The role of hydrogen in the energy transition:
Opportunities, challenges and trends of development on the whole value chain

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OUTLINE

1. Introduction

Hydrogen usages

Usage in 2023

“Industrial” H_2

- World ≈ 97 Mt/yr
- Europe ≈ 7.9 Mt/yr
- France ≈ 0.9 Mt/yr

- **Chemistry (ammonia)**
- **Oil Refining**
- **Iron & steel**

Usages in 2030 and beyond

“Industrial” and “energy” H_2

Achieving deep decarbonization of >80% of CO_2 emissions requires hydrogen

Ultra-low-carbon H_2 as feedstock, e.g, chemistry

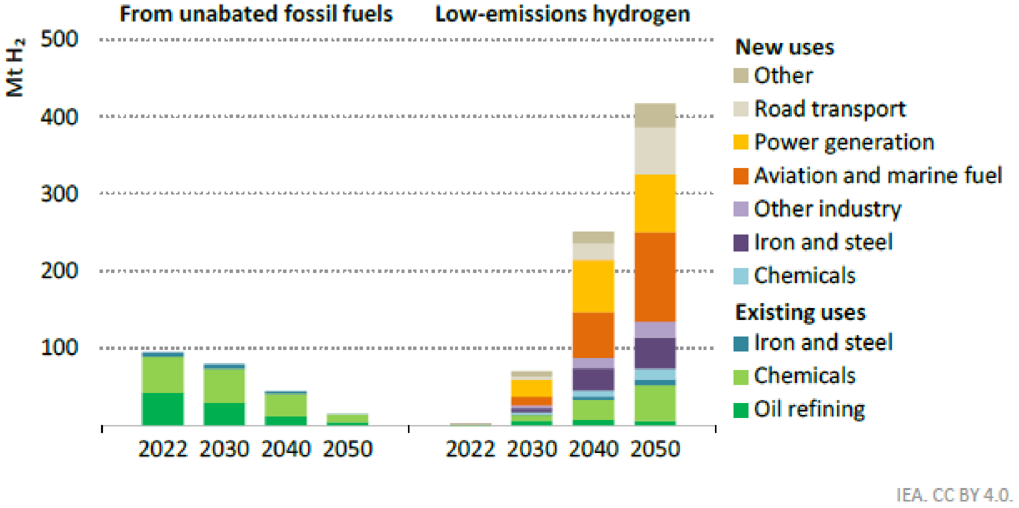
Decarbonization of industrial process :

- directly: e.g. steel (direct reduction of iron)

- indirectly: high-grade heat

Store variable renewable electricity and bring stability and flexibility to the electricity grid

Fuel cells/synfuels for heavy transport and long distances



Use of low-emissions hydrogen rises significantly to 70 Mt by 2030 and extends to new applications such as in aviation and shipping

Source : IEA, NetZero Roadmap (2023)

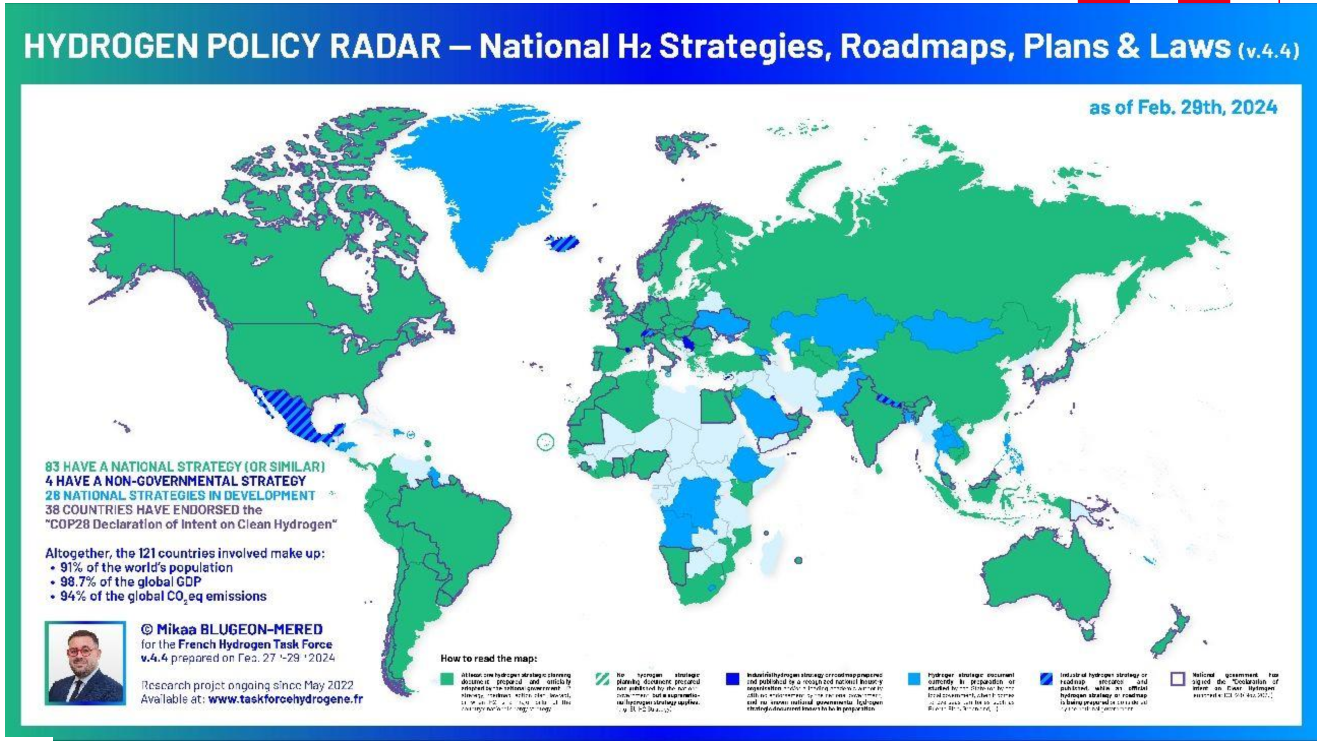
H_2 Needs x5 until 2050

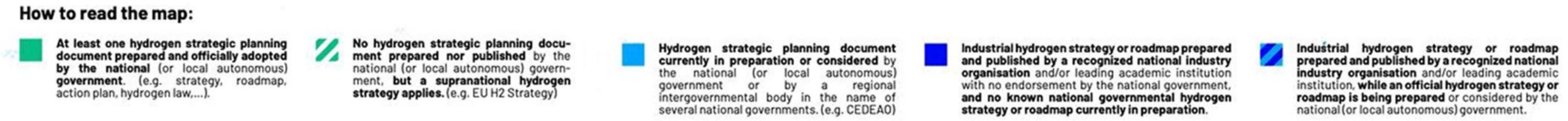
- E-fuels (SAF, SMF): increasing share from 2030 to become majoritary in 2050
- Regulatory constraint:
  - ReFuelEU Aviation
    - 2030: 1.2% e-kerosene; 6% SAF
    - 2050: 35% e-kerosene; 70% SAF
  - FuelEU Maritime
    - 2030: 6% GHG reduction vs. 2020
    - 2050: 80% GHG reduction

International context

More and more countries have national H_2 strategies:

- 83 have a national strategy
- 28 national strategies in development
- 38 countries endorsed COP28 Declaration of intent on Clean H_2

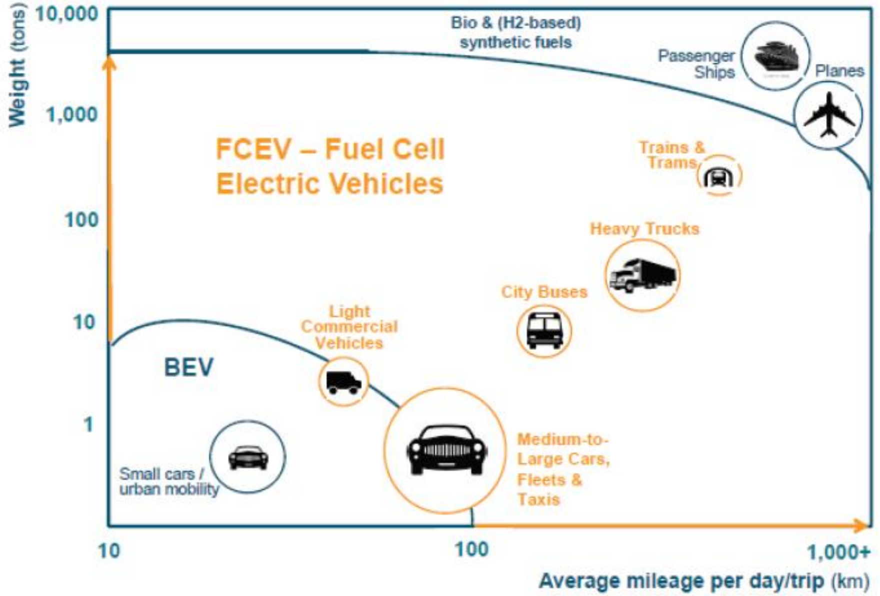


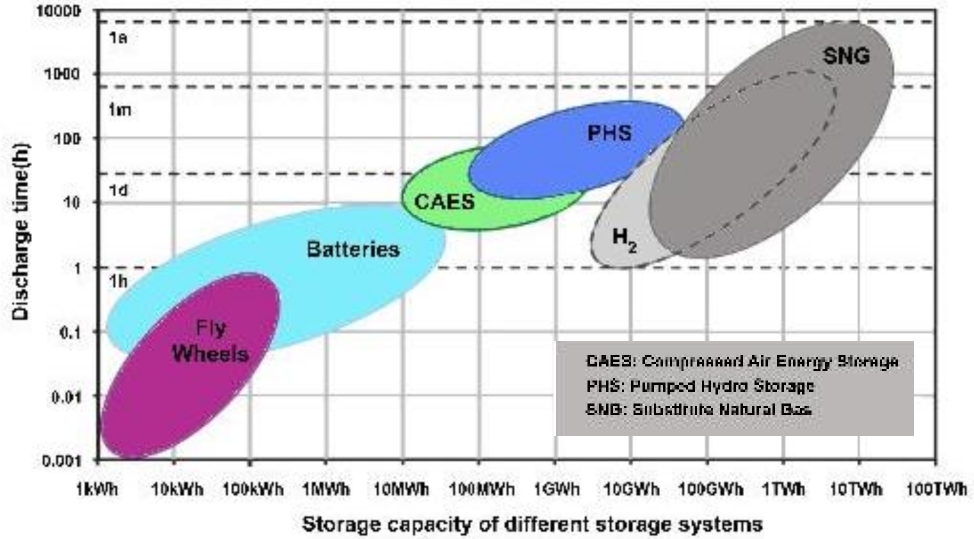


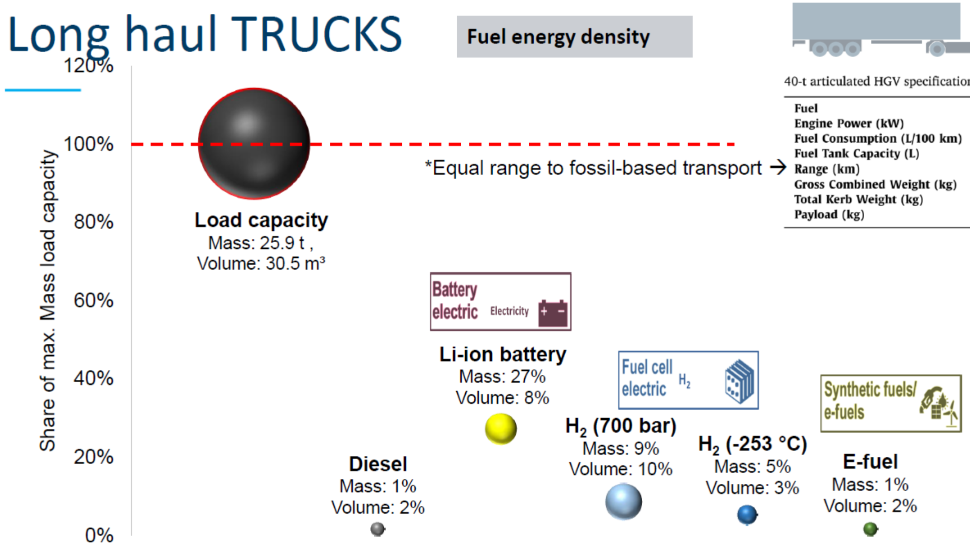
- At EU level: RePowerEU plan: for saving energy, producing clean energy, and diversifying energy supplies.
- H2 Accelerator = one of its main pillars, sets out a strategy to:
    - double the previous EU renewable H2 target to 10 million tons of annual domestic production,
    - plus an additional 10 million tons of annual H2 imports

Complementarity of hydrogen and batteries

- For transportation
  - H_2 benefit for:
    - long distance
    - Quick refill
    - Mass load capacity
- For electricity storage
  - H_2 benefit:
    - large capacity
    - long time
    - long distance







40-t articulated HGV specifications.

