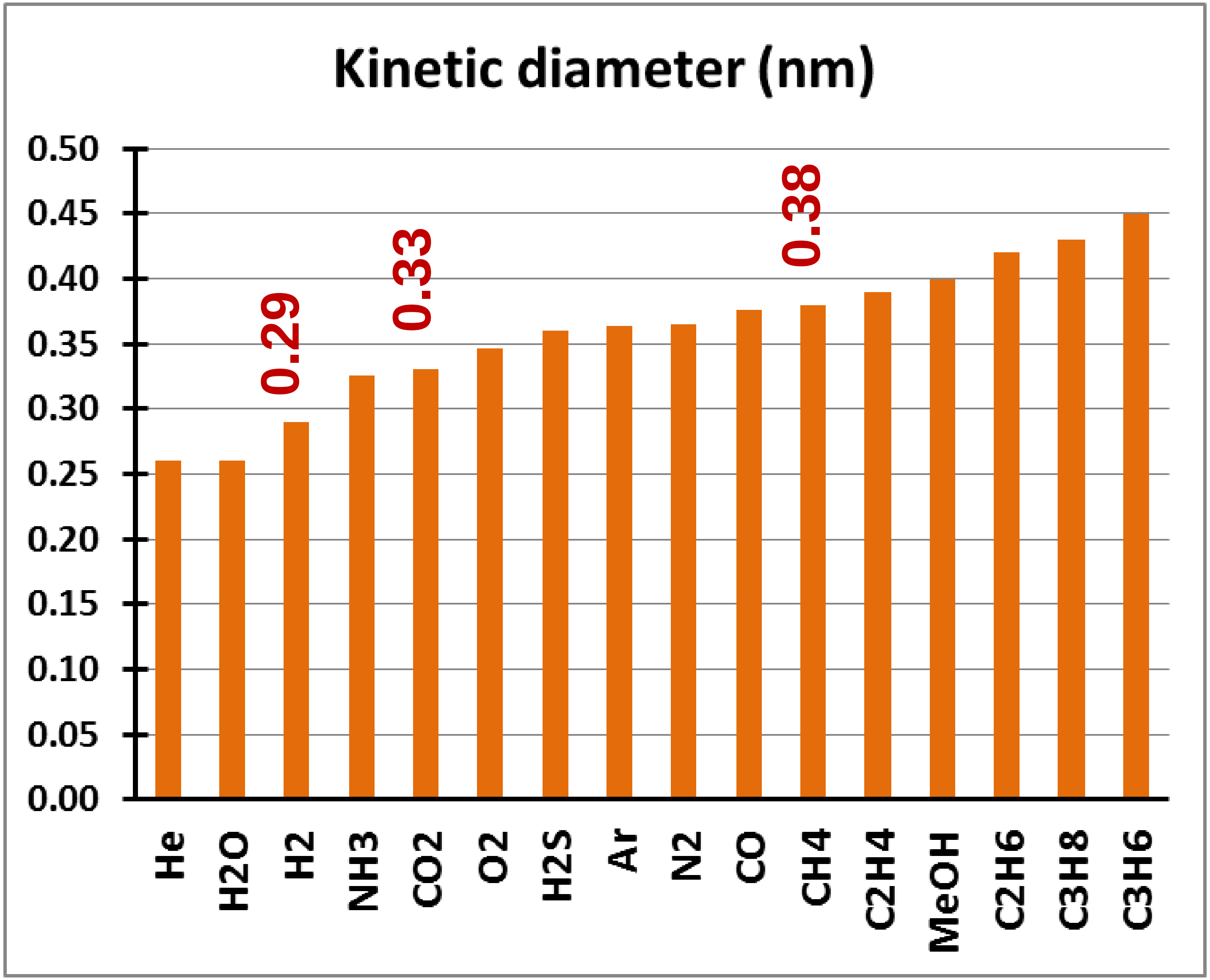
Carbon Molecular sieves membranes

Carbonization of a polymer precursor under inert atmosphere or vacuum



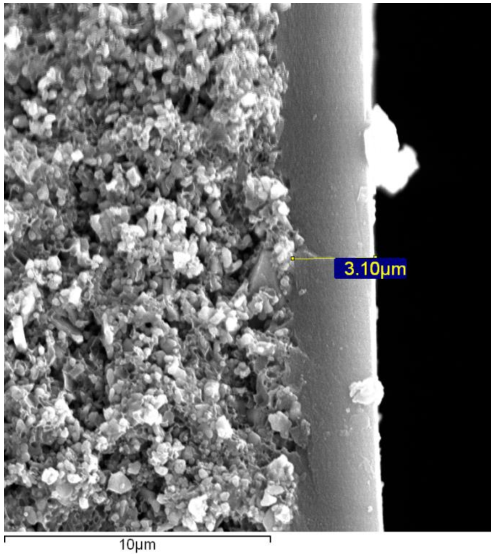
Presence of micropores and ultramicropores

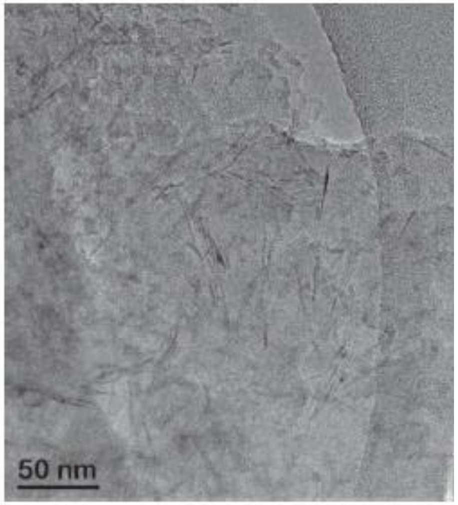
Kinetic diameter of various gases



Composite Alumina carbon molecular sieves membranes Al-CMSM

Prepared by one dip –carbonization step
Using phenolic resin and bohemite

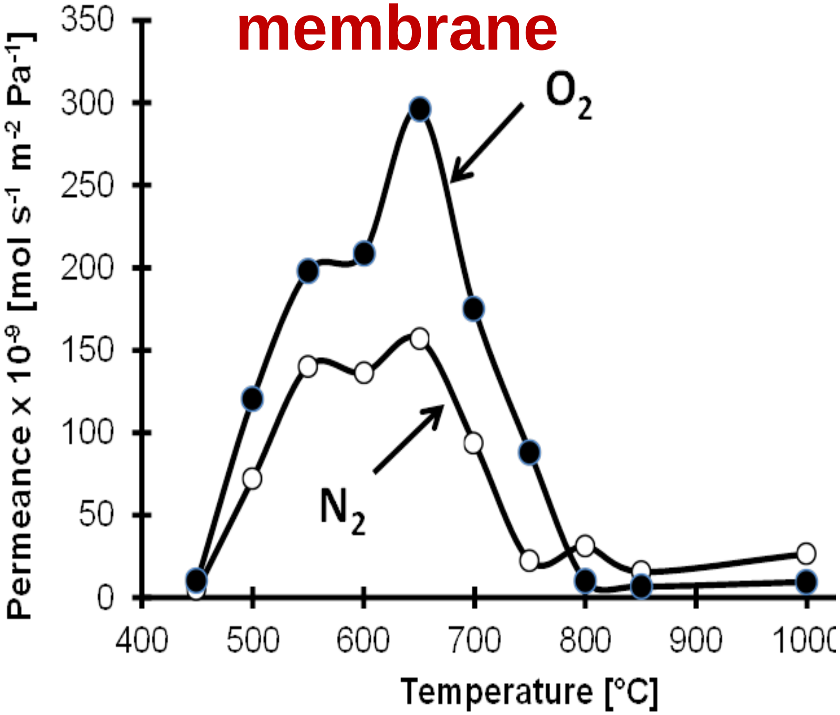




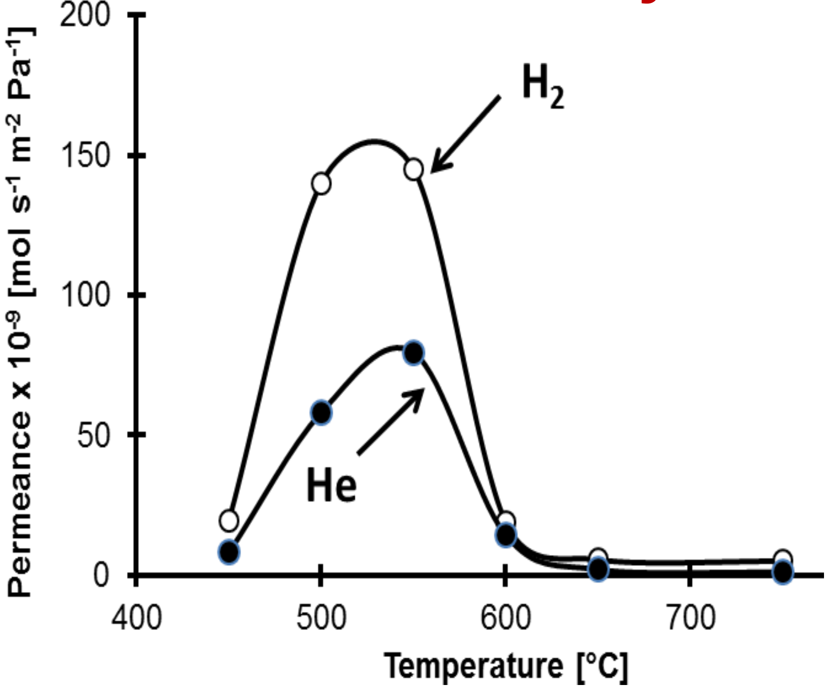
Composite phenolic resin CMSM, exeira, Campo, Tanaka, Llosa, Magen, Mendes, Carbon 49 (2011) 4348

Effect of carbonization temperature

Fresh membrane



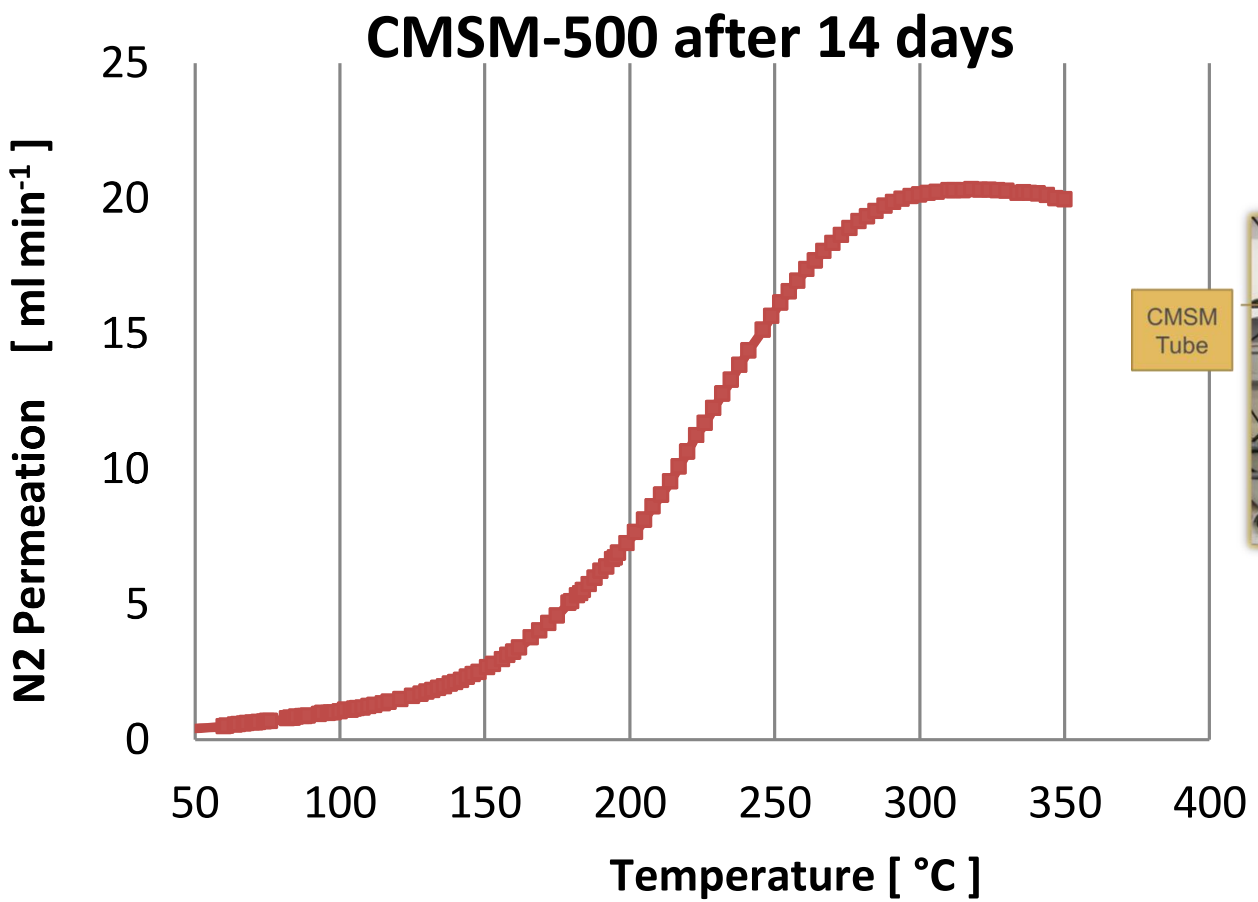
After one day

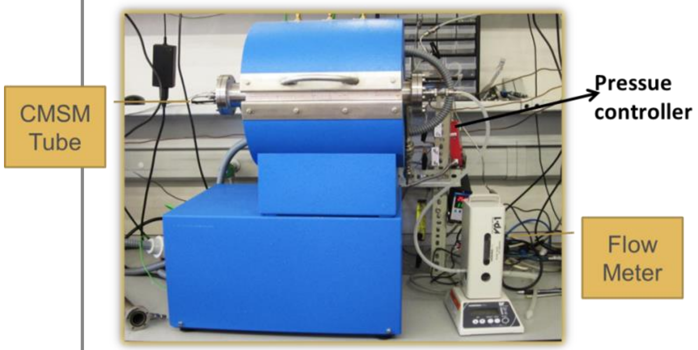


O_2 and N_2 very low flux

Llosa , Pacheco et.al Int J.hydrogen energy 40 (2015) 5653 40 (2015) 3485

N_2 permeation of c-CMSM-500 in function of the temperature at 400 kpa





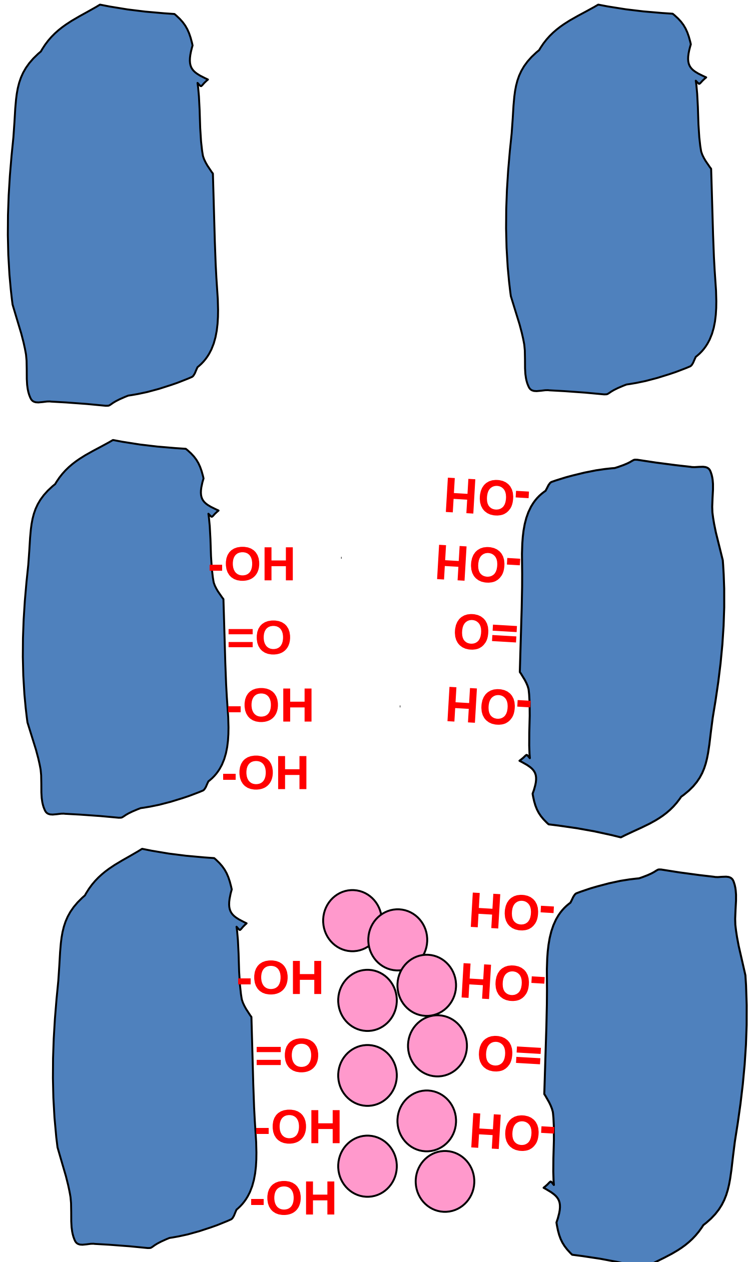
N_2 permeation of fresh membrane 66.8 ml min^{-1}

Modification on the porous

Just after carbonization

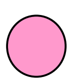
Active places react with water (water chemisorption)

Water physisorption



N_2 66 ml/min

N_2 20 ml/min



water

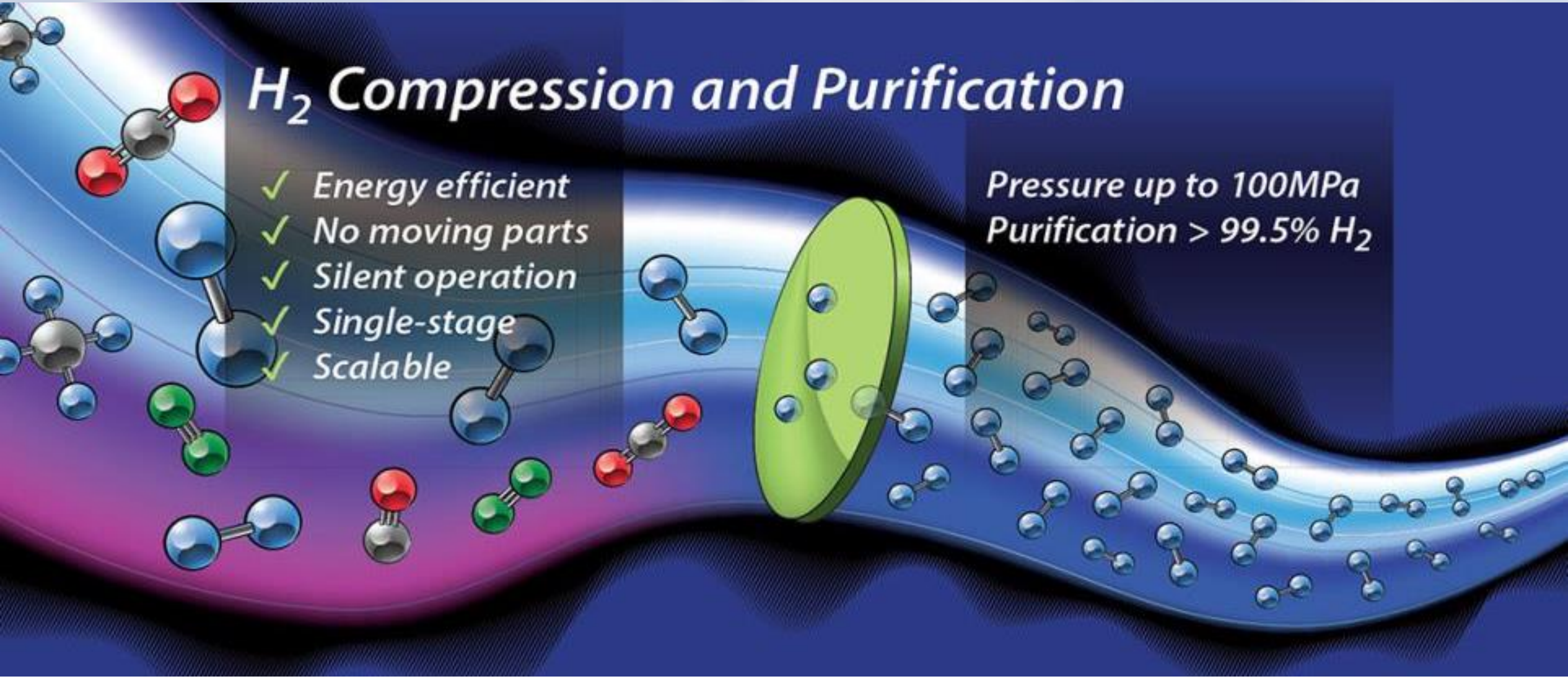
Flexible Hybrid separation system for H2 recovery from NG Grids

HyGrid

Thank you for your attention

Contacts: F.Gallucci@tue.nl

HyET Hydrogen
Efficient purification & compression



Electrochemical Hydrogen Compression and Purification

Leonard Raymakers
HyET Hydrogen

May 17, 2018

leonard.raymakers@hyet.nl *www.hyet.nl*

Pure Pressure

Table of contents

HyET Hydrogen
Efficient purification & compression

HyGrid

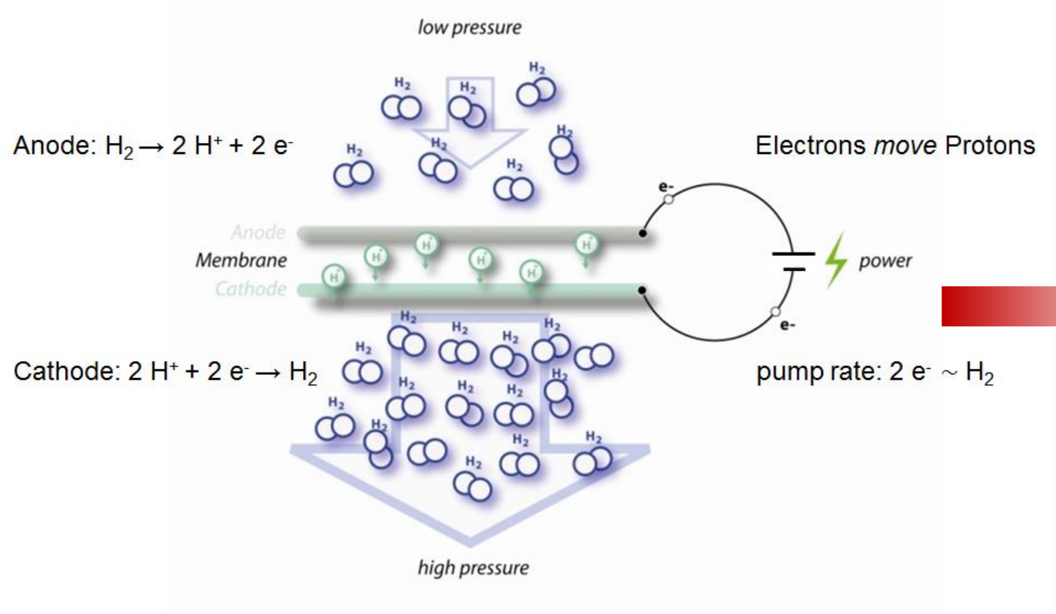
HyET Hydrogen Efficient purification & compression

2. EHC:
ELECTROCHEMICAL HYDROGEN COMPRESSION

HyGrid

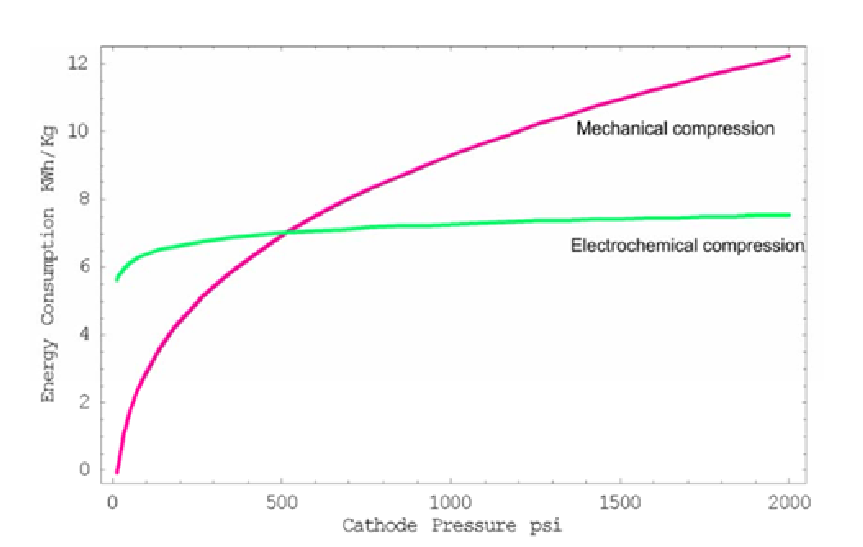
EHC:

Electro-chemical Hydrogen Compression



Compression fundamentals

Beyond 35bar/500PSI electrochemical compression is more energy efficient then mechanical compression