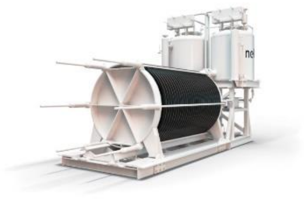
Fuel	Diesel
Engine Power (kW)	326
Fuel Consumption (L/100 km)	35 [128]
Fuel Tank Capacity (L)	450
Range (km)	1216
Gross Combined Weight (kg)	40,000
Total Kerb Weight (kg)	14,550 [81]
Payload (kg)	25,450 [81]

Source: Dr. Jonas Martin, PhD-study at NTNU, Norway, now with Institute of Future Fuels, DLR, supplemented by data from Gray et al. 2021: Decarbonizing ships, planes, and trucks

SINTEF

Hydrogen value chain

Production | Storage & distribution | Conversion | Decarbonization of usages

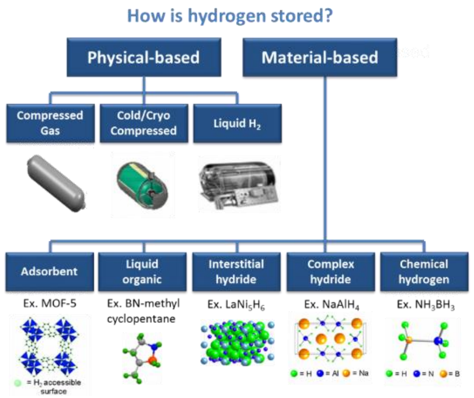


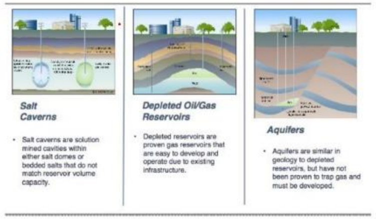
Source: NEL

Electrolysis

Other production routes

Natural hydrogen…





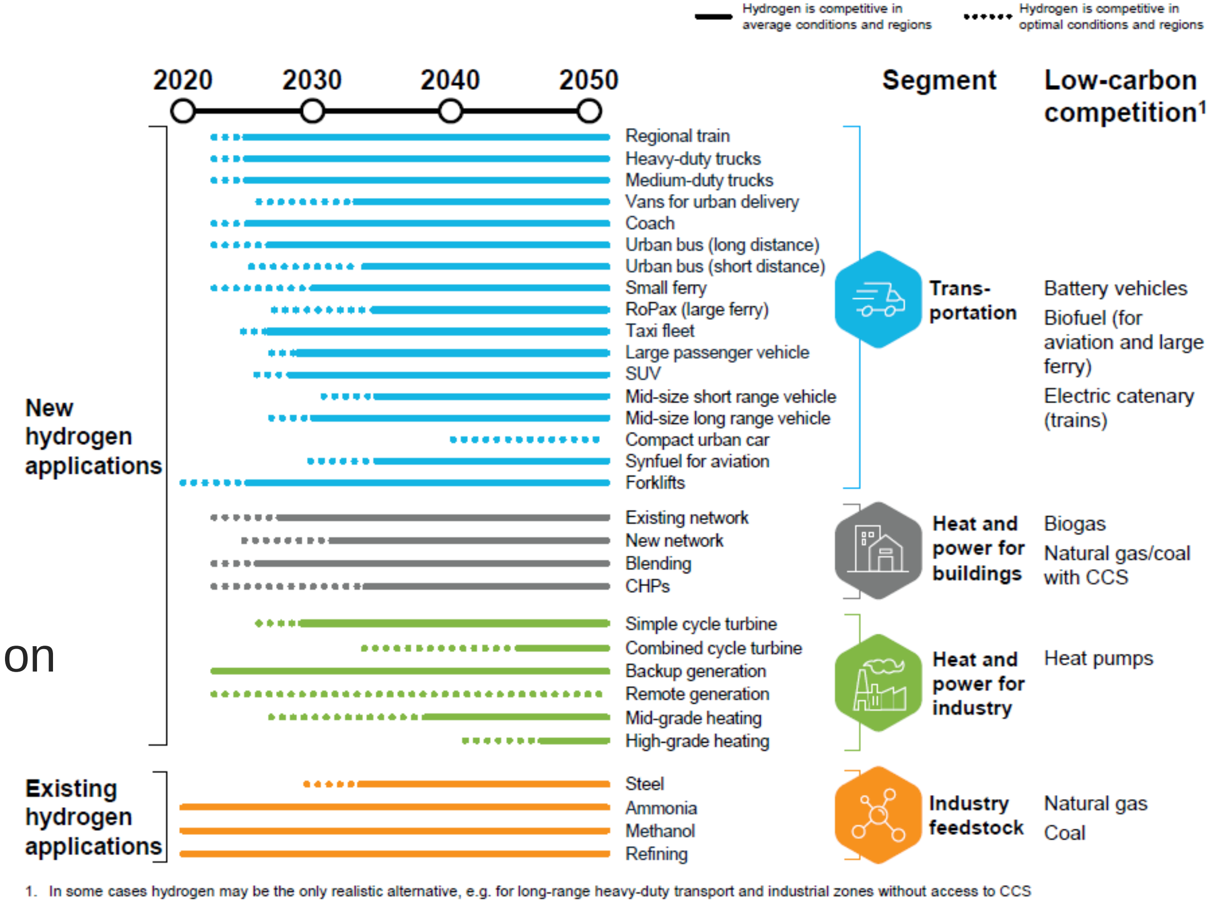
Storage

Source: SYMBIO

Fuel cell

Source: Toyota

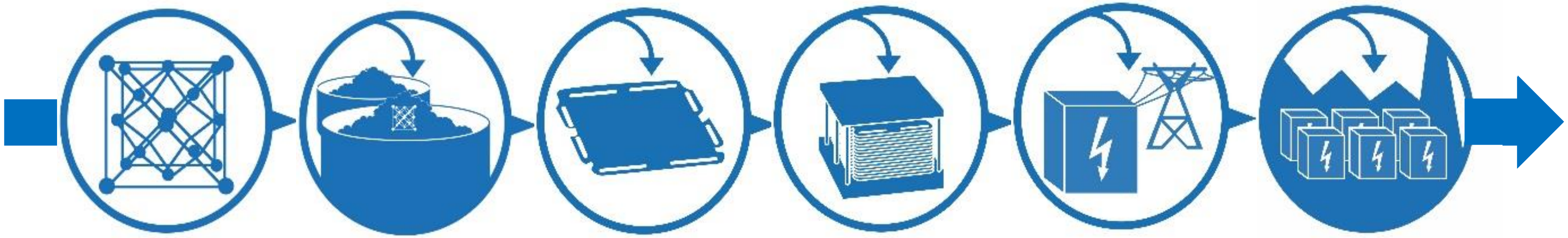
Internal combustion engines



Source: Hydrogen Council, Jan 2020, Path to H2 competitiveness

Hydrogen value chain

Production → Storage & distribution → Conversion → Decarbonation of usages



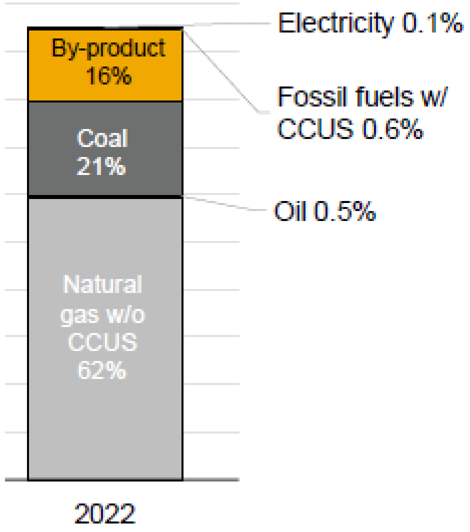
- Development and optimisation
- From materials to systems through components and key technology bricks

2. H2 production

2.1 Overview of the different production routes

Introduction: Hydrogen production routes

Currently: Fossile H_2



≈ 11-19 kg of CO_2 per kg of H_2

Steam methane reforming
$CH_4 + H_2O \leftrightarrow CO + 3H_2$
Water Gas Shift (WGS)
$CO + H_2O \leftrightarrow CO_2 + H_2$

Source: Global Hydrogen Review 2023, IEA

Challenge for 2030 and beyond

- Need to find/develop low carbon H_2 production route
- Different possible options

Compound containing H (H_2O, CH_4, …)

Thermochemical processes

Split with heat
- Biomass pyrolysis, gasification
- Solar thermochemical water splitting

Electrolytic processes

Split with electricity
- Electrolysis

Direct solar splitting processes

Split with light
- Photocatalysis
- Photelectrochemical process

Biological processes

Split with living organisms
- Microbial conversion
- Photobiological process

- Natural hydrogen…

2.2 Focus on electrolysis technologies

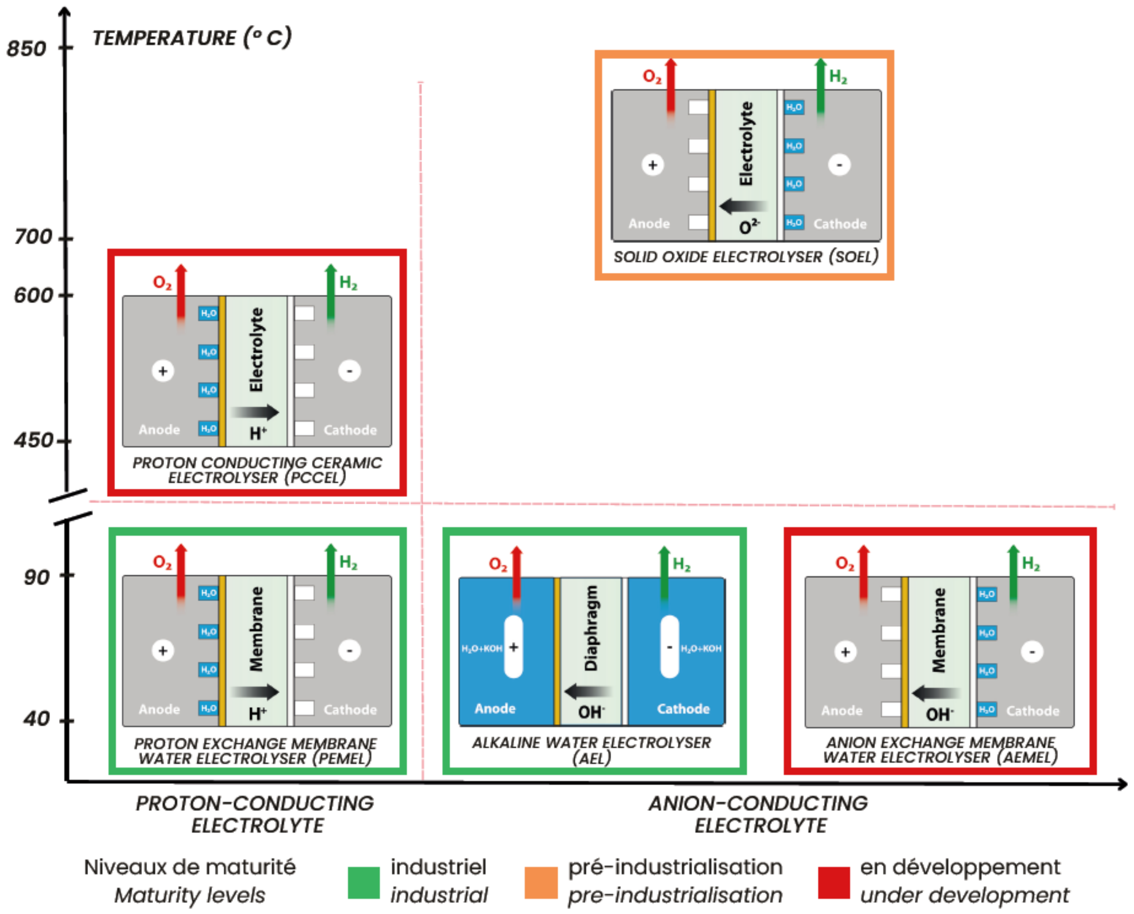
Hydrogen production routes: focus on electrolysis

Electrolytic processes: split with electricity

- For all electrolysis technologies: H_2O decomposed into H_2 and O_2 thanks to an electric current
- 5 technologies that can be classified depending on temperature: water or steam is the starting compound

Steam

Water



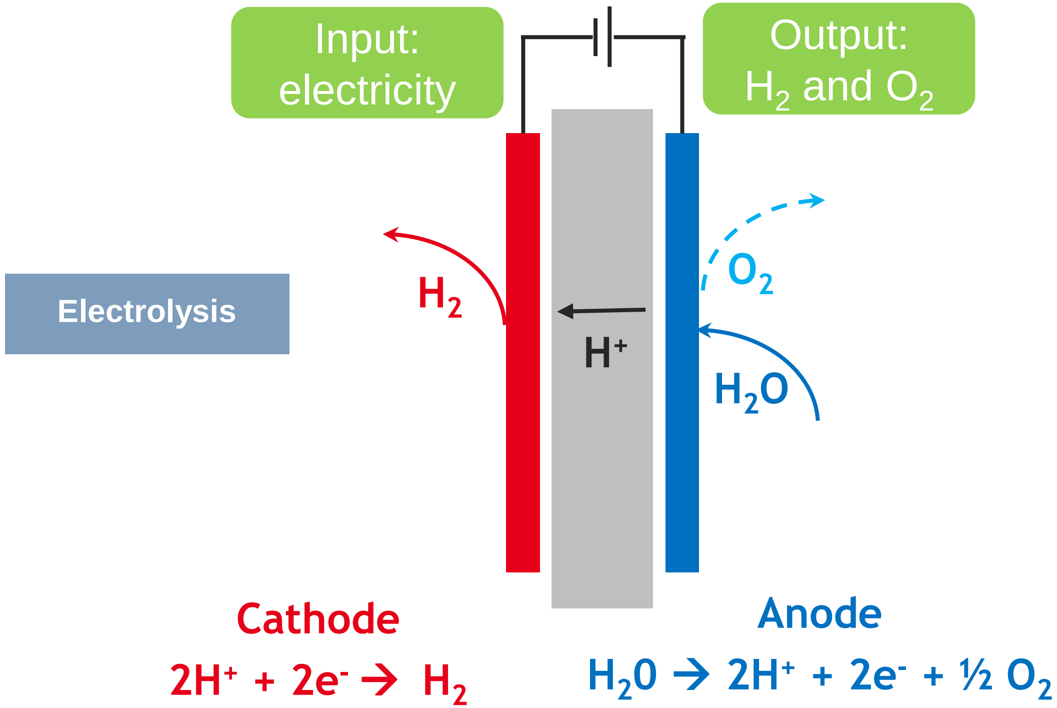
- **Several technologies with different levels of maturity**