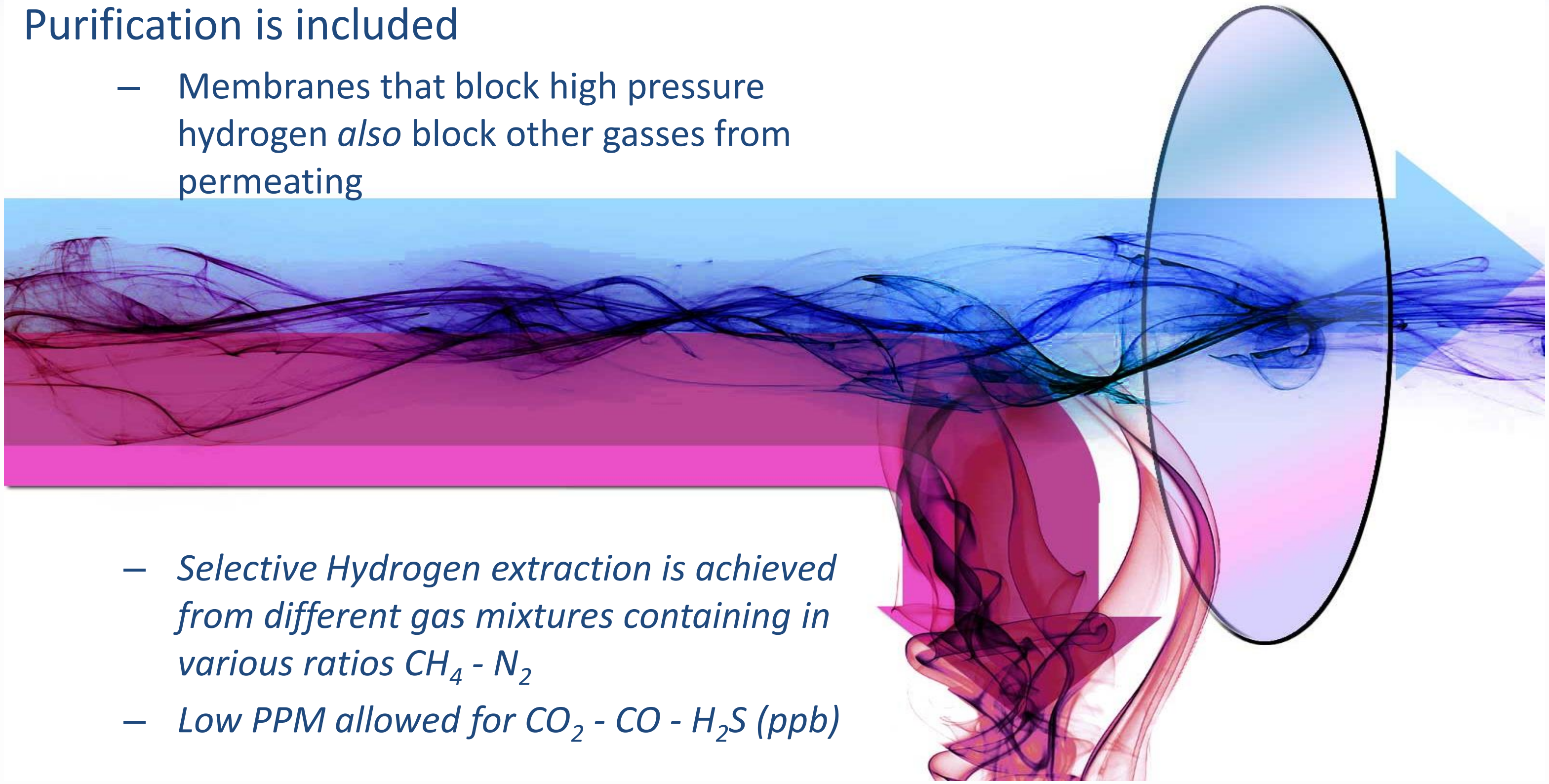
EHC can achieve very high pressures with a single stage, mechanical compressors require multiple

"Modeling and analysis of electrochemical hydrogen compression"
Dale et al (2008)

EHC Compression & Purification

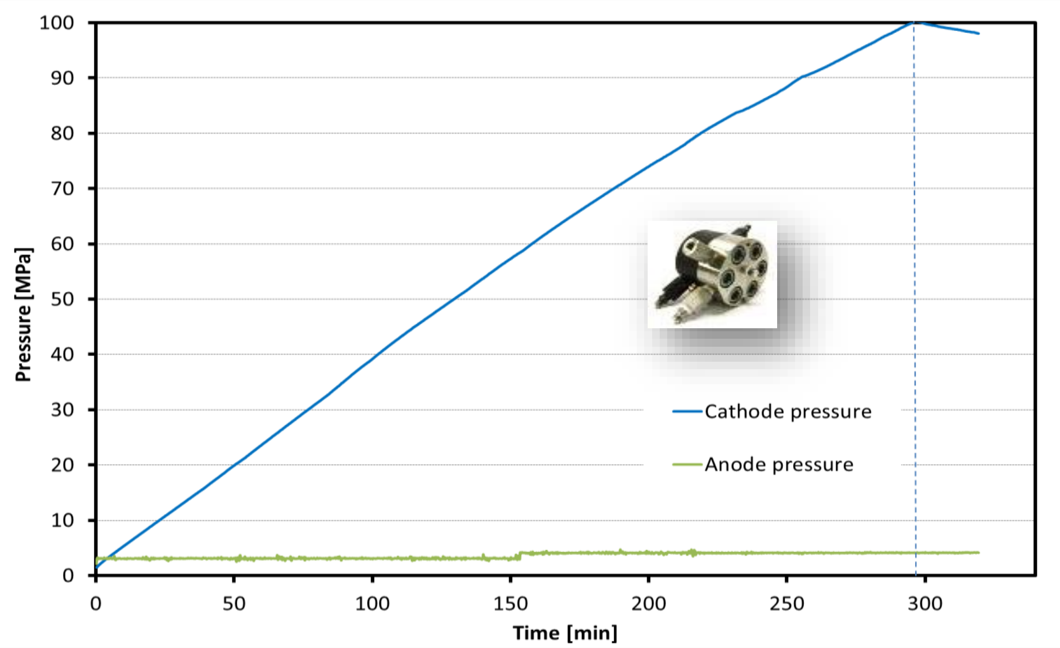
Purification is included

- Membranes that block high pressure hydrogen *also* block other gasses from permeating



- *Selective Hydrogen extraction is achieved from different gas mixtures containing in various ratios CH_4 - N_2*
- *Low PPM allowed for CO_2 - CO - H_2S (ppb)*

EHC World Compression Record



HyET broke the world record electrochemical compression and achieved 1000 bar in 2011 with a single stage laboratory cell - until now unchallenged.

EHC Technology Roadmap

- Current technical development primarily focusses on:
- Further lowering costs
  - Raw material usage
  - Manufacturing
- Further improving performance:
  - Improving current density
  - Improving membrane performance
  - Increasing surface area per cell*
  - Increasing MTBF

(*) forms part of the Joint Technology Development project of HyET and Shell Hydrogen at L. Berkeley National Laboratory

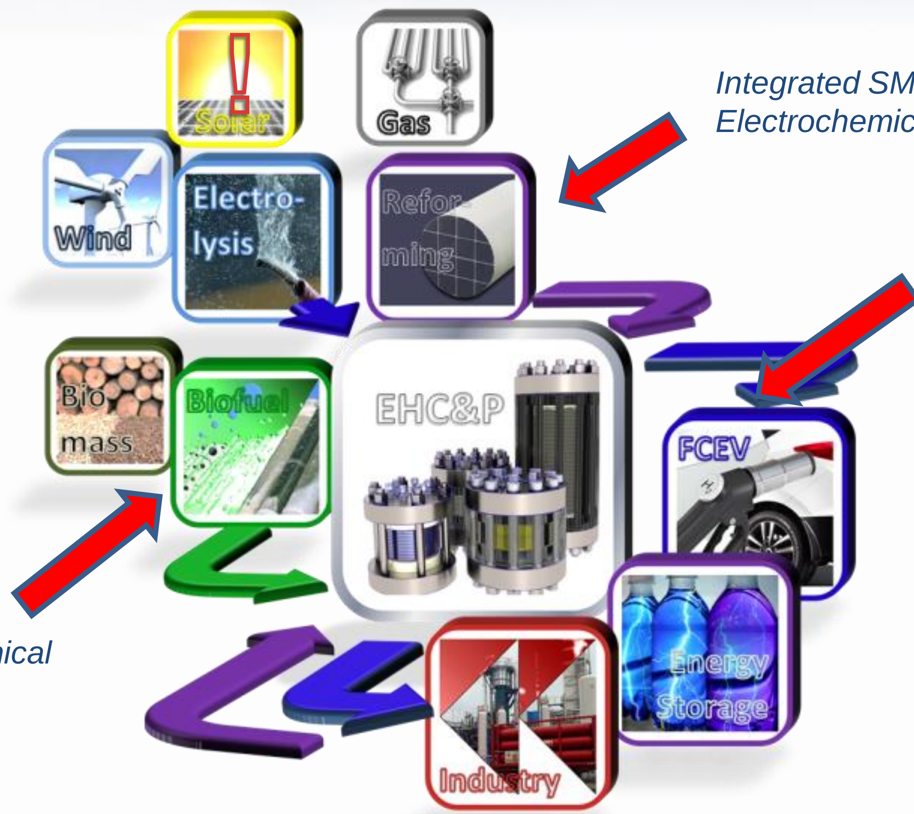
3. HYET
APPLICATIONS & PRODUCTS

Applications
Focus refuelling, purification and storage

Integrated SMR & Electrochemical purification

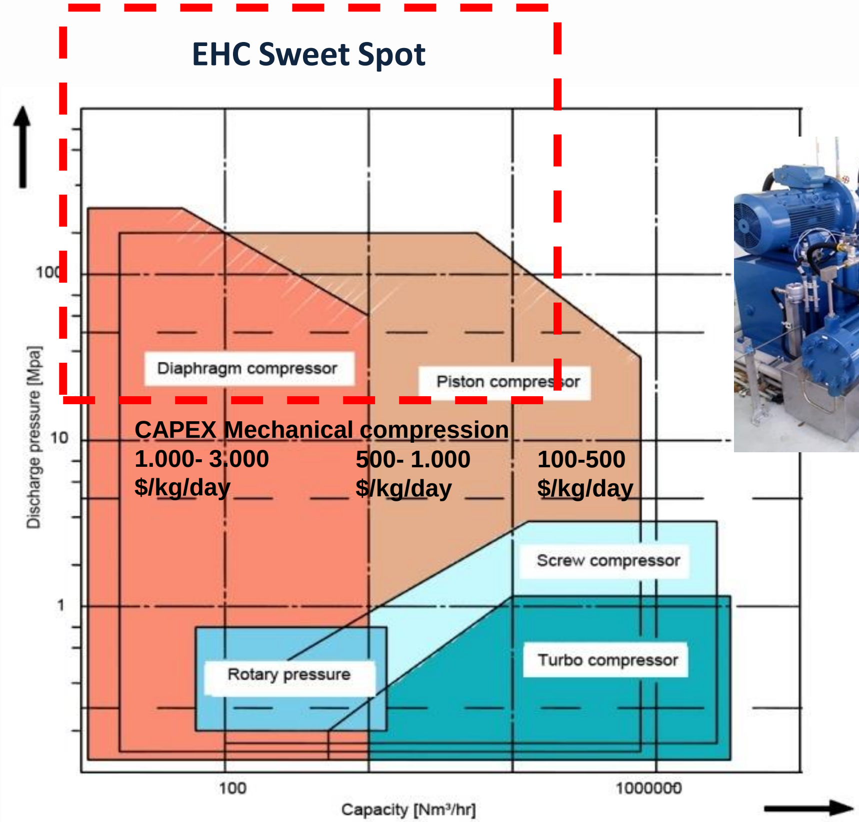
Electrochemical Compression

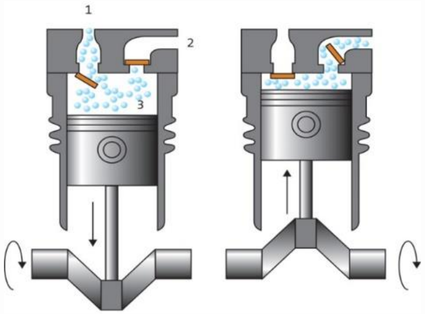
Biogas Electrochemical Purification



HyET provides essential pieces of the "Puzzle"

Market structure hydrogen compression / costs mechanical hydrogen compressors





Classical compressors need:

- Minimum feed pressure
- Multi-stage configuration
- Interstage cooling
- Regular maintenance
- High degree of redundancy

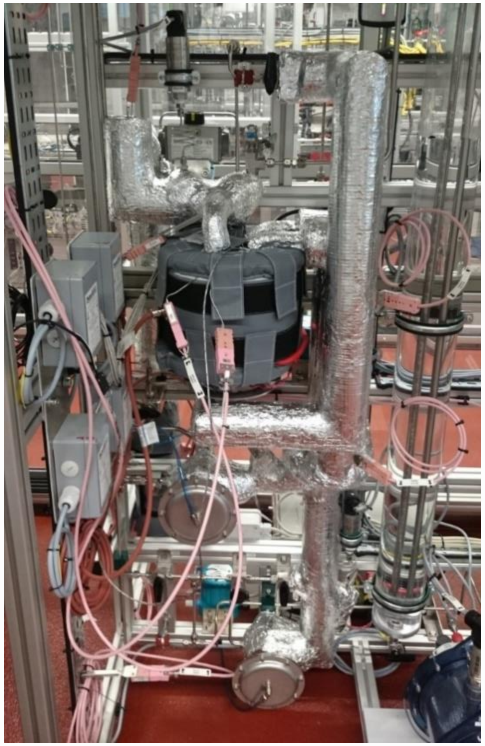
EHC: Disruptive Technology

- Purification and compression up to 1000bar in one single step
- No moving parts – high availability
- Compact, simple, minimal BOP
- Scalable, from very small to very large volumes
- Quiet, urban area application possible
- Energy efficient
- On demand → Instant on/off, 0-100% capacity
- Low CAPEX
- Low OPEX (Energy & Maintenance)

HyET Hydrogen Efficient purification & compression

Customer: Shell

- 2016: First commercial delivery of HCS48
- Shell Technology Center Amsterdam
- Long duration qualification of purification duty (ongoing)
- 2018: Upgrading to newest EHC stack platform



HyGrid

Customer: US Naval Research Laboratory

- (Q3 2017) First commercial delivery of multicell stack (32 cells)
- Design specification: 2kg/d; 415 bar (achieved >3kg/d; 700 bar)