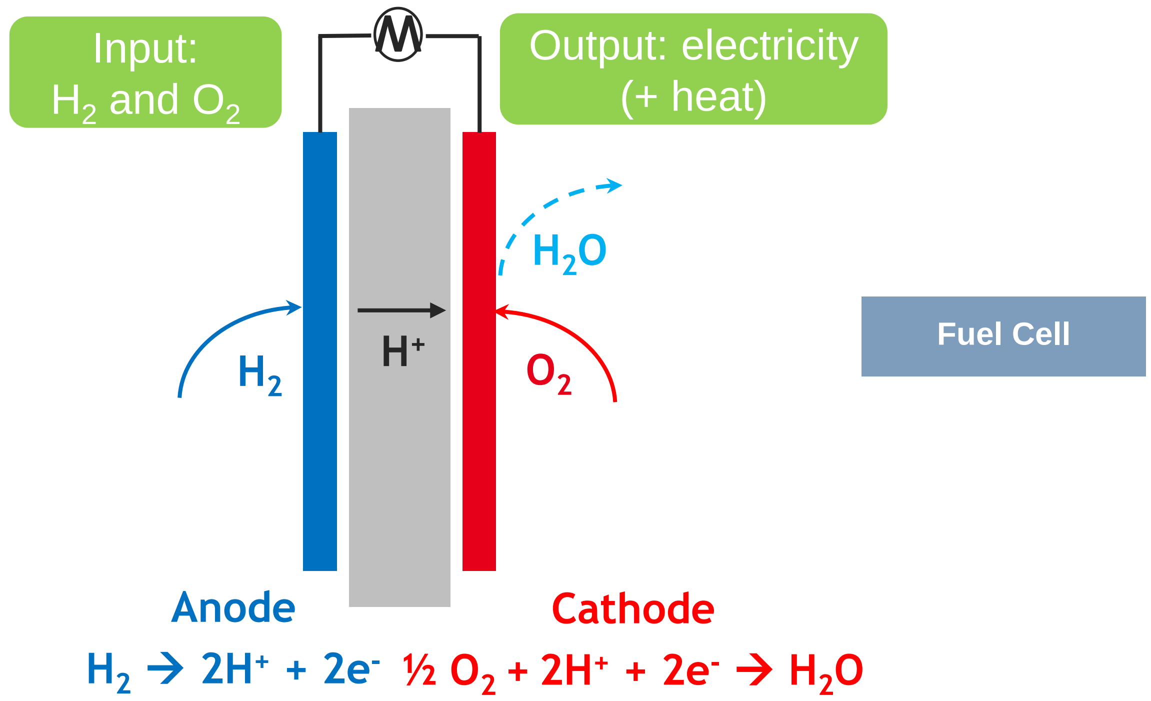
Source for pictures: B. Pollet, Chem. Rev. Soc. 2022, 51 4583-4762

Hydrogen production by electrolysis

- **Principle of electrolysis**

- **Electrolysis and fuel cells:**
  - Electrochemical converters
  - Electrolyser: transforms electrical energy into chemical energy
  - Fuel cell: transforms chemical energy into electrical energy (+ heat)





Exemple for PEMEL and PEMFC

Hydrogen production by electrolysis

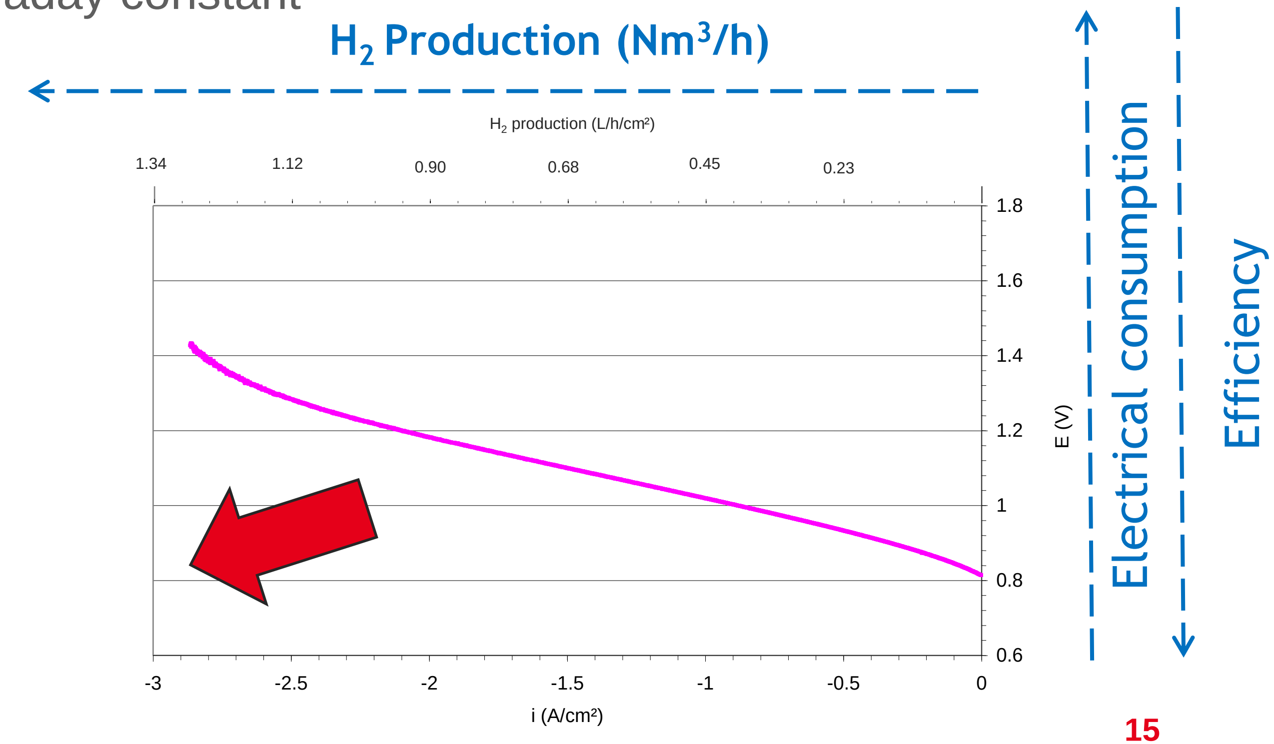
- **Principle of electrolysis**
  - **An electrochemical converter that transforms electrical energy into chemical energy**
  - **Electrolysis of water to produce H_2 using CO_2-free electricity :**

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

    - H_2 production: proportional to electrical intensity
    - Q = I / 2F Q = H_2 flow, I = current, F = Faraday constant

  - **Higher current density (A/cm²)**
    - ➔ compactness
    - ➔ investment decrease

  - **Efficiency (kWh/Nm³ or kWh/kg) : inversely proportional to voltage**

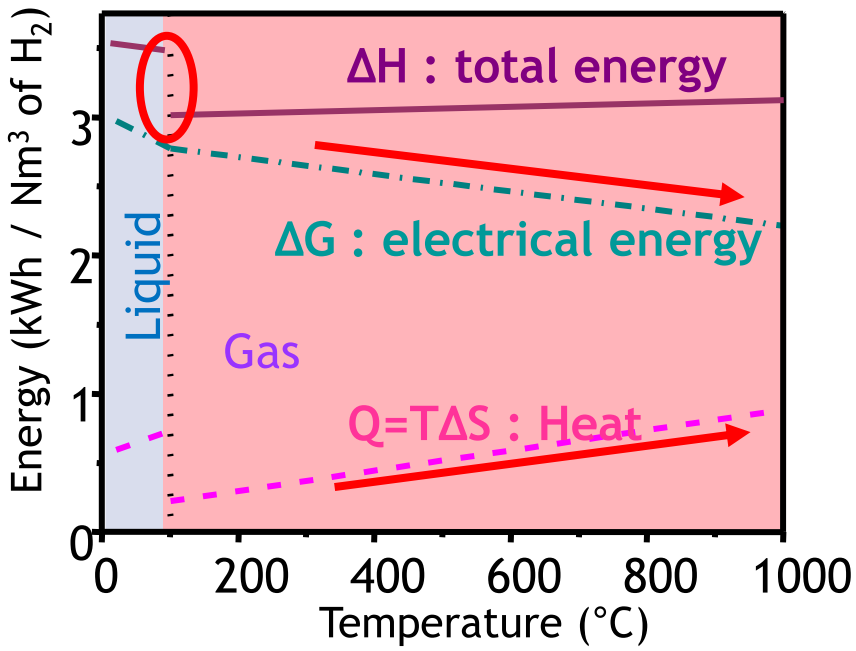


Hydrogen production by electrolysis

- **Overview of the different technologies**

  - Same overall reaction:
    - Low T: H_2O (l) → H_2 (g) + ½ O_2 (g)   ΔH° = 285.84 kJ/mol
    - High T: H_2O (g) → H_2 (g) + ½ O_2 (g)   ΔH° = 250 kJ/mol

  - Different energy needs:



ΔH = ΔG + TΔS

Energy gain with gas phases

ΔH almost constant ~ 250 kJ/mol

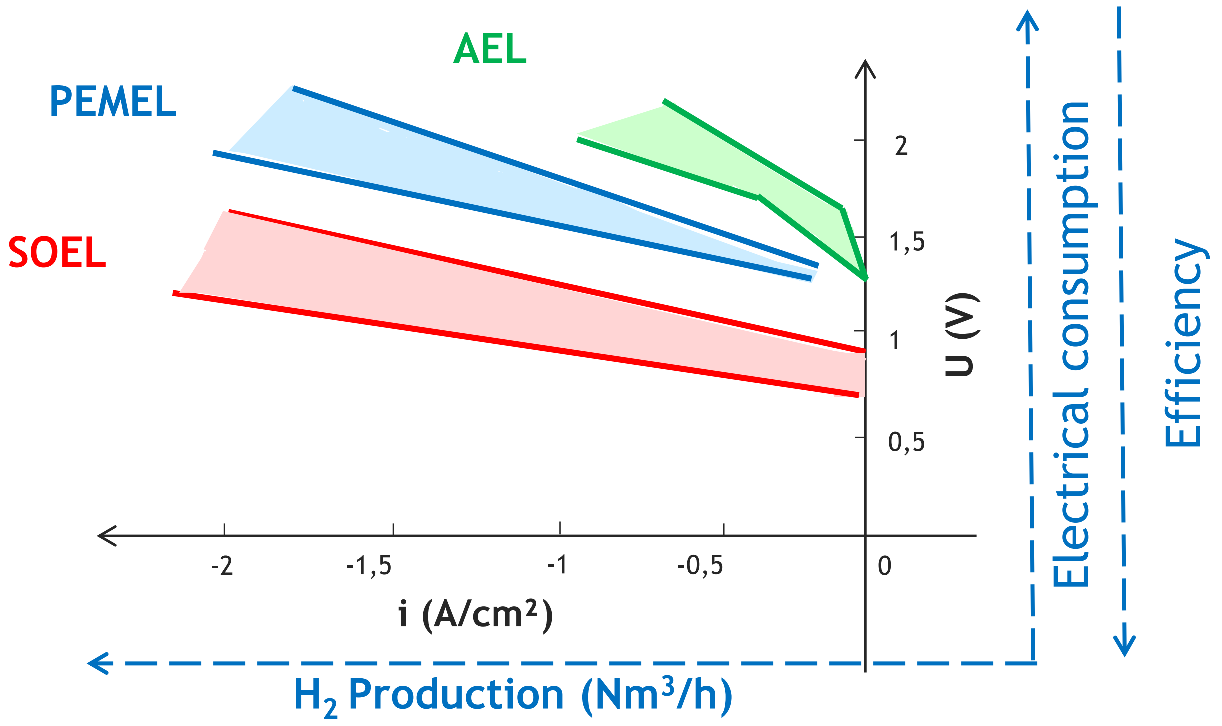
ΔG decreases with T
TΔS increases with T

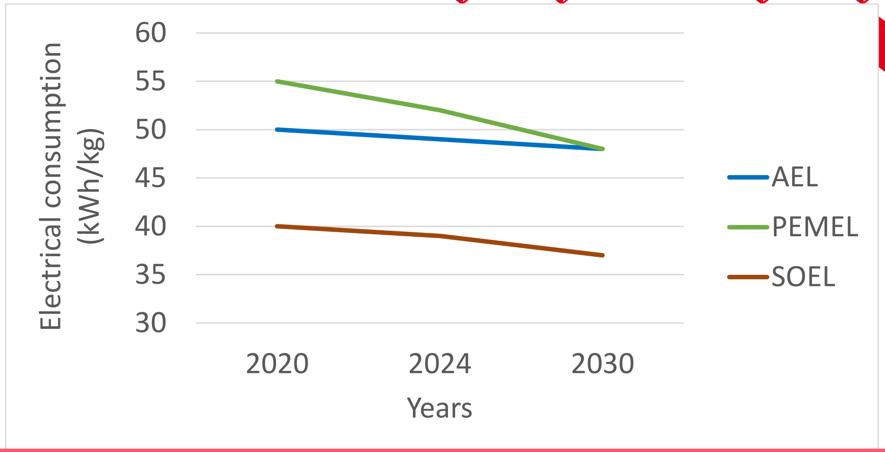
- **Low T: energy = 85% electricity / 15% heat**
- **High T: energy = 70% electricity, 30% heat**

Hydrogen production by electrolysis

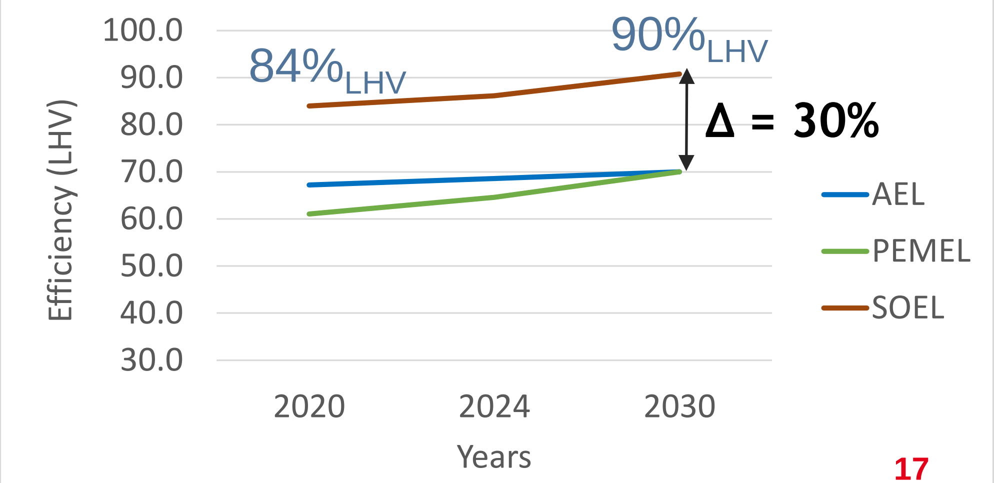
- **Overview of the different technologies**

- **Electrolysis efficiency:**
  - Comparison of operating points of alkaline, PEM and High Temperature Steam electrolysis



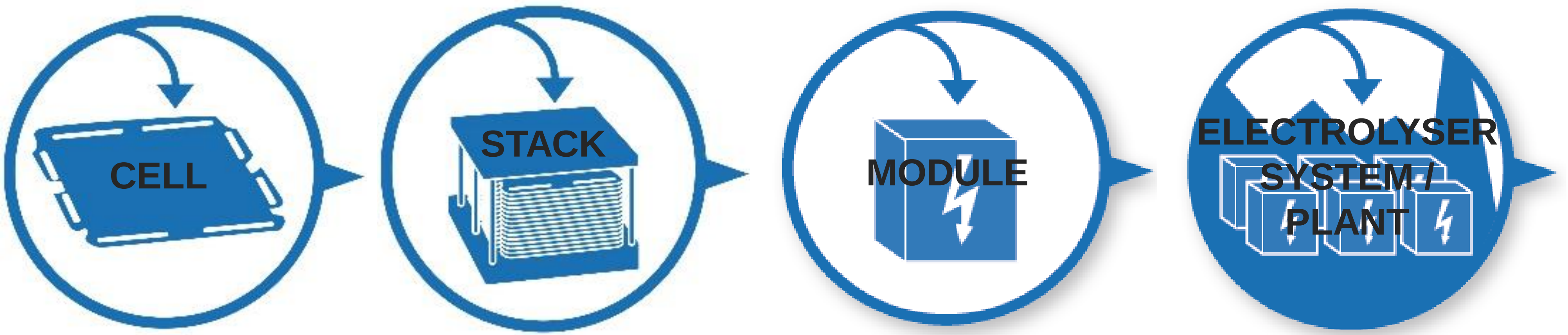


- low T electrolysis : 50 to 55 kWh/kg
- high T electrolysis (SOEL): 40 kWh/kg
- Both will tend to decrease by 2030 thanks to material, cell & stack design, but also BoP improvement (power electronics, parasitic consumption,…) but gap remains



Source : Strategic Research and Innovation Agenda, Clean H2 partnership, Feb 2022

Electrolysis = Modular technology



Electrolysis cell composed of:
- 2 electrodes (anode and cathode)
- One electrolyte
- Need of electricity (and heat)

Stacking of several electrolysis cells to increase the power

Integration of stacks into a **module** including 1st level Balance of Plant components
Can/will include several stacks into a module

Integration of modules into an **electrolysis system/plant** including all Balance of Plant components = electrolyser
Can/will include several modules into the electrolysis system/plant

- **Helpful for scaling up and flexibility of operation**

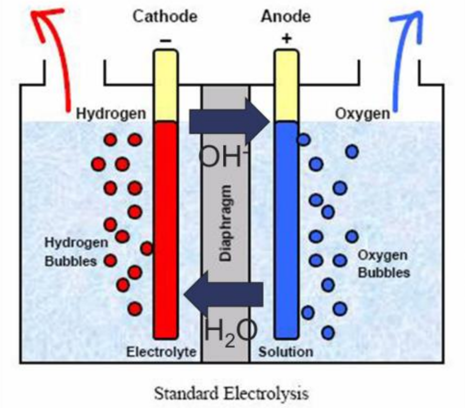
2.2. Presentation of the different electrolysis technologies

Alkaline Electrolysis (AEL)

McPhy stack

John Cockrill installation

Cathode (-):
$2H_2O + 2e^- \rightarrow 2OH^- + H_2$



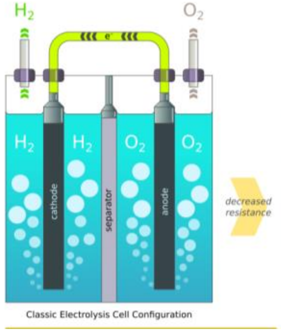
Anode (+):
$2OH^- \rightarrow H_2O + 2e^- + ½ O_2$

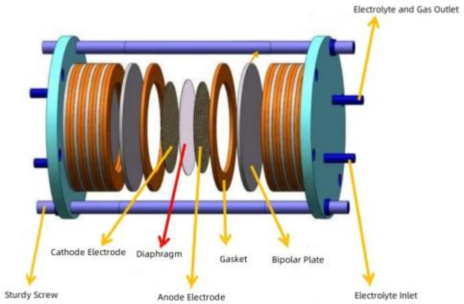
Charge carrier: OH^-
Electrolyte: liquid - KOH

Usual operating temperature: 70-90°C
Usual operating pressure: 1-30 bars

To improve performance

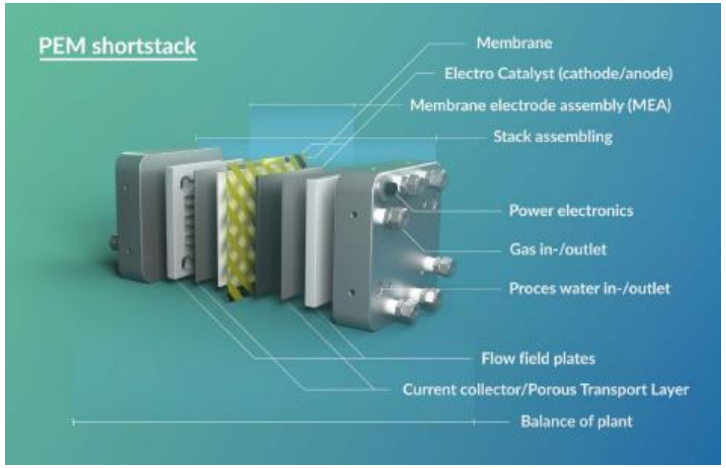
- Bipolar zero gap technology
- Diaphragm as thin as possible (down to 200 µm)
- Addition of some PGM elements to improve catalyst properties: to be removed in future
- Conditions to achieve small bubbles





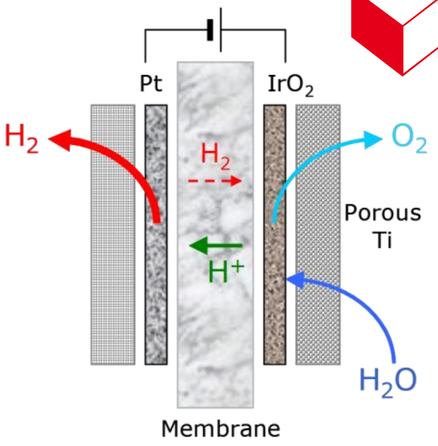
Component	Material
Cathode	Raney-Nickel in various forms (Ni-Al, Ni-Zn) NiMo (MoNi4 + MoO2)
Anode	Ni-X (X=Co,Fe) Oxide Hydroxides: Ni(OH)2, NiOOH + dopants
Membrane / Separator / diaphragm	Zirfon perl materials ZrO2 and polyphenylene sulfide
Electrolyte	KOH 30wt%
Bipolar plate	Ni-coated Steel, nickel
Porous transport layer / substrate	Foams, fibers, meshed, expanded metals (Ni)
Frame and sealing	polymer

Proton Exchange Membrane Water Electrolysis (PEMEL)



Siemens installation with 24 stacks
335 kg/h H2

Cathode
$2H^+ + 2e^- \rightarrow H_2$



Anode
$H_2O \rightarrow 2H^+ + 2e^- + ½ O_2$

Charge carrier: H^+
Electrolyte: solid - polymer

Usual operating temperature: 50-80°C
Usual operating pressure: 1-70 bars

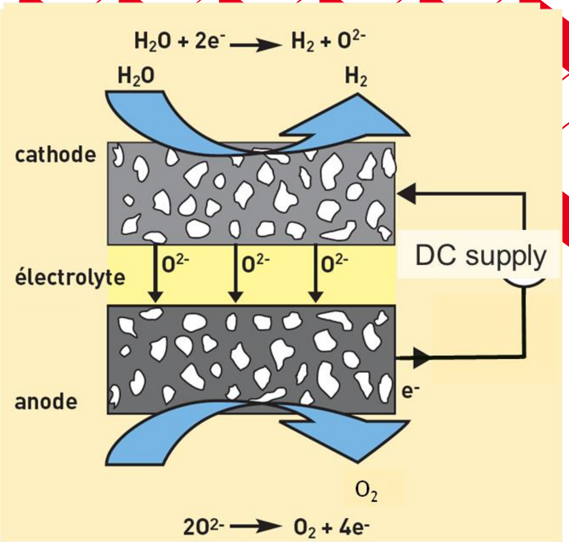
To improve performance

- Membrane as thin as possible (< 200 µm)
- Catalysts as active as possible (PGM)
- Decrease the use of Platinum Group Metals as catalysts
  - Higher catalytic activity by new catalyst compositions/ morphologies
  - Increased catalyst utilization by optimized electrode structures

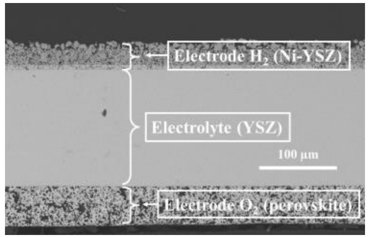
	Material
Cathode	Pt/C ~ 0.5 – 1 mg/cm²
Anode	Ir,Ru or IrOx ~ 2 mg/cm²
Separator / diaphragm	/
Electrolyte	Perfluorosulfonic acid PFSA (Nafion^R, Fumapem^R)
Bipolar plate	Ti sheet coated with Au or Pt
Porous transport layer / substrate	Pt coated sintered Ti fibers/particles for anode Sintered Ti or C cloth for cathode
Frame and sealing	polymer

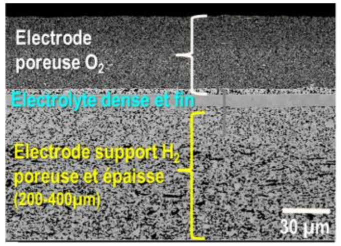
Solid Oxide Electrolysis (SOEL)

Sunfire :
2.4 MW SOEL



Charge carrier: O^{2-}
Electrolyte: solid ceramic
Usual operating temperature: 700-850°C
Usual operating pressure: 1 bar
(30 bar demonstrated at small scale)





To improve performance

- Thin electrolyte (< 10 µm)
- Electrode materials with improved conductivity
- Increase Durability

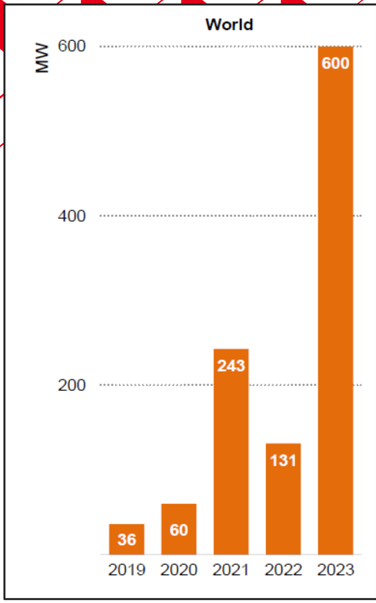
Component	Material
Cathode	Ni-YSZ
Anode Diffusion barrier layer	Perovskite: $(La_{0.60}Sr_{0.40})_{0.95}Co_{0.20}Fe_{0.80}O_{3-X}$ Gadolinia doped ceria
Separator / diaphragm	/
Electrolyte	YSZ (ZrO_2 doped with Y_2O_3)
Bipolar plate	Ferritic stainless steel, often coated with Co
Porous transport layer / substrate	Ni mesh on cathode side
Frame and sealing	Ceramic glass

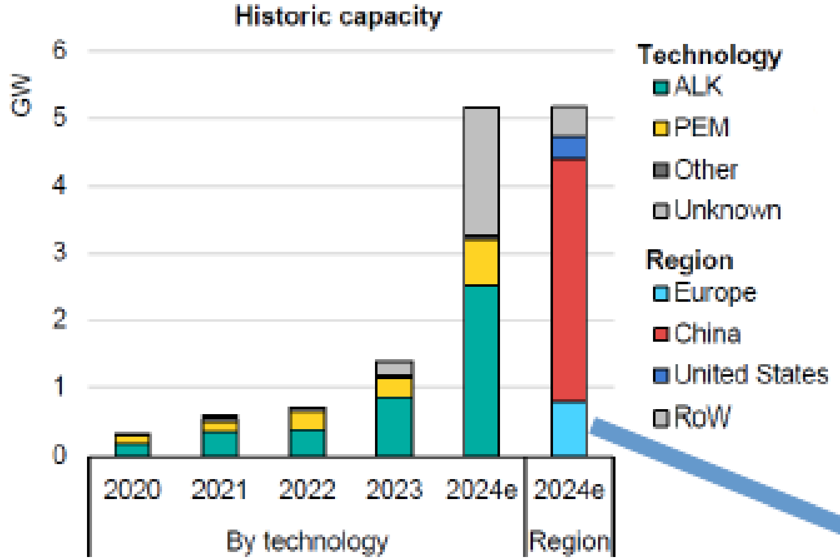
No noble catalysts
Some rare earth elements

Current status for electrolysis deployment

- 2024: could reach 5 GW
- 2023: ~ 1300 MW installed worldwide (capacity added in 2023 nearly matched cumulative global installed capacity up to 2022)
- Big AEL and PEMEL electrolysers already installed
- Biggest electrolysis plant installed = 260 MW in China
- Several electrolysers installed in EU
- Forecasts:

~200 GW by 2030, based on announced projects;
and even 420 GW including early-stage projects.