U.S. NAVAL RESEARCH LABORATORY

HyET Hydrogen Efficient purification & compression

Project:
Commercial refuelling station

Arnhem Hydrogen Refueling Station at HyGear;

Specification:

- 120 kg/d;
- 400/875 bar;
- 5 kWh/kg H_2

HyGrid

FCH

Products

Available per 2018Q2:

- Single stack system
- 10 kg/day
- 700 bar

Next step:

- Multi-stack system
- 200 kg/d
- 850 bar

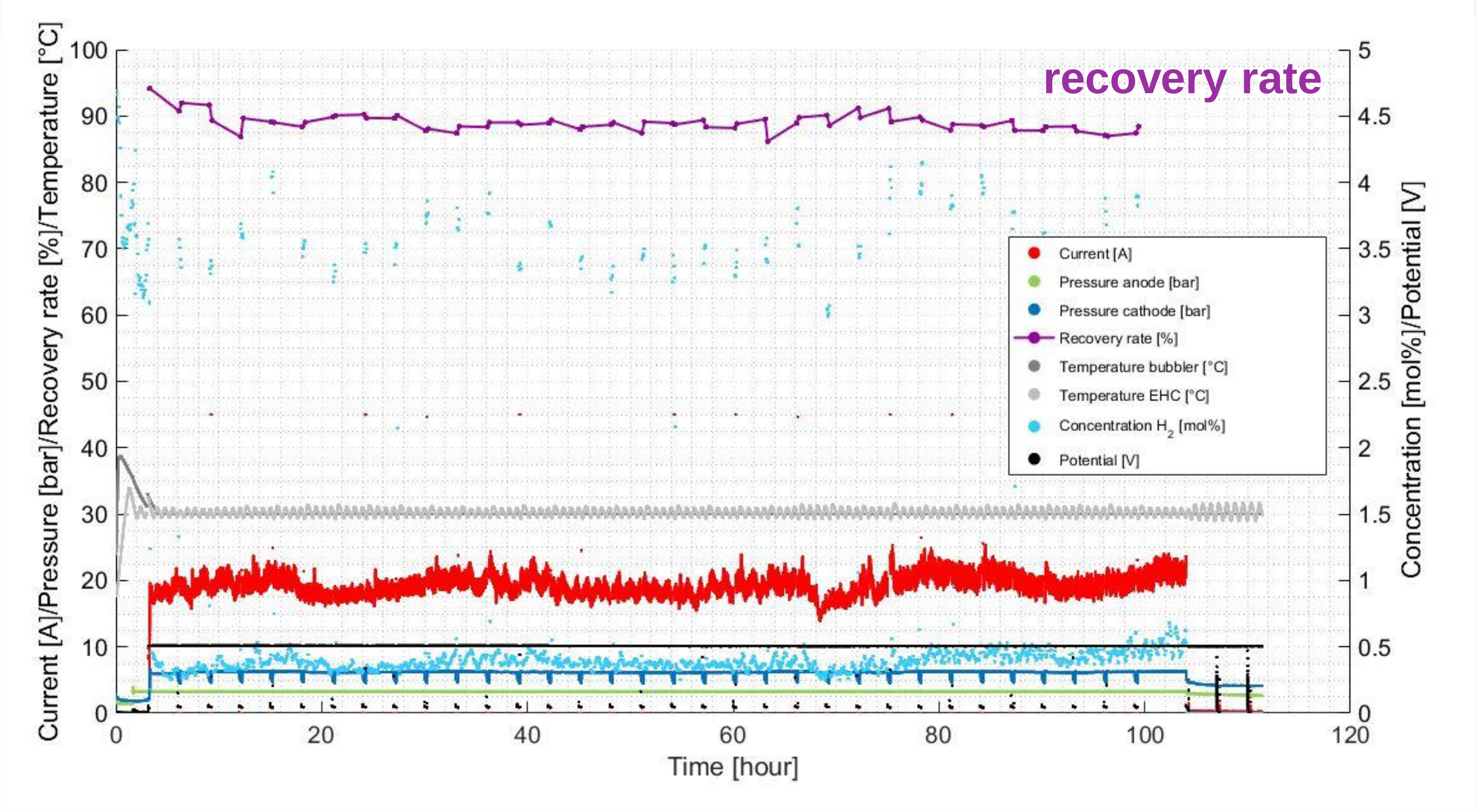
4. HYGRID PROJECT

HyGrid – prelimanary field test

- Purification of P2G methanation reactor output gas: remove H2 (2.5-4% to 0.5%) to allow NG grid injection
- Establishing base-line EHP performance with sub-optimal EHP cell hardware

HyGrid – prelimanary field test

- 90% recovery rate feasible with high surface area



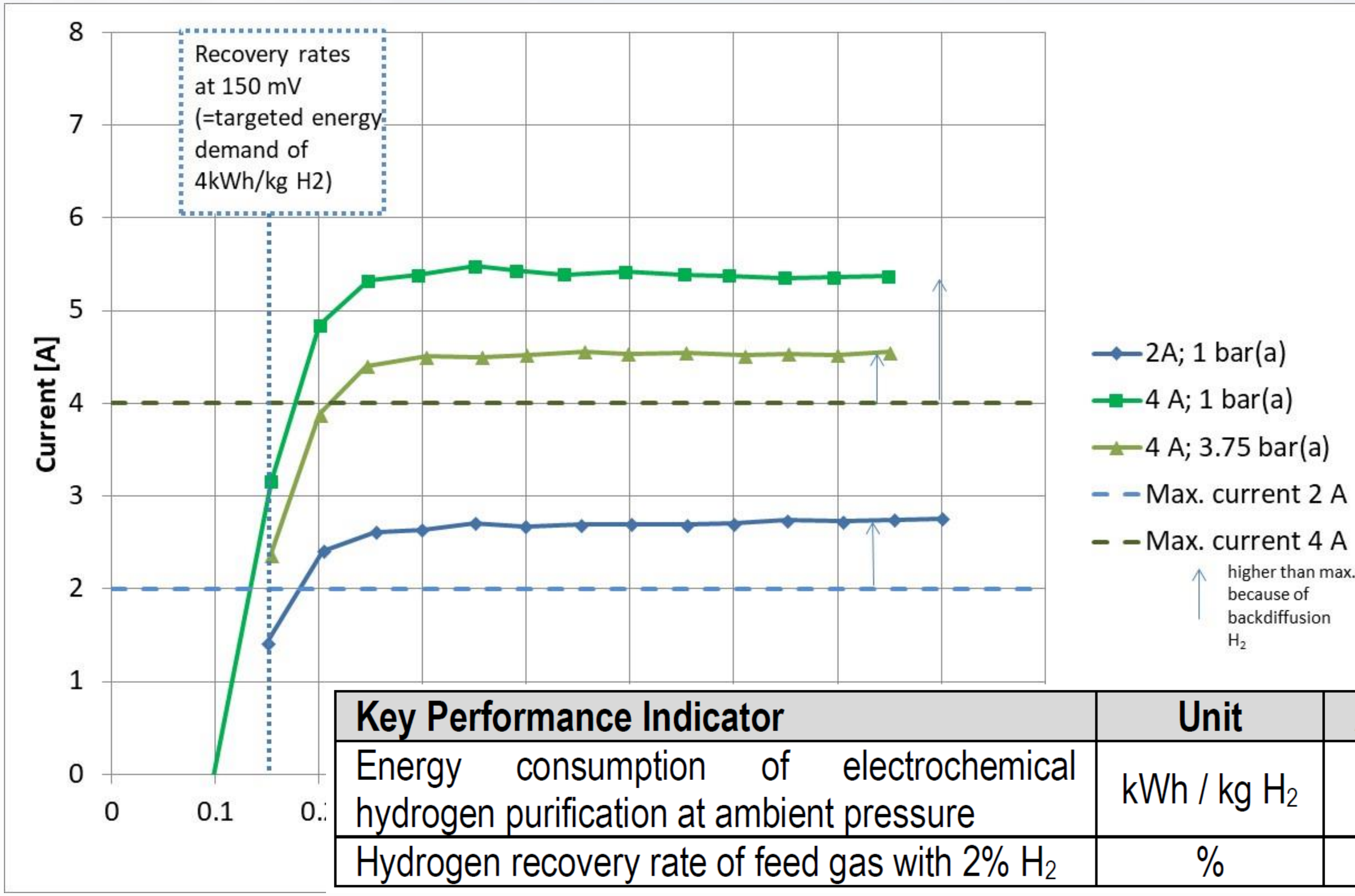
HyGrid - First prototype realized

Current HyET compressor stack	HyGrid design purifier/compressor stack
	

- 150 bar reached on single cell at 1.0 A/cm2
- Multicell stacks up to 30 cells at 1.0 A/cm2

HyGrid testing

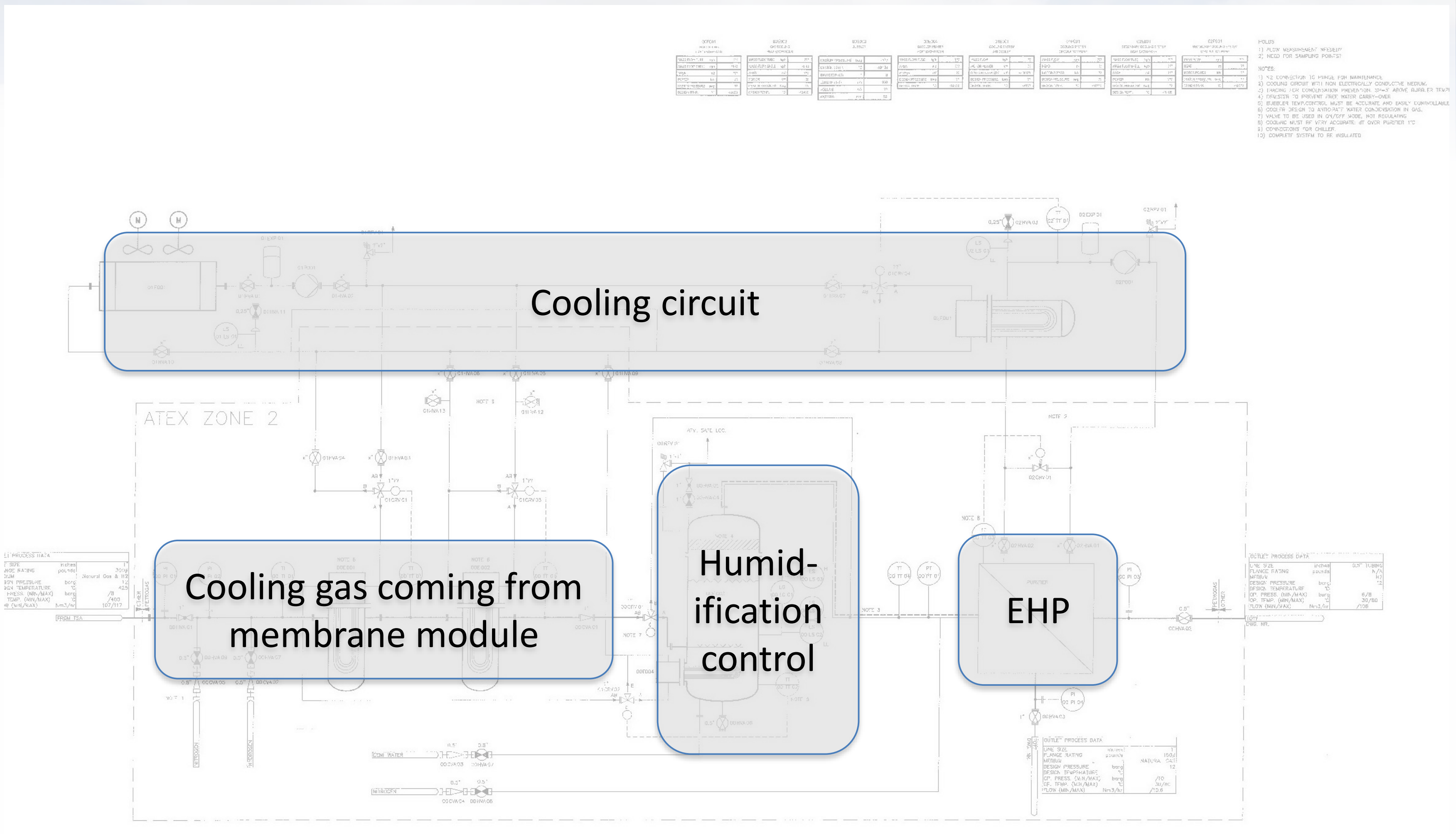
- Single cell testing



Key Performance Indicator	Unit	Actual	Target
Energy consumption of electrochemical hydrogen purification at ambient pressure	kWh / kg H_2	6	4
Hydrogen recovery rate of feed gas with 2% H_2	%	30	60

HyGrid

HyGrid – EHP sub-system



HyET Hydrogen Efficient purification & compression

THANK YOU!

HyGrid

Flexible Hybrid separation system for H2 recovery from NG Grids

HyGrid

Exploitation Workshop – 17-05-2018 Lainate, Italy

TSA Development and Prototype Description

HyGear

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 700355. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY

Duration: 3 years. Starting date: 01-May-2016

Contact project coordinator: F.Gallucci@tue.nl

Outline

- Company introduction
- Quality standards for hydrogen and natural gas
- Commercial Design HyGrid
- Lab scale testing: design and testing
- Prototype development
- Integration

HyGear

- SME based in Arnhem, The Netherlands
- Founded in 2002
- Employing 65 people
- Offices in Europe, Asia and US (support)

- Small-scale gas processing experts

Products

- HyGear sells gases…

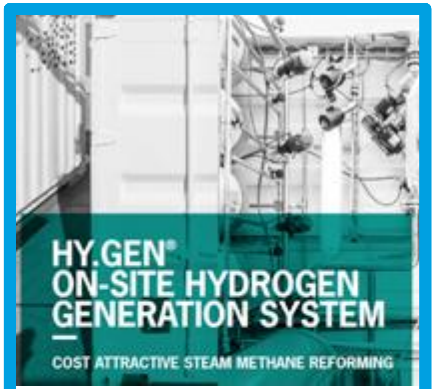
HYDROGEN

NITROGEN

OXYGEN

Technology

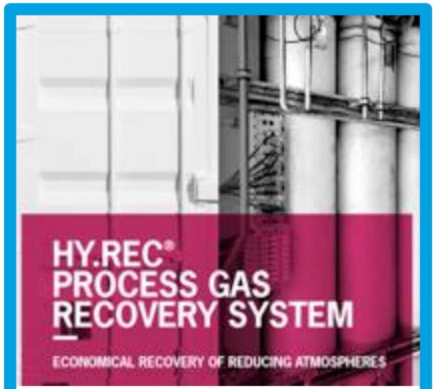
- … by using own developed technology



STEAM METHANE REFORMING

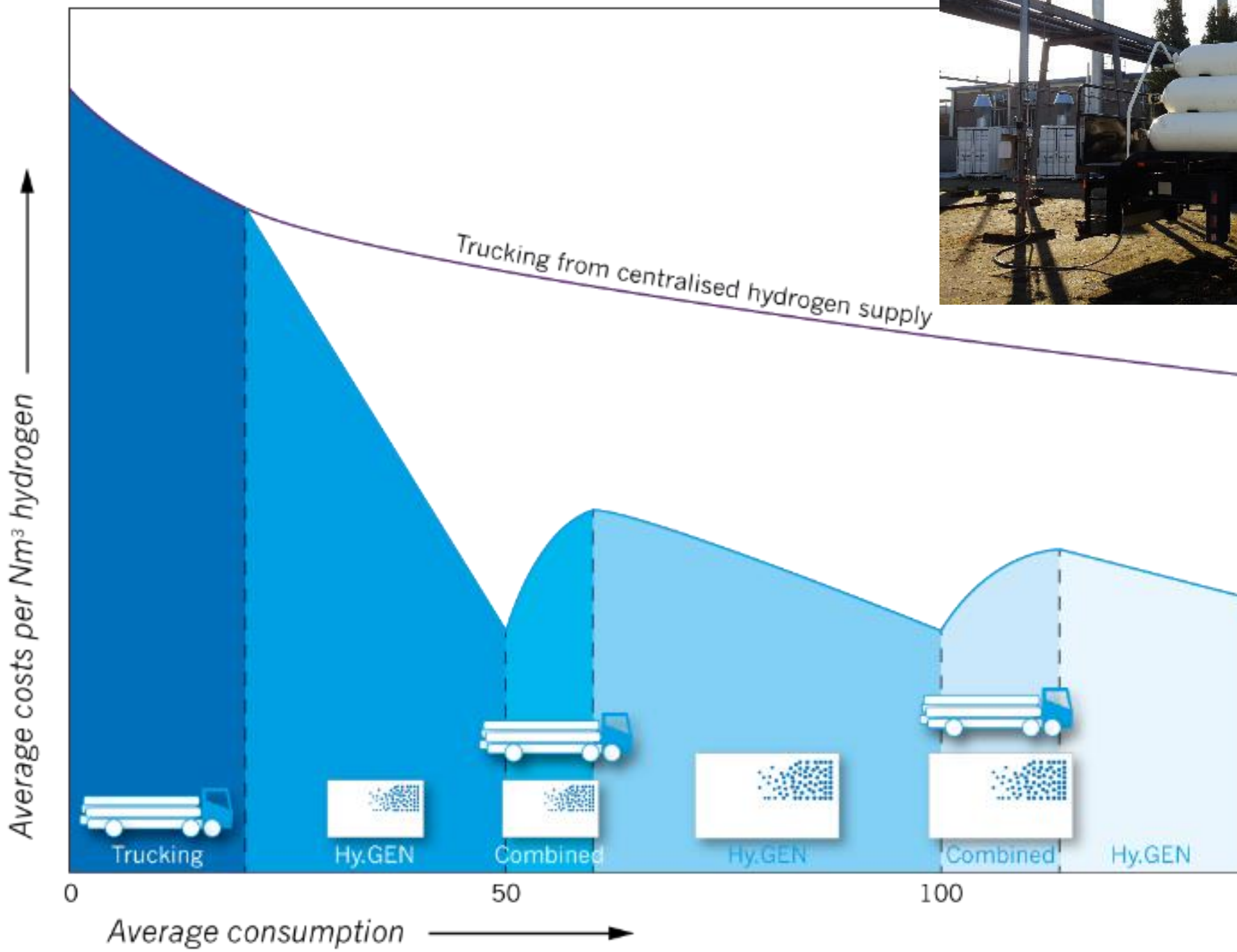
LOW PRESSURE AIR SEPARATION BY (V)PSA

LOW PRESSURE AIR SEPARATION BY PSA



IN-LINE RECOVERY OF SPENT GAS

Lowest costs with combination on-site & trucked-in



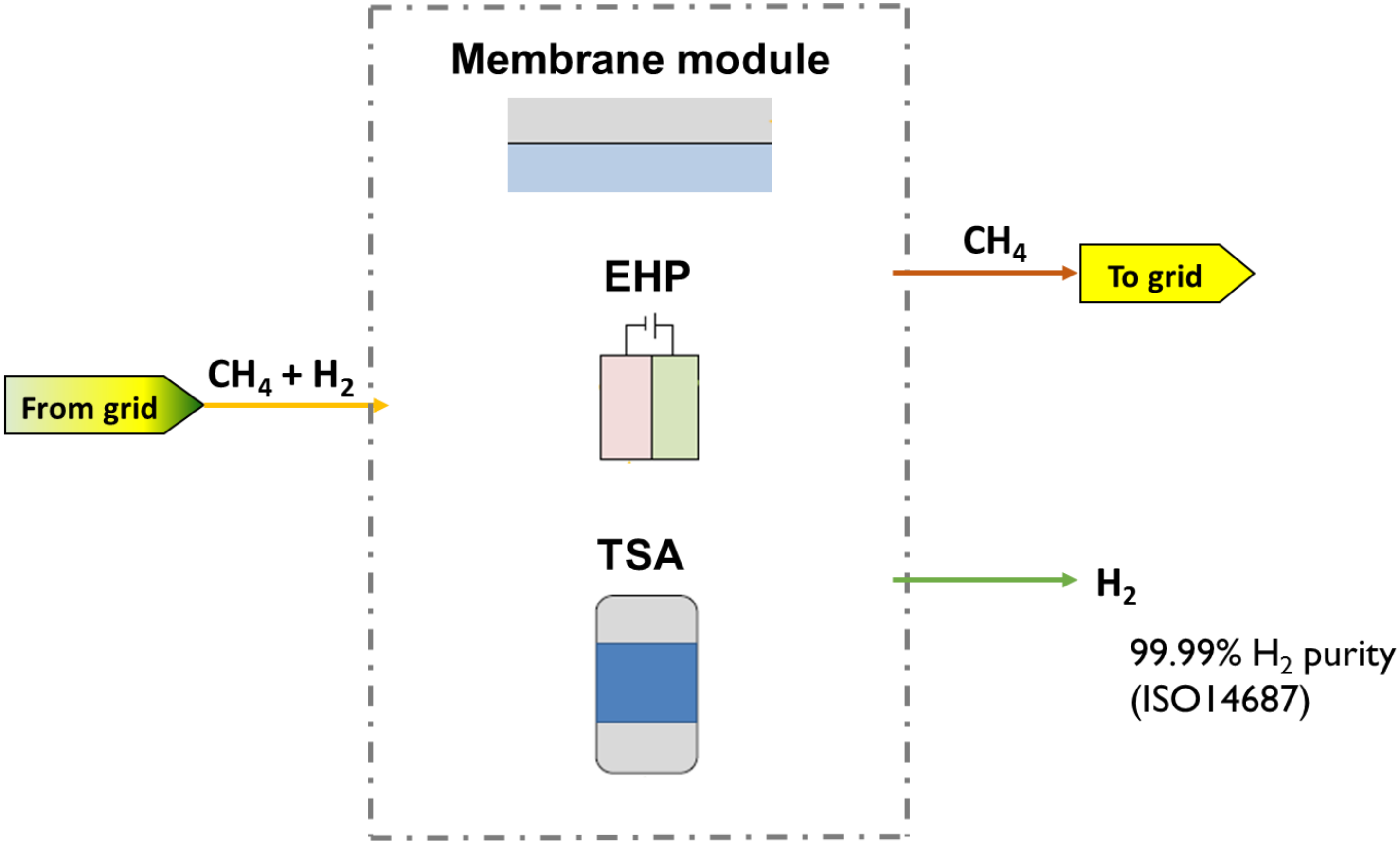
Demands HyGrid system

- Usage HyGrid system
  - Remove hydrogen from natural gas to protect downstream customers
    - Max 1 vol% H_2 in NG
  - Extract clean hydrogen for energy use from natural gas
    - Use natural gas network for H_2 transport
    - ISO 14687:2012
  - Target at commercial scale
    - < 5 kWh / kg H2 and < 1.5 € / kg H2

Consumers			
	State-of-the-Art	Impurities (a.o.)	Cause
CH_4	Gas turbines	1-5 vol% H_2	Ineff. of rotor blade cooling, NOx abatement etc.
	Automotive applications	2 vol% H_2	Embrittlement of storage and leakage of valves
	Gas engines	2-5 vol% H_2	Sensitivity systems for increase of flame speed
	Household appliances	< 25 vol% H_2	Potential backdraft burner
H_2	Internal combustion engines Grade A: 98 vol% H_2	100 ppm CH_4: NC H_2O	
	Automotive fuel cells Grade D: 99.99 vol% H_2	100 ppm CH_4: 5 ppm H_2O	
	Stationary fuel cells Grade E: > 99.99 vol% H_2	100 ppm CH_4: NC H_2O	

Commercial Design HyGrid

- Feed 10%vol in NG, production capacity 200 kg H_2 /day
- Quality (CH_4, H_2) applies to end-user spec.



Scaled testing

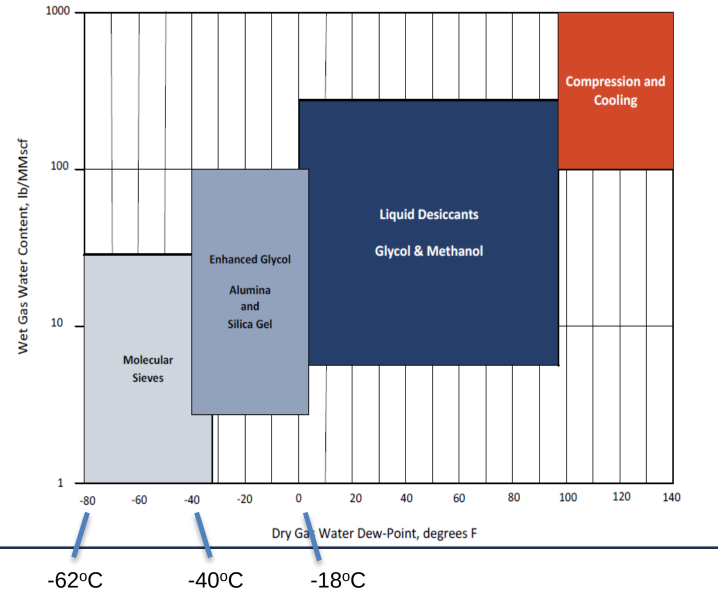
- Labscale module testing
  - *Membranes : Tecnalia/Tue/SAES*
  - *Electrochemical Hydrogen Purifier : HyET*
  - Temperature Swing Adsorption (TSA) : HyGear

- System Integration and Prototype testing
  - HyGrid Prototype : HyGear

Drivers for testing TSA

- State-of-the-Art TSA

Applicability of dehydration processes



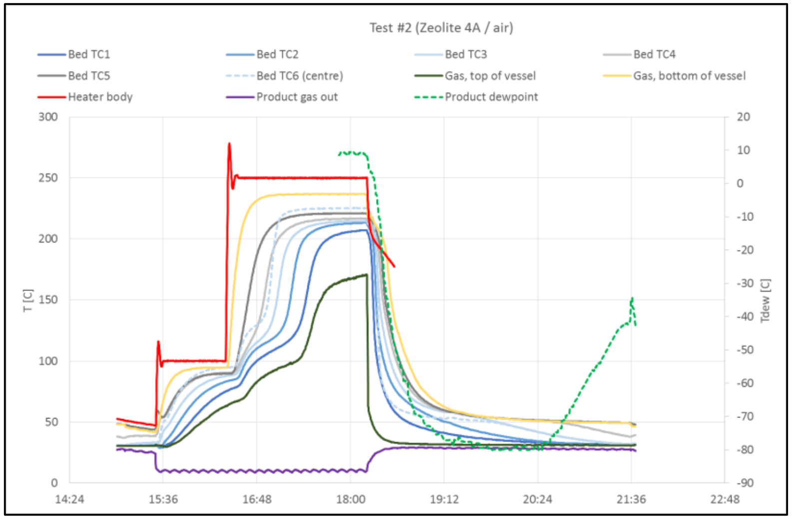
- Minimizing operational costs and energy consumption
- Drying H_2 challenging: Safety
- Saturated conditions: Commercial systems not available
- Model validation for design conditions