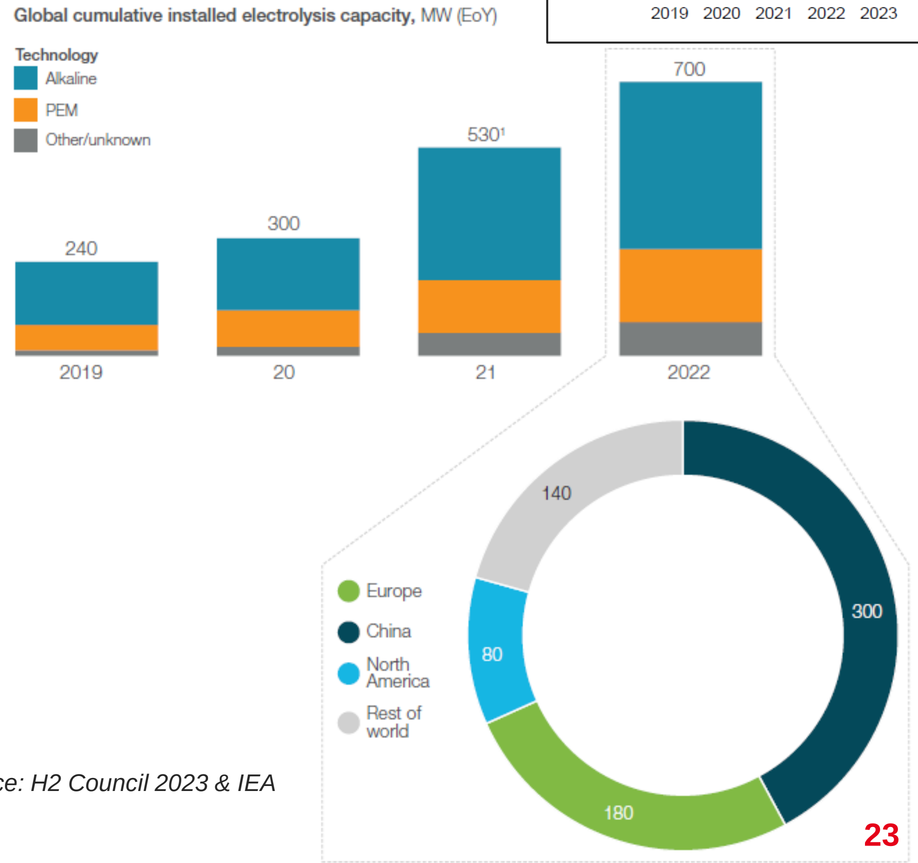




700MW in Europe

out of which the Clean Hydrogen JU projects:

- **Installed 43 MW**
- **Planned 400 MW**



Source: H2 Council 2023 & IEA 2024

Current status for electrolysis deployment

- In 12 years, electrolysers capacity increases 200x and funding per MW reduced 100x in EU

Source: Clean H2 JU

Current status for electrolysis deployment

- **SOEL now at multi- MW scale**

2014 1er SOEL system in operation at CEA

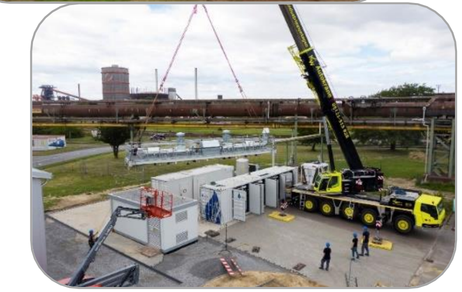
- 1 stack – 1 Nm^3/h of H_2 produced at 700°C
  Efficiency measured 84%LHV

2017 Sunfire Grinhy system installed in a steelmaking plant in Germany

- 150 kW - 40 Nm^3/h of H_2

2020 720 kW SOEL installed in August 2020 on the steel plant (Grinhy 2.0)

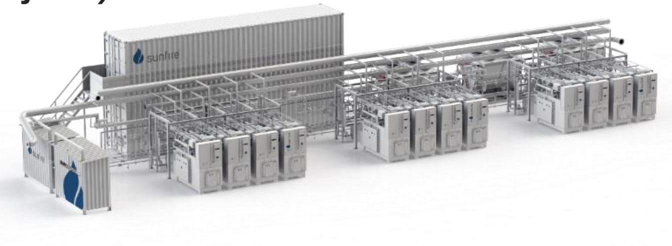
- produced 100t of H_2 until end of 2022



2023 Installation of a 2.6 MW SOEL unit in a renewable products refinery in Rotterdam (MULTIPLHY project)

- 60 kg/h of H2

Installation of a 4 MW SOEL unit at NASA-USA

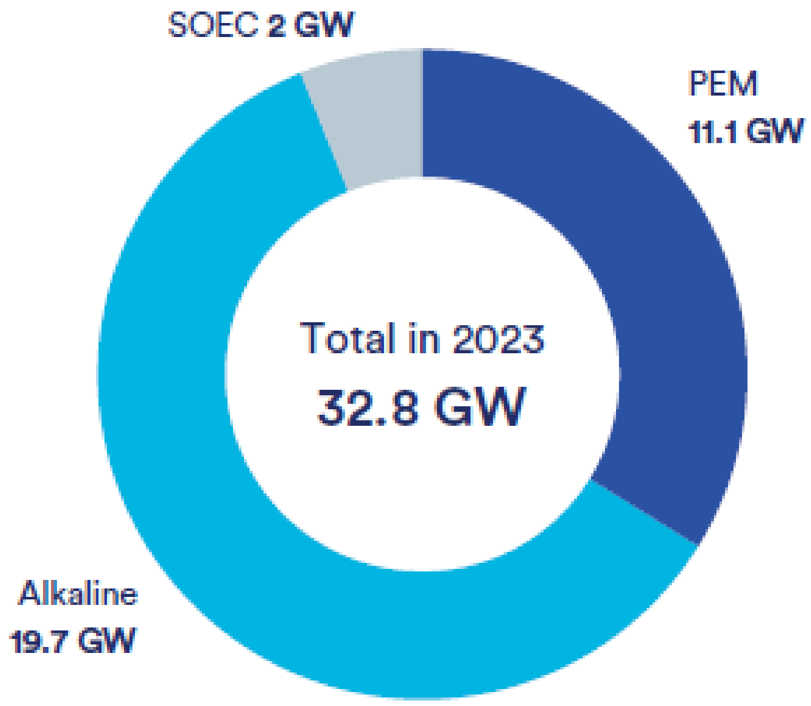


- All manufacturers currently have a MW-scale product in testing or in the design/manufacturing phase: Sunfire, BloomEnergy, Topsoe, FuelCellEnergy, Ceres, Solydera, Convion, Genvia
- Need to move to tens/hundreds of MW for commercial deployment
- Need for reliability on this scale

Current status for electrolysis manufacturing

- To install the needed electrolysers capacities ~ > 3000 GW by 2050
- ➔ **need for gigafactories for electrolysers manufacturing**
- In 2020 : production capacity for electrolysers just 2 GW globally
- ITM Power completed the world's 1st electrolyser Gigafactory in 2021 in the UK
- End 2022: 9 GW electrolysis production capacity worldwide
- Over the past 3 years, western electrolyser manufacturers have committed to building factories that can produce over 42 GW of electrolysers per year by 2030, for different technologies (AEL, PEMEL, SOEL)
- In France: 2 gigafactories started on AEL, 2 planned for PEMEL and SOEL
- In 2023: total manufacturing capacity = 32.8 GW: not limiting factor…

Figure 29: Global Nameplate Electrolyzer Manufacturing Capacity[58]



Source: G. Flis et al, Solid Oxide electrolysis, A technology status assessment, November 2023

Trend of development

- **Still some work on AEL, PEMEL, SOEL to meet the key performance indicators**

Table 2: KPIs for Alkaline Electrolysis (AEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	50	49	48
2	Capital cost	€/(kg/d)	1,250	1,000	800
		€/kW	600	480	400
3	O&M cost	€/(kg/d)/y	50	43	35
4	Hot idle ramp time	sec	60	30	10
5	Cold start ramp time	sec	3,600	900	300
6	Degradation	%/1,000h	0.12	0.11	0.1
7	Current density	A/cm^2	0.6	0.7	1.0
8	Use of critical raw materials as catalysts	mg/W	0.6	0.3	0.0

Table 3: KPIs for Proton Exchange Membrane Electrolysis (PEMEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	55	52	48
2	Capital cost	€/(kg/d) €/kW	2,100 900	1,550 700	1,000 500
3	O&M cost	€/(kg/d)/y	41	30	21
4	Hot idle ramp time	sec	2	1	1
5	Cold start ramp time	sec	30	10	10
6	Degradation	%/1,000h	0.19	0.15	0.12
7	Current density	A/cm^2	2.2	2.4	3
8	Use of critical raw materials as catalysts	mg/W	2.5	1.25	0.25

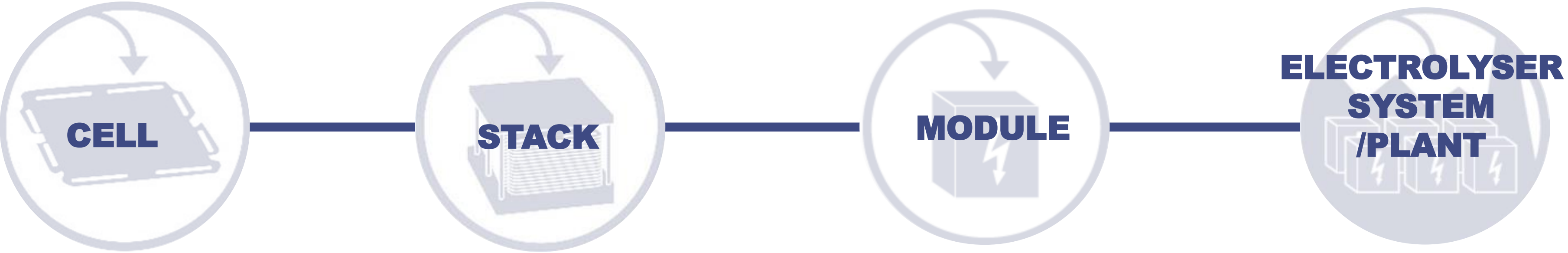
Table 4: KPIs for Solid Oxide Electrolysis (SOEL)

No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity Heat demand @ nominal capacity	kWh/kg	40 9.9	39 9	37 8
2	Capital cost	€/(kg/d) €/kW	3,550 2,130	2,000 1,250	800 520
3	O&M cost	€/(kg/d)/y	410	130	45
4	Hot idle ramp time	sec	600	300	180
5	Cold start ramp time	h	12	8	4
6	Degradation @ U_{TN}	%/1,000h	1.9	1	0.5
7	Current density	A/cm^2	0.6	0.85	1.5
8	Roundtrip electrical efficiency	%	46	50	57
9	Reversible capacity	%	25	30	40

Source: SRIA EU Feb 2022

Trend of development

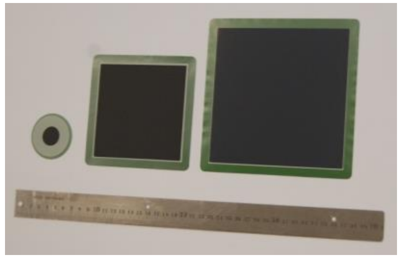
- **For SOEL: Activities on the whole value chain**



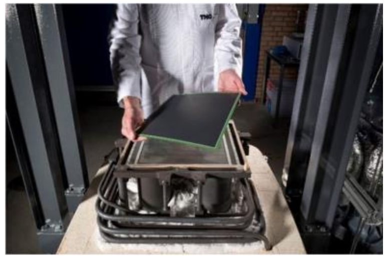
CELL

- Materials/microstructures
- Processes
- Cells architectures
- Upscaling: 100 ➔ 200 cm^2 at CEA, even 900 cm^2 at TNO

CEA



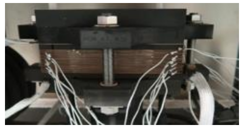
TNO

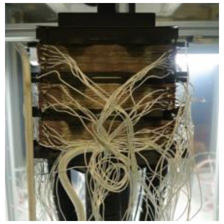


STACK

- Fluidic, thermal management
- Sealings, coatings
- Mechanical behavior
- Manufacturing and Assembly Processes
- Upscaling: 25 cells of 100 cm^2 ➔ 75 cells of 200 cm^2 at CEA, even 350 cells at FCE

CEA





Fuel Cell Energy

SOFC Stack
7 kW DC Power Generation
36 kW DC / 25 kg H_2/day electrolysis
350 cells, 17" height

MODULE

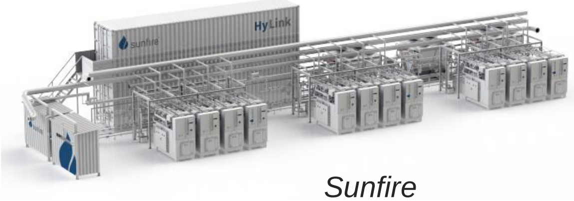
- Upscaling: 1 stack ➔ 4 stacks at CEA, even much more in large modules like Sunfire