Lab scale testing TSA

- Small scale TSA lab test unit developed
  - Single 1L vessel
  - Sorbent check
    - Type, shapes and sizes
  - Air and hydrogen carrier gas operated
  - Automated control
  - Process variables check
  - HyGear model validation

Results from lab scale testing TSA

- Sorbent check
  - Material:
    - Required dew-point not reached with Silica gel
    - Zeolite 4A requires less desorption energy compared to Zeolite 13X
  - Influence of bead size:
    - Optimum size selected
  - Pellets *vs* beads:
    - Slightly different overall capacities
- Air / H_2 carrier
  - In H_2 higher adsorption capacity (MTZ is smaller)

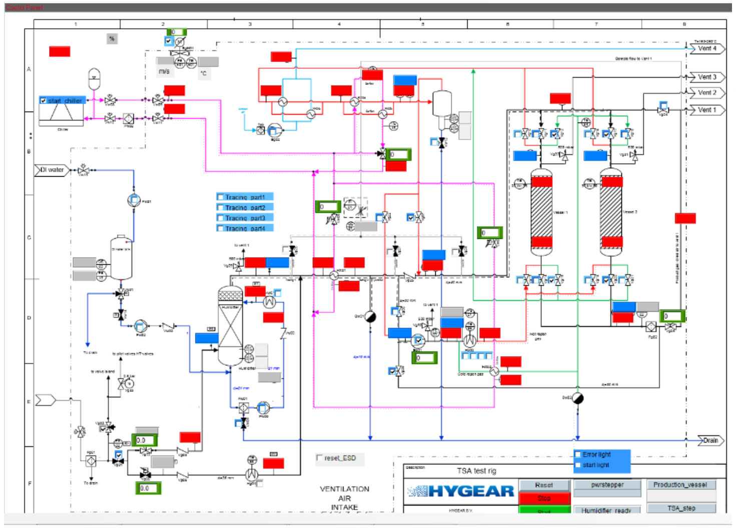


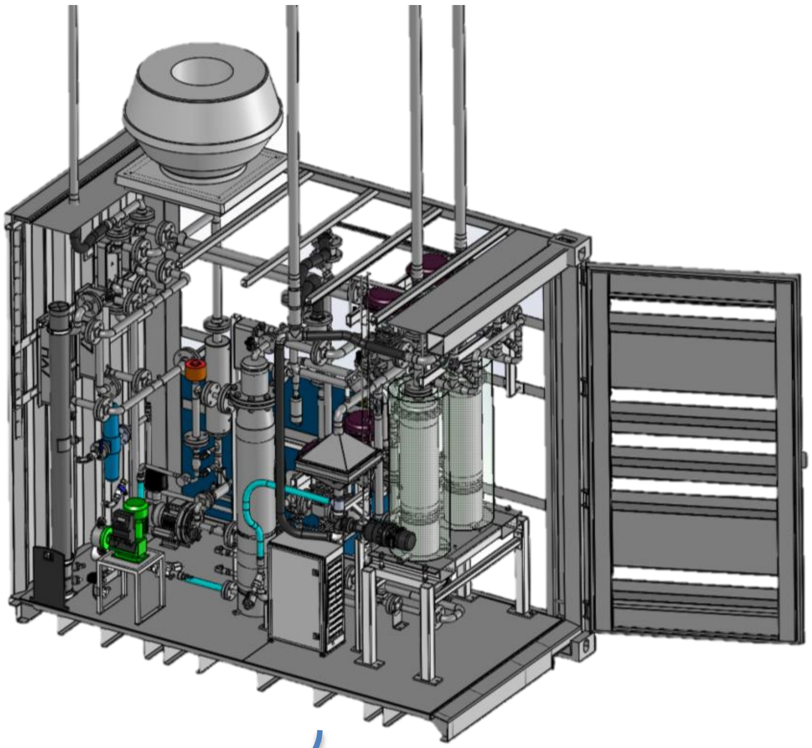
- Model validation
  - Applicability Dubinin-Ashtakov (zeolite) and Toth (silica gel) isotherms validated

Development of TSA pilot plant

- TSA design
  - Continuous (2 vessel) operation
    - Adsorption / desorption (separated vessels) simultaneous
  - Capacity 25 kg H_2 / day (12 Nm^3 H_2 / h)
  - Non-PED (operational pressure < 0.5 barg)
    - Low CAPEX, low OPEX
  - Standalone design for testing → includes humidifier
  - Water saturated feed stock
  - ATEX zoning 2NE

From design to prototype





Prelude to system integration

- Production (and mixing capacity) 30 kg H_2 /day (in 126 Nm^3 NG/h)
- Flexibility in hydrogen content and sweep gas to membrane
- Module H_2 separation efficiencies:
  - Membrane separation module: 80%
  - EHP module: 50%
- Pressure drop modules max. several tens of mbar
  - Under evaluation by partners
  - Optimization on pressure drop ongoing
- Design towards
  - Lowest costs per recovered hydrogen
    - CAPEX, OPEX
  - Efficiency is important, but not holy
- Systems separately housed
  - PED
  - ATEX zoning certification challenging

Flexible Hybrid separation system for H2 recovery from NG Grids

HyGrid

Thank you for your attention

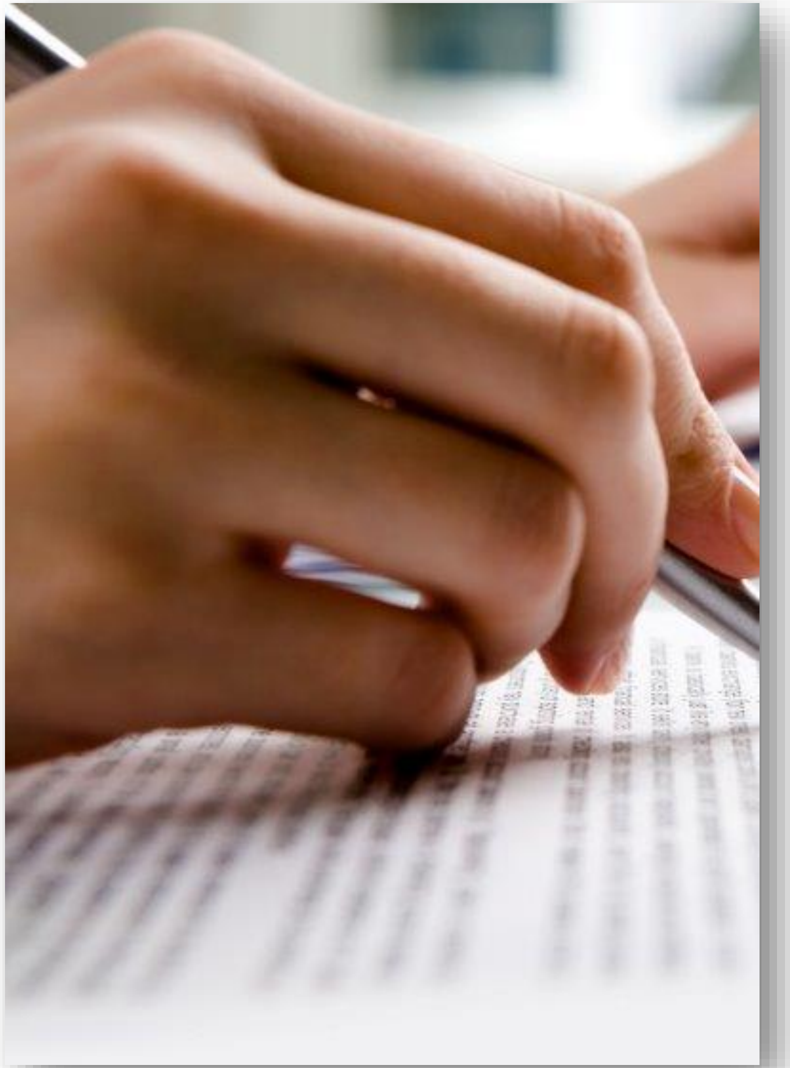
Contact HyGear: marco.rep@hygear.com

Purity requirements for hydrogen applications: the latest on ISO 14687

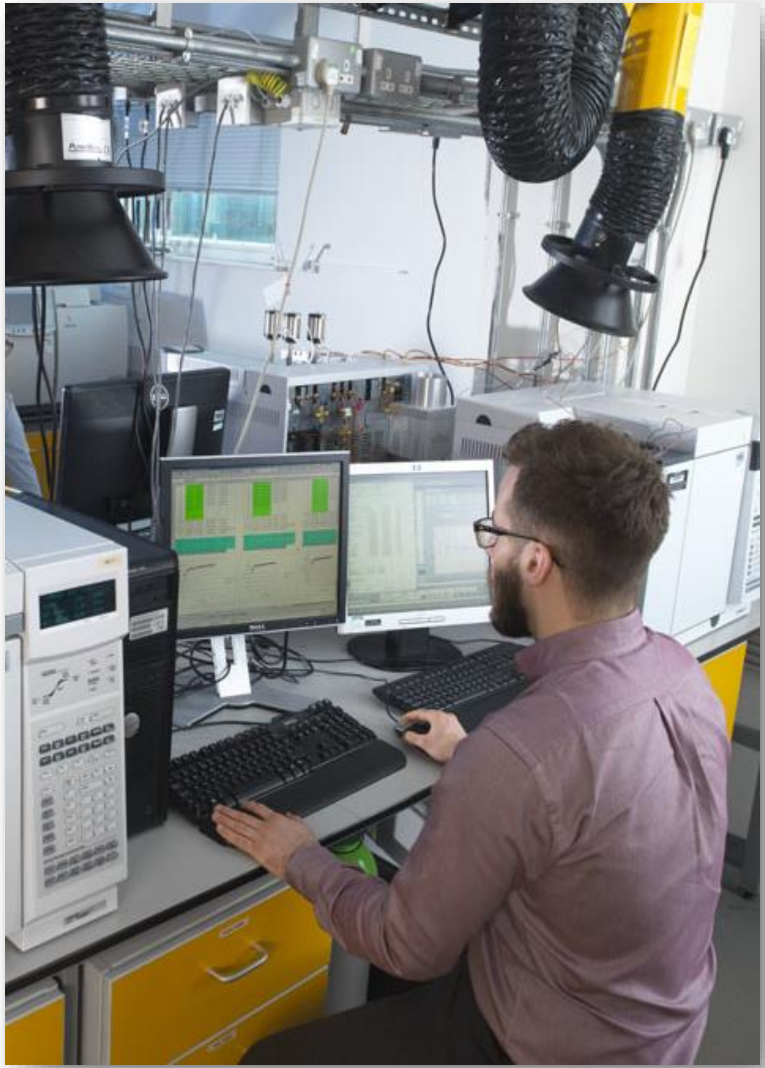
Dr Arul Murugan
Senior Research Scientist – Energy Gases

Overview

NPL
National Physical Laboratory



Standards for Hydrogen Purity



Hydrogen Purity Laboratory

Future Work

ISO 14687

National Physical Laboratory

ISO TC 197 WG 27 – Hydrogen Fuel Quality

National Physical Laboratory

NPL sits as a UK expert on WG 27

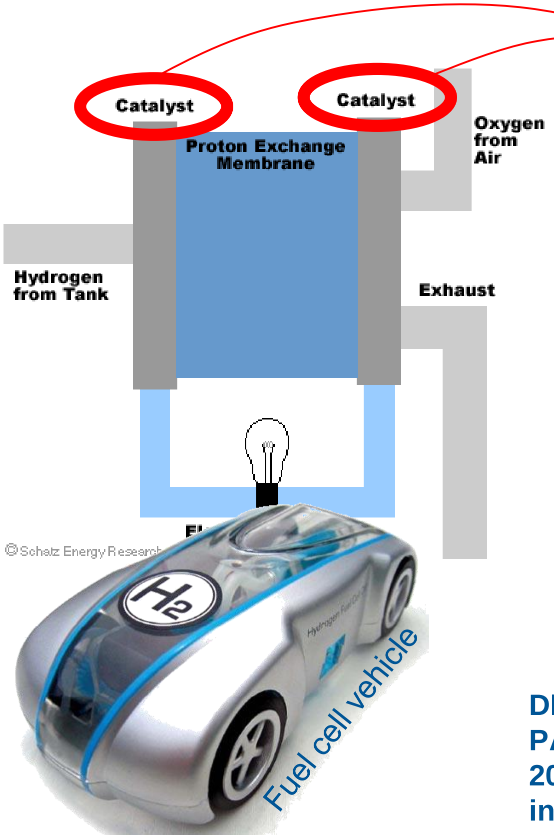
ISO 14687-1
Non-fuel cells

ISO 14687-2
Fuel cell vehicles

ISO 14687-3
Stationary fuel cells

ISO 14687-2:2015

Hydrogen purity for PEM fuel cell vehicles



Usually platinum – can degrade in the presence of impurities (such as hydrogen sulphide or carbon monoxide)

DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 October 2014 on the deployment of alternative fuels infrastructure:

"The hydrogen purity dispensed by hydrogen refuelling points shall comply with the technical specifications included in the ISO 14687-2 standard."

Reactive gases	
•Water	(5 µmol/mol)
•Oxygen	(5 µmol/mol)
•Carbon dioxide	(2 µmol/mol)
•Total hydrocarbon compounds	(2 µmol/mol)
•Formic acid	(0.2 µmol/mol)
•Carbon monoxide	(0.2 µmol/mol)
•Ammonia	(0.1 µmol/mol)
•Total halogenated compounds	(0.05 µmol/mol)
•Formaldehyde	(0.01 µmol/mol)
•Total sulphur compounds	(0.004 µmol/mol)
Inert gases	
•Helium	(300 µmol/mol)
•Nitrogen	(100 µmol/mol)
•Argon	(100 µmol/mol)
Non-gases	
•Particulates	(1 mg/kg)

ISO 14687-3:2014

Hydrogen purity for stationary PEM fuel cells

NPL National Physical Laboratory

Category 1, 2 and 3 assigned by manufacturer

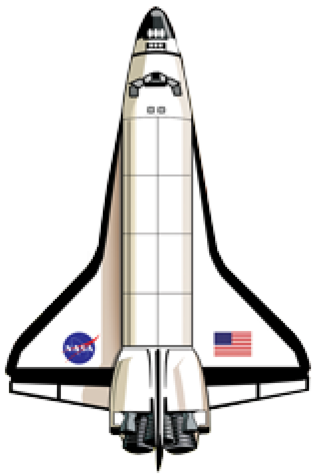
Characteristics[a] (assay)	Type I, grade E		
	Category 1	Category 2	Category 3
Hydrogen fuel index (minimum mole fraction)	50 %	50 %	99,9 %
Total non-hydrogen gases (maximum mole fraction)	50 %	50 %	0,1 %
Water (H_2O)[b]	Non-condensing at all ambient conditions	Non-condensing at all ambient conditions	Non-condensing at all ambient conditions
Maximum concentration of individual contaminants			
Total hydrocarbons (C_1 basis)[c]	10 µmol/mol	2 µmol/mol	2 µmol/mol
Oxygen (O_2)	200 µmol/mol	200 µmol/mol	50 µmol/mol
Nitrogen (N_2), Argon (Ar), Helium (He) (mole fraction)	50 %	50 %	0,1 %
Carbon dioxide (CO_2)	Included in total non-hydrogen gases	Included in total non-hydrogen gases	2 µmol/mol
Carbon monoxide (CO)	10 µmol/mol	10 µmol/mol	0,2 µmol/mol
Total sulfur compounds[d]	0,004 µmol/mol	0,004 µmol/mol	0,004 µmol/mol
Formaldehyde (HCHO)	3,0 µmol/mol	0,01 µmol/mol	0,01 µmol/mol
Formic acid (HCOOH)	10 µmol/mol	0,2 µmol/mol	0,2 µmol/mol
Ammonia (NH_3)	0,1 µmol/mol	0,1 µmol/mol	0,1 µmol/mol
Total halogenated compounds[e]	0,05 µmol/mol	0,05 µmol/mol	0,05 µmol/mol
Maximum particulates concentration	1 mg/kg	1 mg/kg	1 mg/kg
Maximum particle diameter	75 µm	75 µm	75 µm

ISO 14687-1:1999

Hydrogen purity for all applications except PEM fuel cell

Grade A: Boilers, cookers

Grade B: Heat and power



Grade C: Aircraft and space vehicles

Constituents (assay)	Type I Grade A	Type I Grade B	Type I Grade C
Hydrogen fuel index [a] (minimum mole fraction, %)	98,0 %	99,90 %	99,995 %
Para-hydrogen (minimum mole fraction, %)	NS	NS	NS
Impurities (maximum content)			
Total gases	20.000 µmol/mol	1.000 µmol/mol	50 µmol/mol
Water (mole fraction, %)	Non-condensing at all ambient conditions [b]	Non-condensing at all ambient conditions	c
Total hydrocarbon	100 µmol/mol	Non-condensing at all ambient conditions	c
Oxygen	b	100 µmol/mol	d
Argon	b		d
Nitrogen	b	400 µmol/mol	c
Helium			39 µmol/mol
CO_2			e
CO	1 µmol/mol		e
Mercury		0,004 µmol/mol	
Sulfur	2,0 µmol/mol	10 µmol/mol	
Permanent particulates	g	f	f
Density			

a The hydrogen fuel index is determined by subtracting the "total non-hydrogen gases" expressed in mole percent, from 100 mole percent.

b Combined water, oxygen, nitrogen and argon: maximum mole fraction of 1,9 %.

c Combined nitrogen, water and hydrocarbon: max. 9 µmol/mol.

d Combined oxygen and argon: max. 1 µmol/mol.

e Total CO_2 and CO: max. 1 µmol/mol.

f To be agreed between supplier and customer.

g The hydrogen shall not contain dust, sand, dirt, gums, oils, or other substances in an amount sufficient to damage the fuelling station equipment or the vehicle (engine) being fuelled.

ISO 14687:2018

Hydrogen fuel quality – product specification

Revision is happening now:

1) Combining all three parts

2) Change to vehicle purity requirements:
   - Total formaldehyde, formic acid and carbon monoxide = 0.2 µmol/mol
   - 'Total' halogenated changed to 'key' halogenated
   - Methane added
   - Nitrogen and argon increased

Reactive gases	
•Methane	(100 µmol/mol)
•Water	(5 µmol/mol)
•Oxygen	(5 µmol/mol)
•Carbon dioxide	(2 µmol/mol)
•Non methane hydrocarbons	(2 µmol/mol)
•Formic acid	(0.2 µmol/mol)
•Carbon monoxide	(0.2 µmol/mol)
•Ammonia	(0.1 µmol/mol)
•Key halogenated compounds	(0.05 µmol/mol)
•Formaldehyde	(0.2 µmol/mol)
•Total sulphur compounds	(0.004 µmol/mol)
Inert gases	
•Helium	(300 µmol/mol)
•Nitrogen	(300 µmol/mol)
•Argon	(300 µmol/mol)
Non-gases	
•Particulates	(1 mg/kg)

ISO/DIS 19880-8

Hydrogen fuelling stations – fuel quality control

National Physical Laboratory

OCCURANCE

OCCURRENCE CLASS	CLASS NAME	DESCRIPTION	OCCURRENCE OR FREQUENCY
0	**Very unlikely (Practically impossible)**	Contaminant above threshold never been observed for this type of source in the industry	Never
1	**Very rare**	Heard in the Industry for the type of source/ Supply chain considered	1 per 1 000 000 fuelings
2	**Rare**	Has happened more than once/year in the Industry	1 per 100 000 fuelings
3	**Possible**	Has happened repeatedly for this type of source at a specific location	1 out of 10 000 fuelings
4	**Frequent**	Happens on a regular basis	Often

SEVERITY

SEVERITY CLASS	FCEV Performance impact or damage	Impact categories		
		Performance impact	Hardware impact temporary	Hardware impact permanent
0	• No impact	No	No	No
1	• Minor impact • Temporary loss of power • No impact on hardware • Vehicle still operates	Yes	No	No
2	• Reversible damage • Requires specific procedure, light maintenance. • Vehicle still operates.	Yes or No	Yes	No
3	• Reversible damage • Requires specific procedure and immediate maintenance. • Gradual power loss that does not compromises safety	Yes	Yes	No
4	• Power loss or Vehicle Stop that compromises safety • Irreversible damage • Requires major repair (e.g. stack change)	Yes[1]	Yes	No
			No	Yes

ISO/DIS 19880-8

Hydrogen fuel quality – product specification

		Severity				
Probability per one fueling	**Occurrence**	**0**	**1**	**2**	**3**	**4**
Frequent: Often	**4**					
Possible: 10^{-4}	**3**					
Rare: 10^{-5}	**2**					
Very Rare: 10^{-6}	**1**					
Practically Impossible	**0**					
Key	Unacceptable risk; additional control or barriers required		Further investigations are needed: existing barriers or control may not be enough		Acceptable risk area Existing controls sufficient	

Hydrogen Production

NPL National Physical Laboratory

Table 7 – Probability of contaminant presence in the three models presented in this article (SMR + PSA, PEM water electrolysis + TSA and chlor-alkali membrane electrolysis + TSA).

Probability of contaminant presence	Steam methane reforming with PSA	Chlor-alkali process (membrane cell process)	PEM water electrolysis process with TSA
Frequent	CO	O_2	None identified
Possible	N_2	None identified	None identified
Rare	CH_4, H_2O and Ar	N_2 and H_2O	N_2, O_2 and H_2O
Very rare	CH_2O	CO_2	CO_2
Unlikely	He, CO, O_2, CH_2O_2, NH_3, sulphur compounds, hydrocarbons compounds, halogenated compounds	He, Ar, CO, CH_4, CH_2O, CH_2O_2, NH_3, sulphur compounds, hydrocarbons compounds, halogenated compounds	He, Ar, CO, CH_4, CH_2O, CH_2O_2, NH_3, sulphur compounds, hydrocarbons compounds, halogenated compounds

Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model

Thomas Bacquart, Arul Murugan, Martine Carre, Bruno Gozlan, Fabien Auretre, Frederique Haloua & Thor A. Aarhaug

International Journal of Hydrogen Energy (2018)

EN 17124:2018

Hydrogen fuel quality – product specification

Essentially combines ISO 14687-2:2015 and ISO/DIS 19880-8

CEN TC 268 WG5
Specific hydrogen technologies applications

Reactive gases

•Methane	(100 µmol/mol)
•Water	(5 µmol/mol)
•Oxygen	(5 µmol/mol)
•Carbon dioxide	(2 µmol/mol)
•Non methane hydrocarbons	(2 µmol/mol)
•Formic acid	(0.2 µmol/mol)
•Carbon monoxide	(0.2 µmol/mol)
•Ammonia	(0.1 µmol/mol)
•Total halogenated compounds	(0.05 µmol/mol)
•Formaldehyde	(0.2 µmol/mol)
•Total sulphur compounds	(0.004 µmol/mol)

Inert gases

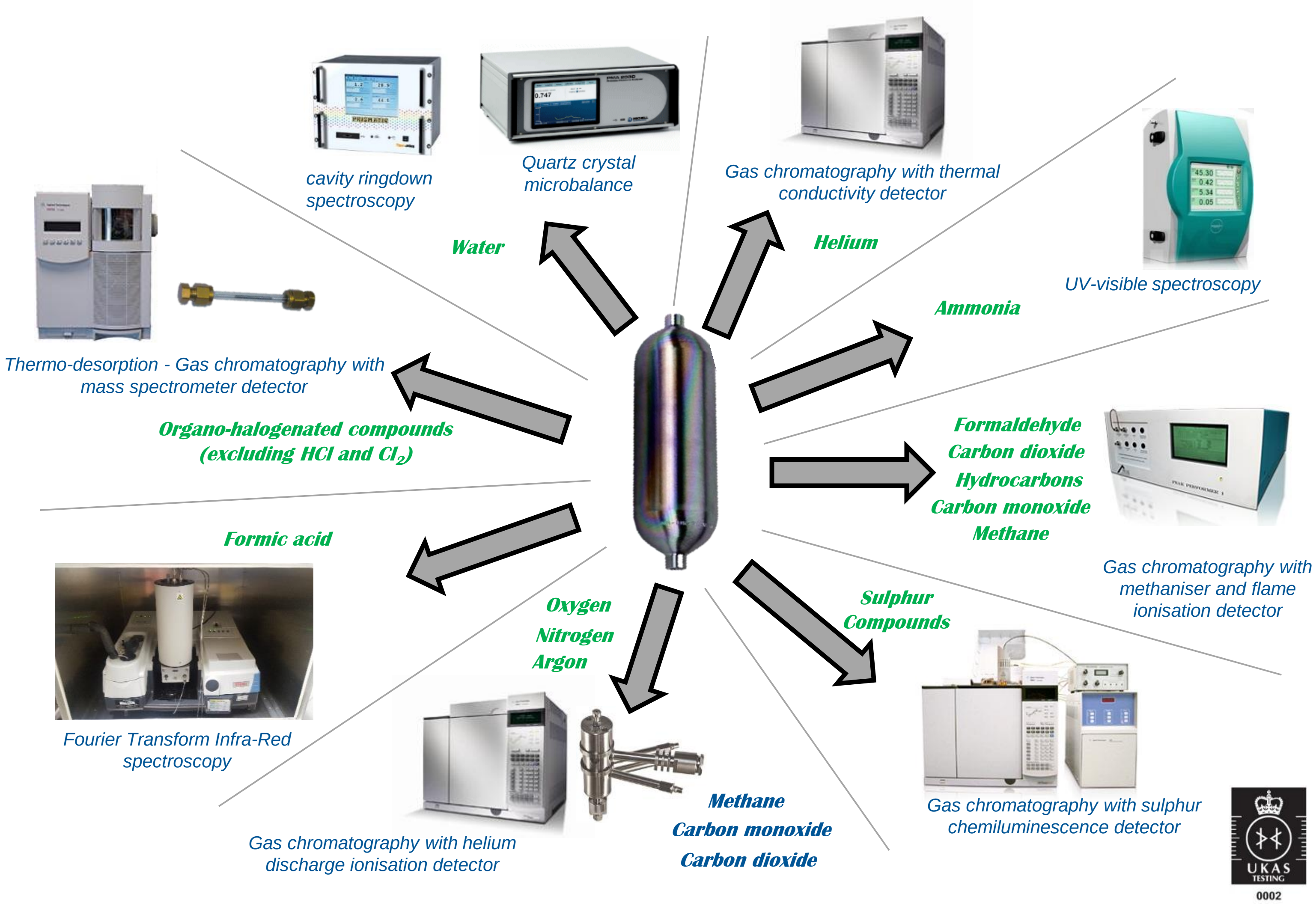
•Helium	(300 µmol/mol)
•Nitrogen	(300 µmol/mol)
•Argon	(300 µmol/mol)