CEA

Sunfire

ELECTROLYSER SYSTEM /PLANT

- Multi-stack multi-modules assembly
- Mutualization of BoP components
- Automation and control



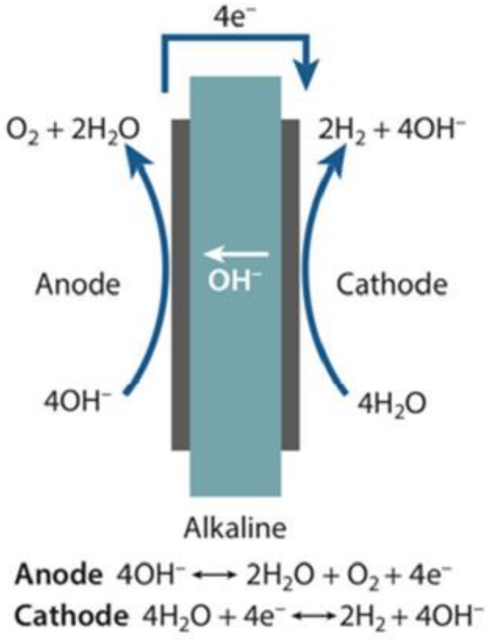
Sunfire

Supported by modelling and simulation, techno-economic and life cycle assessment

Trend of development

- **Work on emerging technologies: AEMEL**

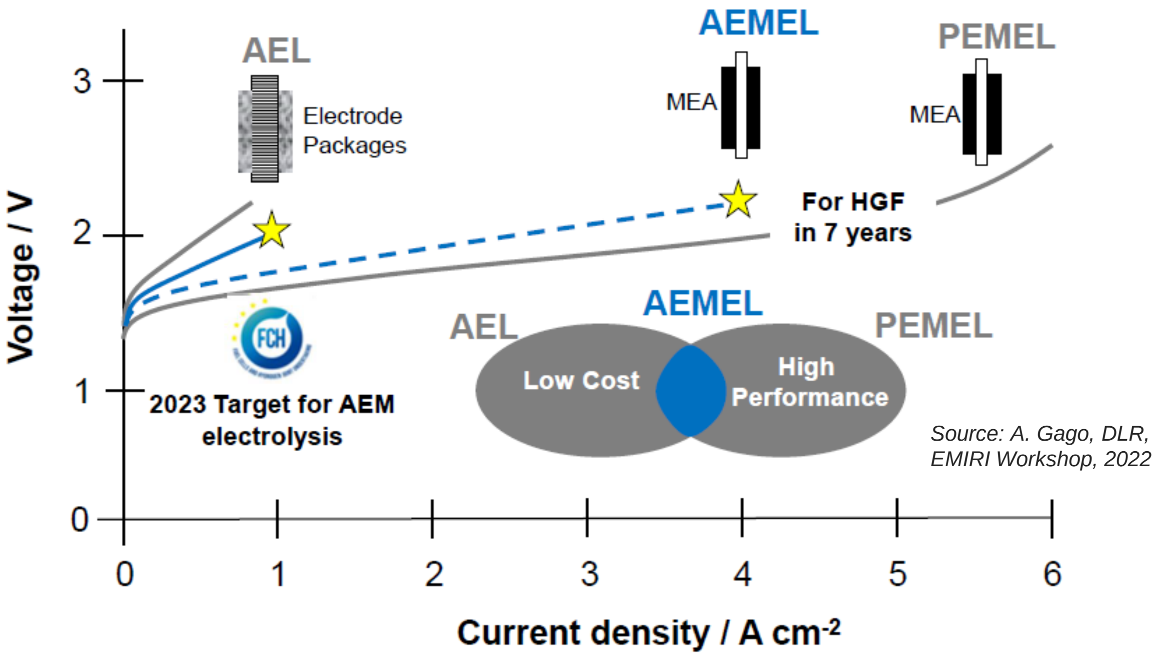
Source: K. Ayers et al., Rev. Chem. Biomol. Eng. 10 (2019) 219-239



Charge carrier: OH^-
Electrolyte: solid - polymer

Usual operating temperature: 40-60°C
Usual operating pressure: 1-30 bars

- **Interest of AEMEL**
  - Higher performance than AEL
  - Lower catalyst loading than PEMEL



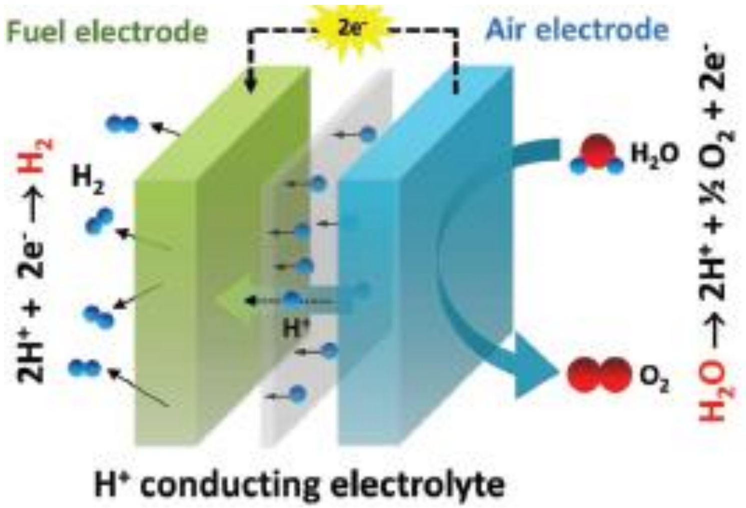
Source: A. Gago, DLR, EMIRI Workshop, 2022

	Unit	SoA	Targets	
		2020	2024	2030
PEMEL	mg/W	2.5	1.25	0.25
AEMEL	mg/W	1.7	0.4	0

- But still some work to improve durability

Trend of development

- **Work on emerging technologies: PCCEL**



Source: S. Choi, Energy Environ. Sci (2019) 12, 206

Charge carrier: H^+
Electrolyte: solid - ceramic

Usual operating temperature: 500-700°C
Usual operating pressure: 1 bar – pressurized operation under development (5 bar)

- **Interest of PCCEL**
  - Dry H_2 produced
  - Lower T than SOEL: advantage for durability and cost
  - But still a lot of work needed to increase performance and stability of materials
  - Before upscaling feasible

2.4. Comparison of the different technologies

Comparison based on a few indicators

- **Selected indicators:**
  - TRL
  - Carbon footprint
  - Energetic efficiency
  - Cost of H_2 produced
- Could also consider other indicators:
  - Water consumption
  - Use of Critical Raw Materials (CRM)
- Other indicators could be added when maturity and REX on the different technologies increase

Hydrogen production routes

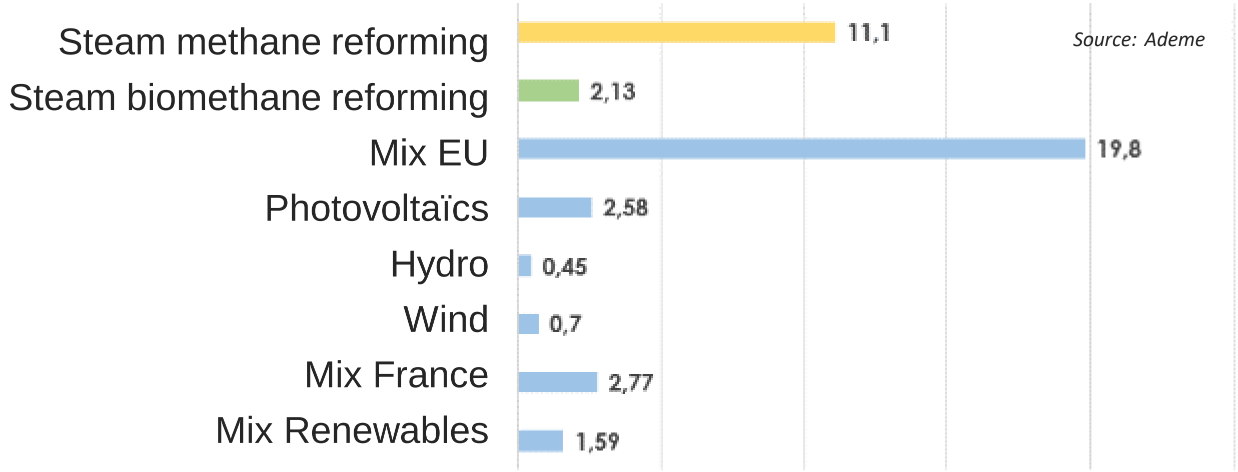
Electrolytic processes: split with electricity

- Synthesis based on a few indicators
  - Impact of electricity (source and price) on C footprint and cost of H2 produced

	TRL	C footprint (kg_{CO2e}/kg_{H2})	Energetic efficiency (LHV)	Cost ($/$kg_{H2}$)
AEL	9	Depends on electricity source	69%	Depends on electricity price: can be between 3.5 and 10
PEMEL	8		69%	
SOEL	7		89%	
AEMEL	4		69%	
PCCEL	3		80%	?

Carbon footprint

- **Carbon footprint ($kg_{CO2}e/kg_{H2}$):** between <1 and ~20 !

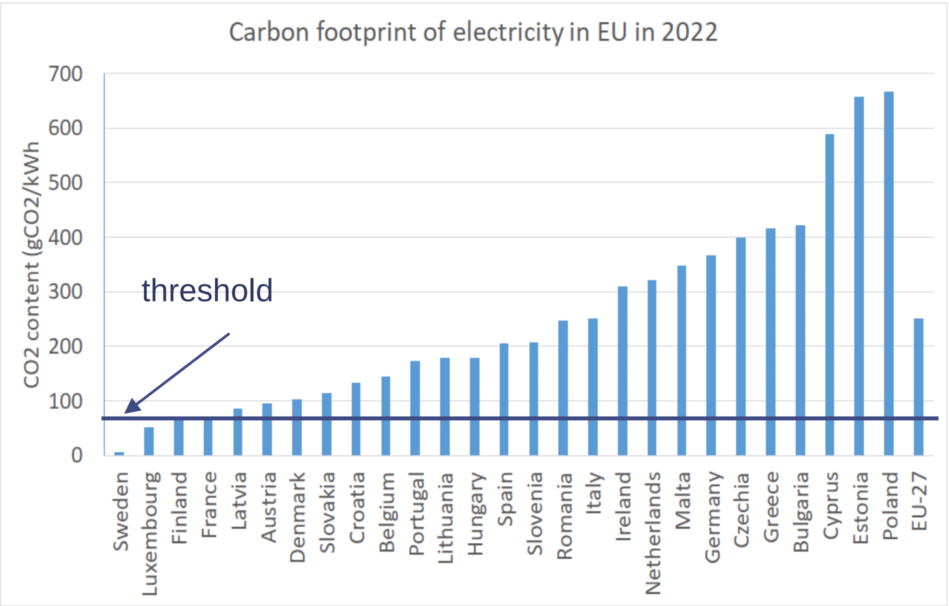


Carbon footprint:

- Depends on the process
- For electrolysis: depends on electricity origin
  - below 2.6 kg_{CO2}/kg_{H2} if renewable or nuclear
  - As high as 19.8 kg_{CO2}/kg_{H2} considering EU electricity mix = worst than reference SMR process !

Low carbon hydrogen : **<3,38 kg_{CO2e}/kg_{H2}**

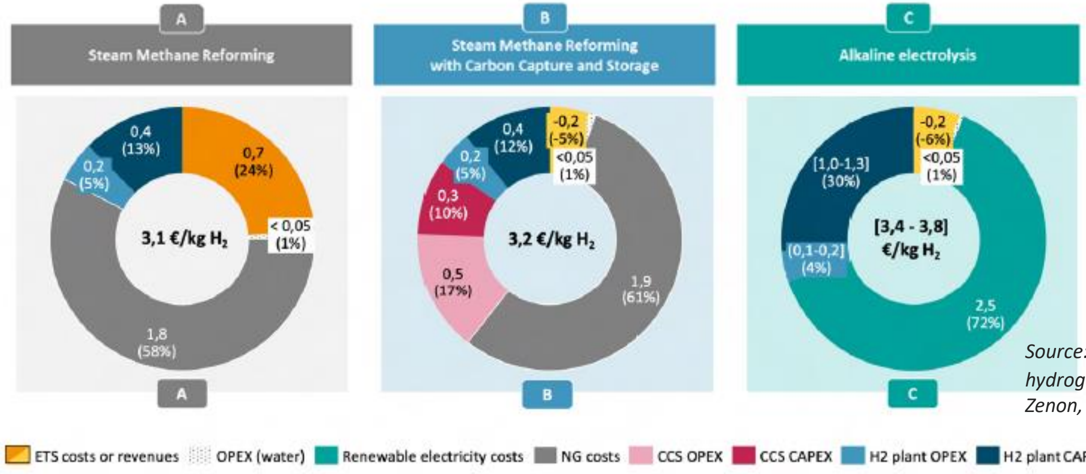
- It requires electricity C content **< 67 g_{CO2}/kWh**
- Only 4 countries in EU have an electricity mix meeting this threshold



Source: European Environment agency

Hydrogen cost

- **Impact of feedstock price (methane or electricity)**
  - Feedstock accounts for more than 60% in the H_2 cost