Non-gases

•Particulates	(1 mg/kg)

Hydrogen Purity Laboratory

NPL's Hydrogen Purity Laboratory



Key points:

- Capital costs ~ €500 k
- All measurements performed against hydrogen gas standards
- We can provide gas standards as well
- Accreditation to ISO 17025
- Developing sampling capability
- Sampling at low pressure and HRS

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Hydrogen Purity Laboratory

Helpful literature for hydrogen purity analysis

Review of purity analysis methods for performing quality assurance of fuel cell hydrogen

Arul Murugan & Andrew S. Brown

International Journal of Hydrogen Energy (2015)

ISO/DIS 21087 Gas analysis – analytical methods for hydrogen fuel

ISO TC 158 JWG 7

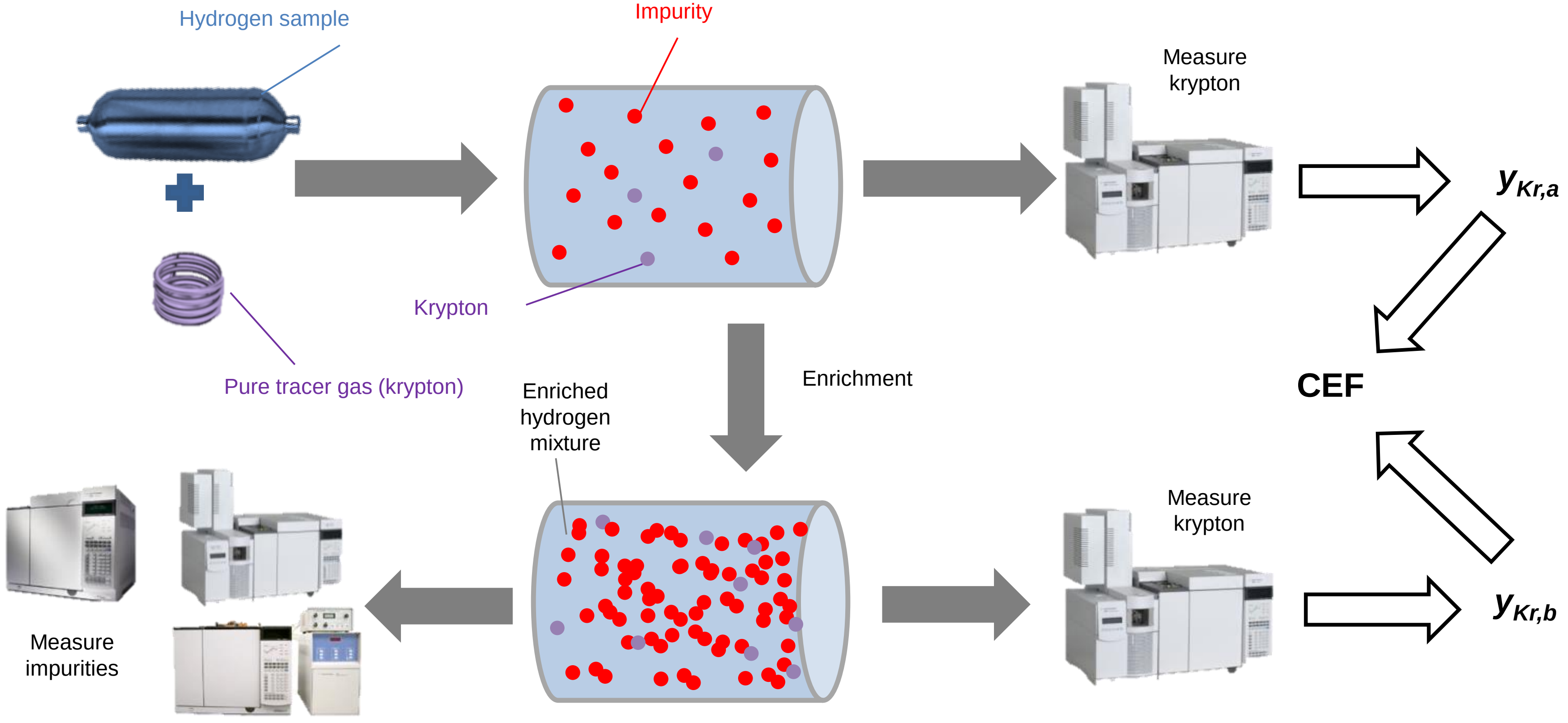
Provides a list of methods for performing ISO 14687 hydrogen purity analysis

Provides a list of methods for performing ISO 14687 hydrogen purity analysis and guidance on validating methods

Hydrogen Purity Laboratory

NPL’s Hydrogen Impurity Enrichment Device

NPL National Physical Laboratory



Key points:
- Capital costs ~€50k
- Used with routine analysers such as GC-MS
- Further testing required to improve membranes

Hydrogen Purity Laboratory

NPL's Sampling

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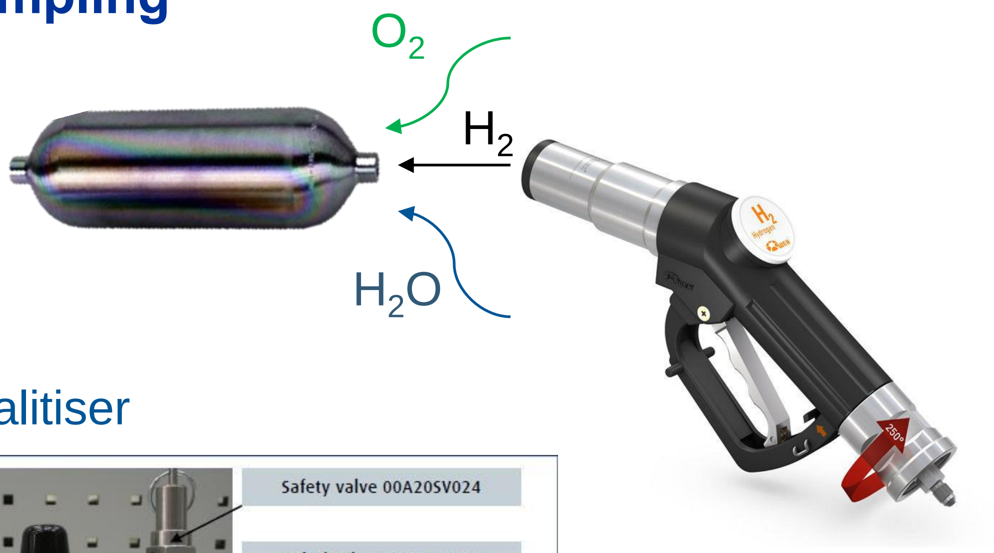
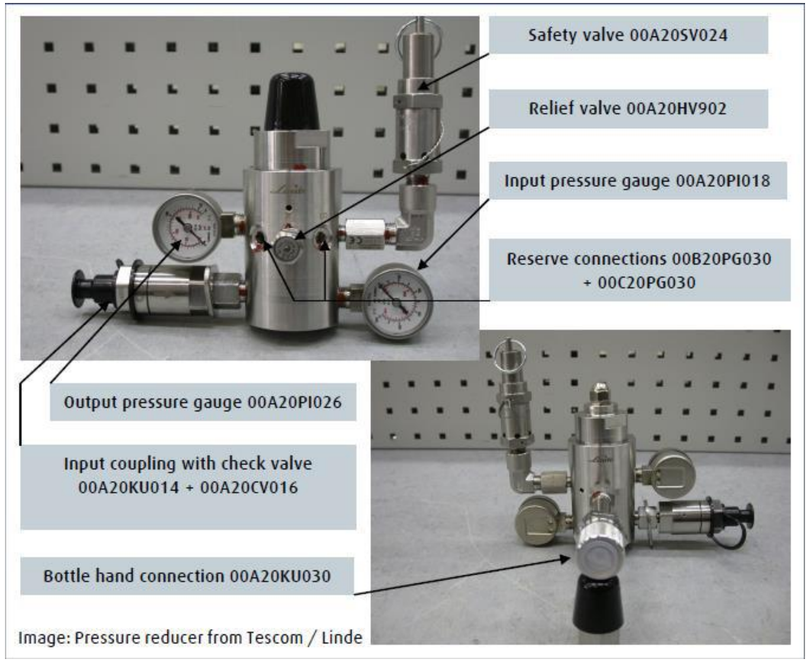


Linde Qualitiser



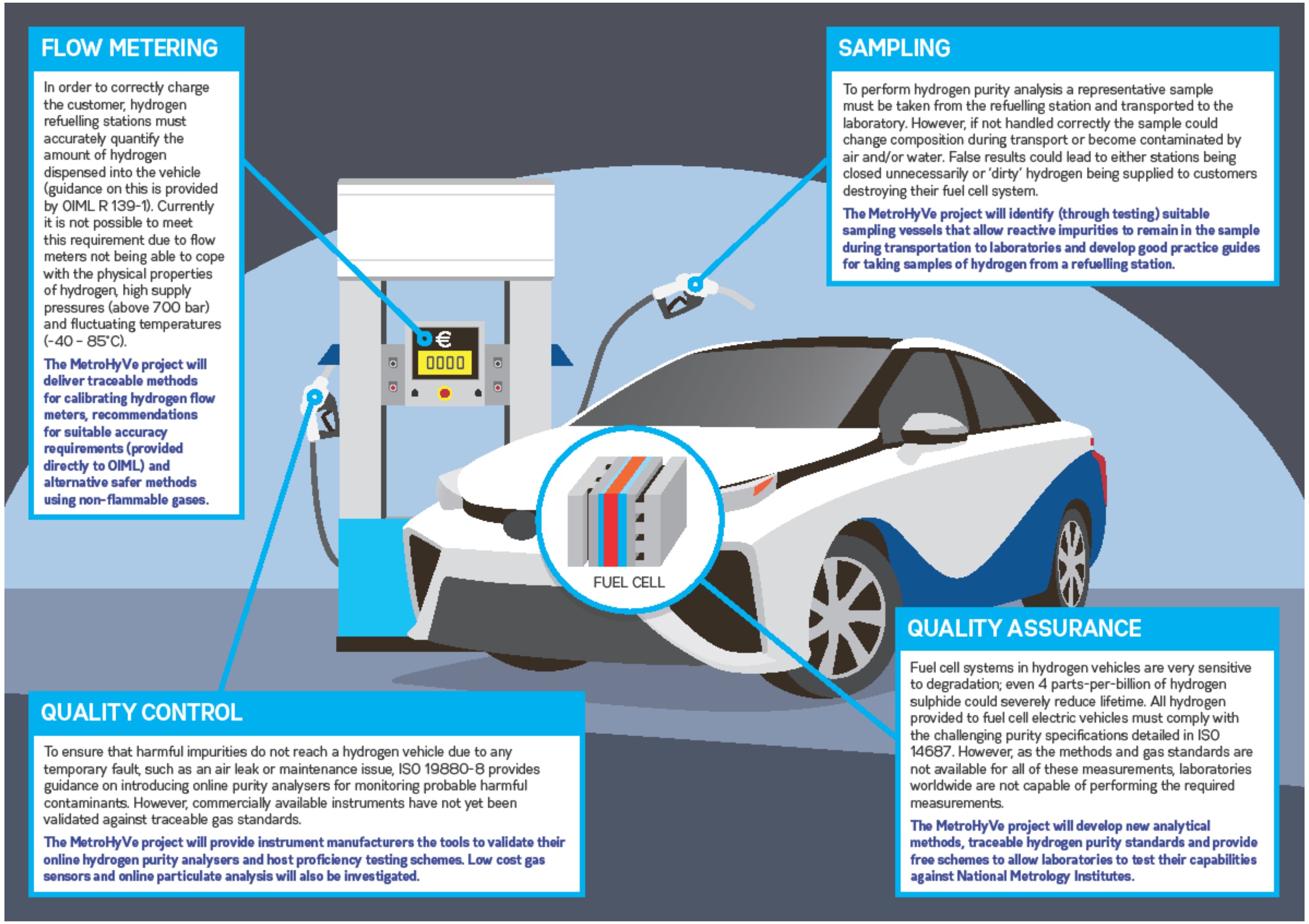
Key points:

- Bad sampling can introduce air and water contaminants
- Wrong choice of sampling vessel could lead to loss of impurities
- Sampling from car will help diagnose faults

Car sampling

Future work

EMPIR Metrology for Hydrogen Vehicles



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Supported by 50 stakeholders including:

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Future work

Other relevant NPL projects

National Physical Laboratory

Hydrogen 100: Hydrogen Odorants and Leak Detection

Identifying suitable odorants and leak detection methods for a 100% hydrogen grid

Testing includes fuel cell degradation, hydrogen boiler, olfactory, pipeline correction.

FCH JU2 Hydraite

Establishing European Hydrogen Purity Laboratories

Developing fuel cell degradation testing facility (for both hydrogen and air side)

EMPIR Hydrogen

Risk analysis and impurity probabilities for hydrogen production methods

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Department for
Business, Energy
& Industrial Strategy

FUNDED BY BEIS

This work was supported by the UK government's Department for Business, Energy and Industrial Strategy (BEIS)


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