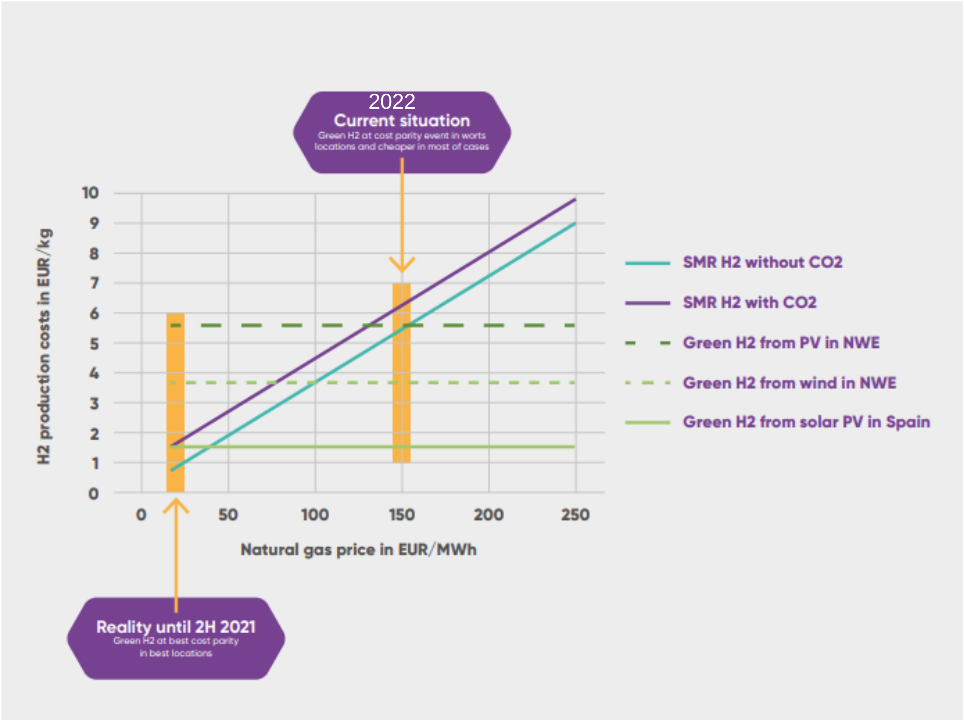


Source: the hydrogen series – Zenon, Dec 2023

Price of natural gas for reference Steam Methane Reforming process:

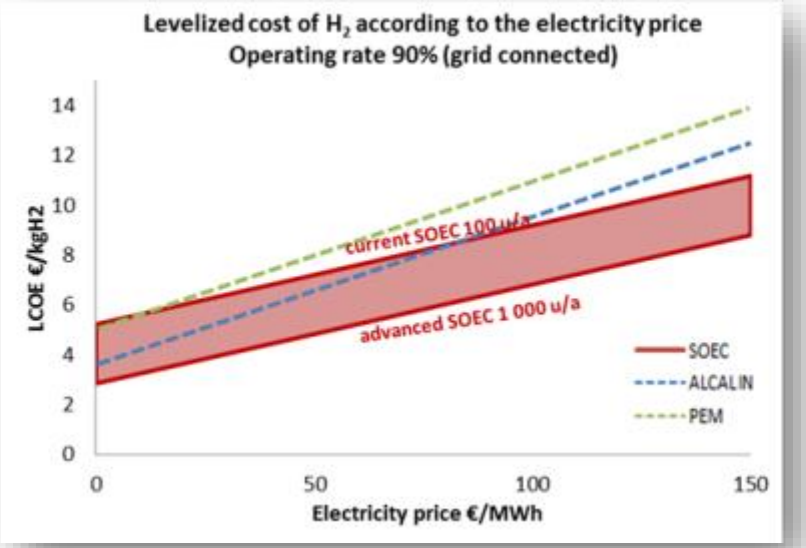
- Impact on H_2 cost: Proportionality law
  - from less than 1 up to 6 €/kg

Figure 15: COMPARISON OF RENEWABLE AND FOSSIL FUEL-BASED HYDROGEN PRODUCTION COSTS BEFORE AND AFTER THE RECENT SPIKE IN ENERGY PRICES.
Source: HYDROGEN EUROPE. 2022



Price of electricity:

- Impact on electrolytic H_2 cost
  - If electricity 2 times more expensive, H_2 50% more expensive
  - H_2 produced with higher efficiency technology (SOEL) less sensitive



Source: J. Mougin, WHEC2014
M. Reytier, et al., IJHE 40/35 (2015) 11370–11377

Hydrogen cost

- Other key parameters to be taken into account, optimised
  - CAPEX, efficiency, load factor, lifetime

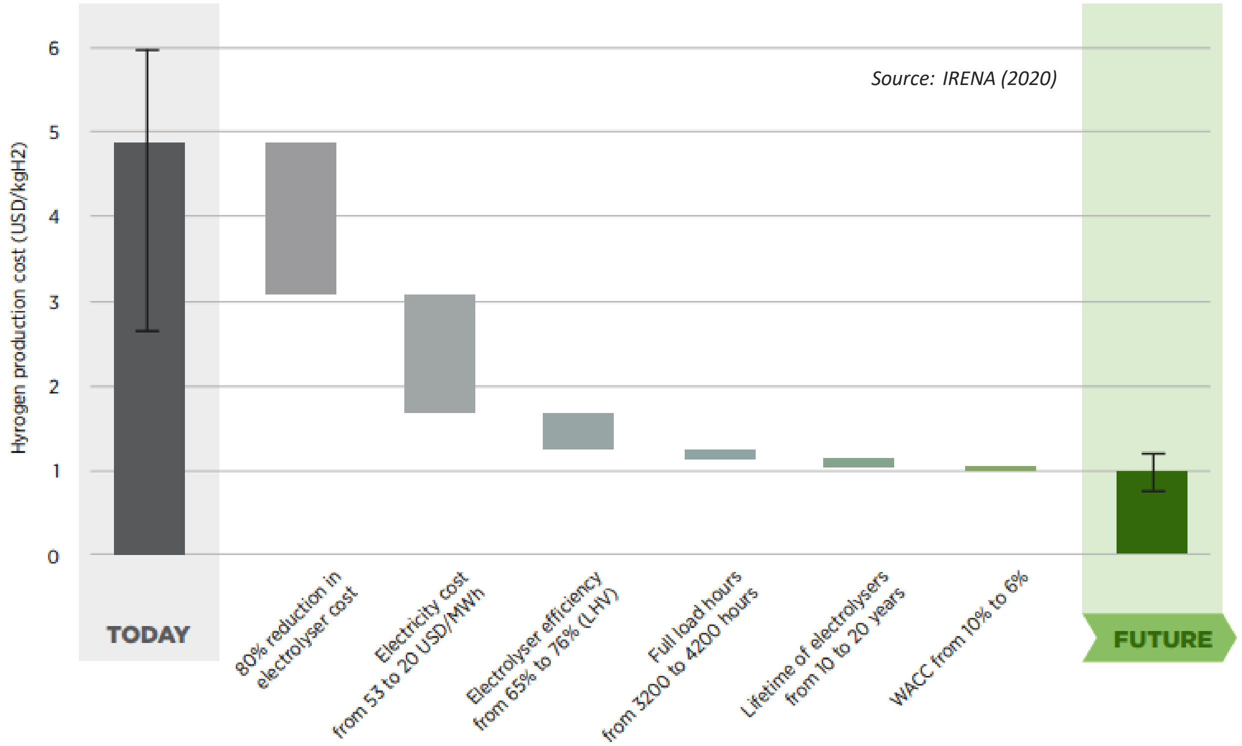


Exhibit 14 | Renewable hydrogen from electrolysis production cost scenarios[5], USD/kg hydrogen

Cost of renewable hydrogen with varying LCOE and load factors
USD/kg H_2

< USD 2/kg · USD 2-3/kg · USD 3-4/kg · > USD 4/kg · Viable medium-term (<2030)

LCOE \ Capex electrolyser	USD 750/kW					USD 500/kW					USD 250/kW				
UDD 0/MWh	5.7	2.8	1.9	1.4	1.1	4.2	2.1	1.4	1.1	0.9	2.8	1.4	0.9	0.7	0.6
USD 10/MWh	6.1	3.3	2.4	1.9	1.6	4.7	2.6	1.9	1.5	1.3	3.2	1.9	1.4	1.2	1.0
USD 20/MWh	6.6	3.8	2.8	2.4	2.1	5.2	3.0	2.3	2.0	1.8	3.7	2.3	1.9	1.6	1.5
USD 30/MWh	7.1	4.2	3.3	2.8	2.5	5.6	3.5	2.8	2.5	2.2	4.2	2.8	2.3	2.1	2.0
USD 40/MWh	7.5	4.7	3.8	3.3	3.0	6.1	4.0	3.3	2.9	2.7	4.6	3.2	2.8	2.6	2.4
USD 50/MWh	8.0	5.2	4.2	3.7	3.5	6.5	4.4	3.7	3.4	3.2	5.1	3.7	3.2	3.0	2.9
USD 100/MWh	10.3	7.5	6.5	6.1	5.8	8.9	6.7	6.0	5.7	5.5	7.4	6.0	5.6	5.3	5.2
Load factor	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%

SOURCE: McKinsey

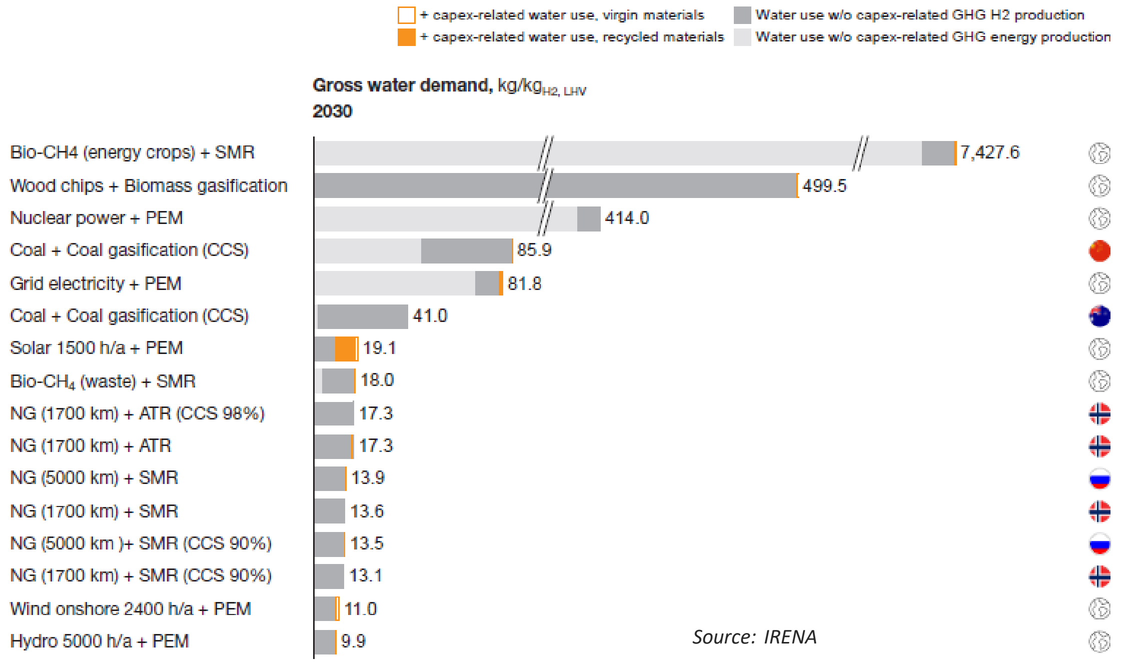
Clean Hydrogen Production Tax Credit (45V) up to $3/kg

Carbon Intensity (kg CO_2 per kg H_2)	Max Tax Credit ($/kg H_2)*
4–2.5	$0.60
2.5–1.5	$0.75
1.5–0.45	$1.00
0.45–0	$3.00

Interest of support mechanisms: Inflation reduction Act in the USA, European Hydrogen Bank

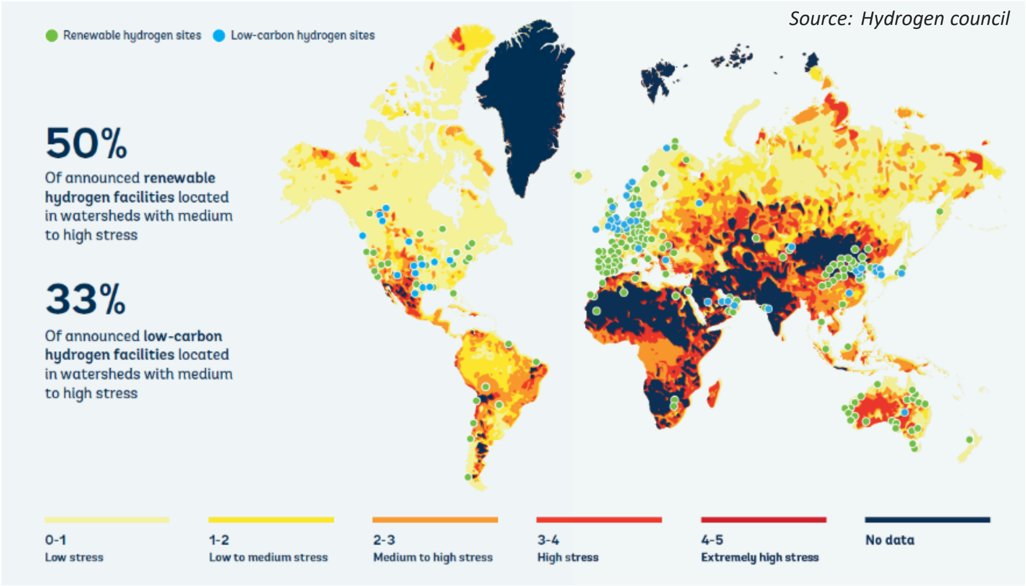
Water consumption

- Water consumption for all H_2 production technologies
- Consumption varies between 10 to 19 kg of water per kg of H_2 for low carbon processes.
- Water consumption indicated for nuclear power is significant but a large part of the water is released into groundwater
- Water consumption can be significant for biomass technologies either in the production stage or in the process
- Necessary to well define the boundaries
- SMR:
  - Stoichiometry: 4.5 L water / kg_{H2}
  - Total system: 13 L water / kg_{H2}
- Electrolysis:
  - Stoichiometry: 9 L water / kg_{H2}
  - Total System: up to 18 L water / kg_{H2}
- Risk for large scale H_2 deployment: areas where low cost electricity are areas with water scarcity



Source: Hydrogen Council, LBST

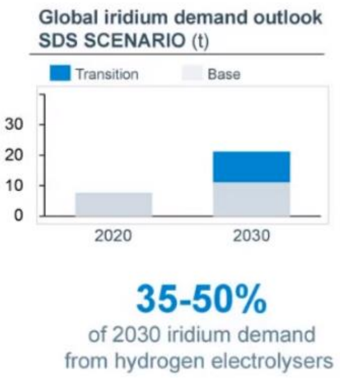
Figure 18: Announced low-carbon and renewable hydrogen locations, and 2020 watershed stress



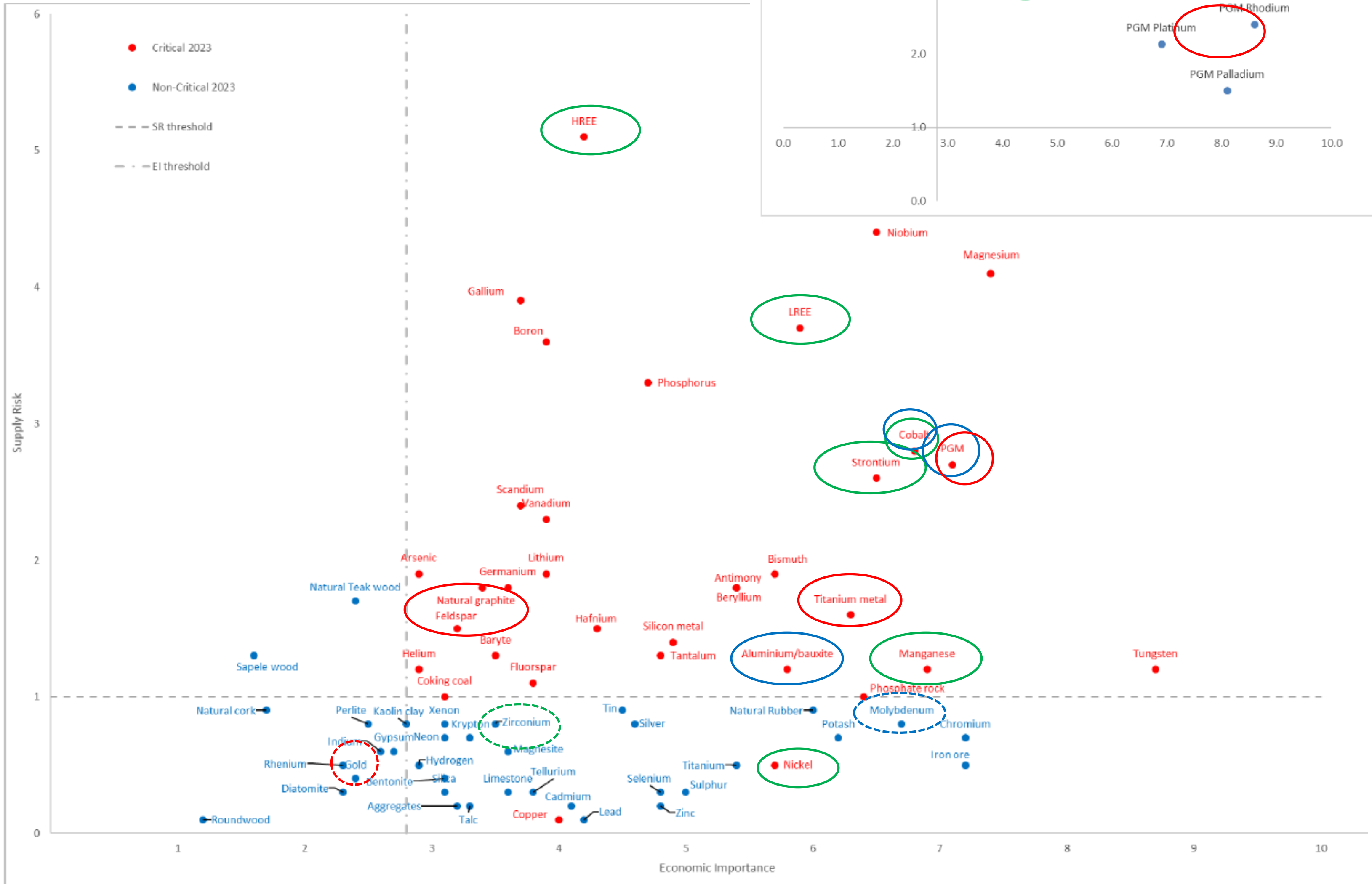
Use of Critical Raw Materials

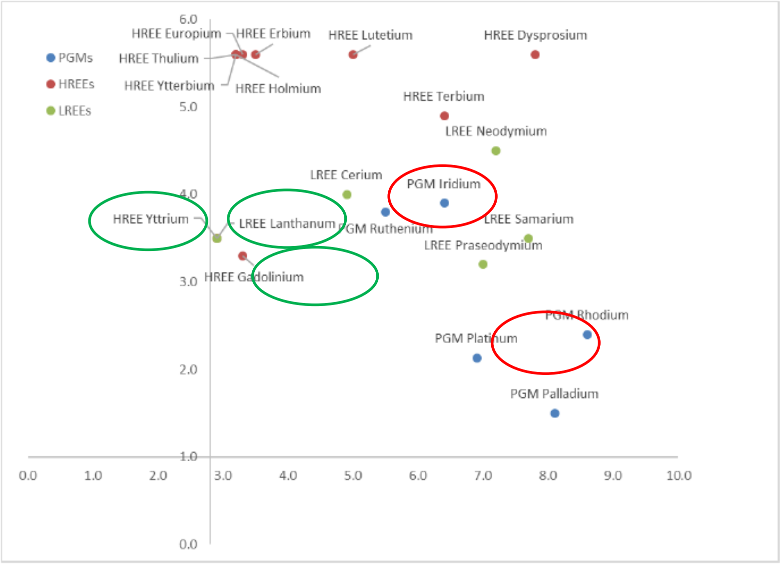
AEL PEMEL SOEL

- Low amounts per kW for most of them
- ➔ Needs to be taken into account for the analysis
- But will become more critical with the increase of the number/size of electrolysers…
- In 2030, PEM electrolysers could ask for 35-50% of global Ir demand



Source: KU Leuven, Eurometaux, Nov 2022





Source: EU CRM list (2023)

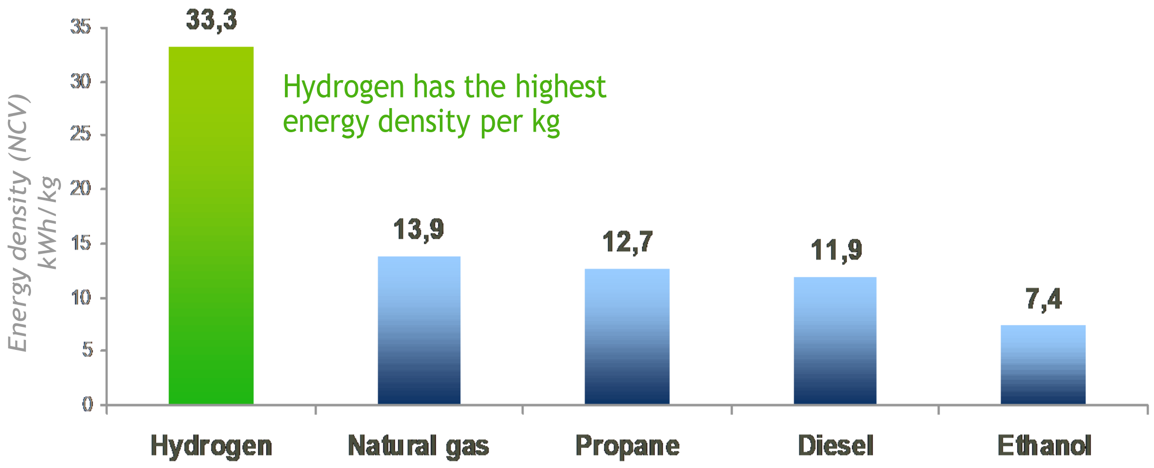
Use of Critical Raw Materials

- **Needs:**
  - Decrease the amount of PGM catalysts
  - Find PGM-free catalysts
  - Replace Co containing materials by new ones without
- **Means at material scale:**
  - Use of high surface area supported catalysts, e.g. titanium or tin oxide supports (Babic, 2017).
  - Increase the catalyst surface area through improved catalyst manufacturing techniques, e.g. using nanostructured thin film catalysts.
  - Use thinner layer of coating material, for example through atomic layer deposition.
  - Reengineer the electrode concept. For example, support nanoparticles of iridium on high conductive semi-conductor oxides, alloy iridium to other transition metals, change the morphology of the electrode and shape the nanoparticle of Ir.
  - Recycling: upstream during manufacturing (scrap), or downstream (end of life)
- **Means at system scale:**
  - Extension of the use of equipment: extend the lifetime of the electrolyser → same amount of material allocated over higher cumulated H2 production
  - or increasing its performance: achieving a higher current density of the stack → smaller area needed for the same production of hydrogen (and less material per kg of H2)

3. Hydrogen storage / transport

Hydrogen storage

- Hydrogen: a few figures



Source: McPhy Energy

- **H_2 offers an excellent energetic content per kg (33 kWh/kg),**
- **higher than any other fuel (Methane, natural Gas…).**
- **But a low volumic density…**

33,3 kWh/kg or 3 kWh/Nm^3 or 120 MJ/kg

1 Toe of hydrogen = 348 kg

1 Toe (ton oil equivalent) = 41,8 GJ = 11,6 MWh
1kWh = 3,6 MJ

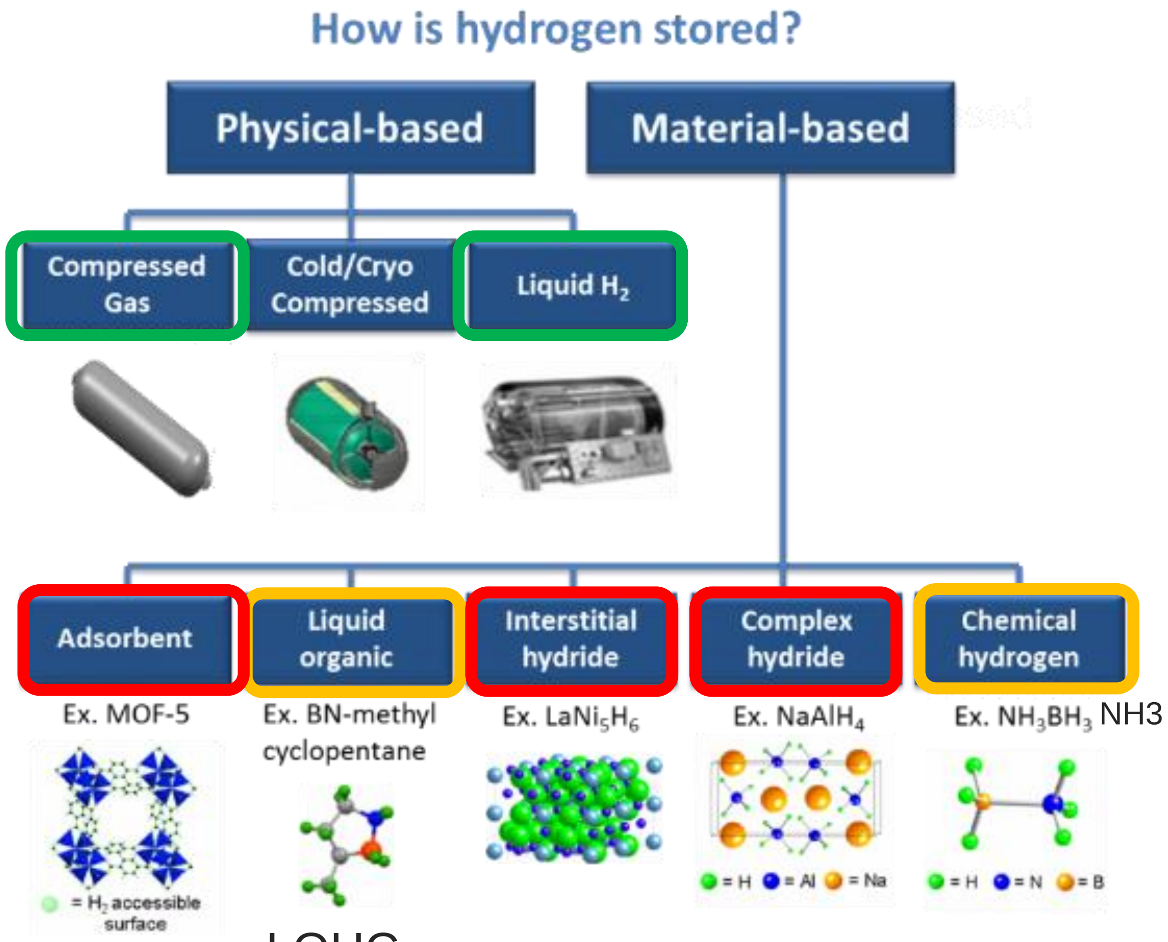
Volume density (kgH_2/m^3)	
Gaseous H_2 (CNTP: Patm-0°C)	0.09
Gaseous H_2 (700 bar)	40
Liquid H_2 (Patm)	71
Solid (MgH_2)	106

Compression or state transformation when a better volumic (and massic) density is needed, for storage and transport of large quantities, or use (long-haul mobility for instance)

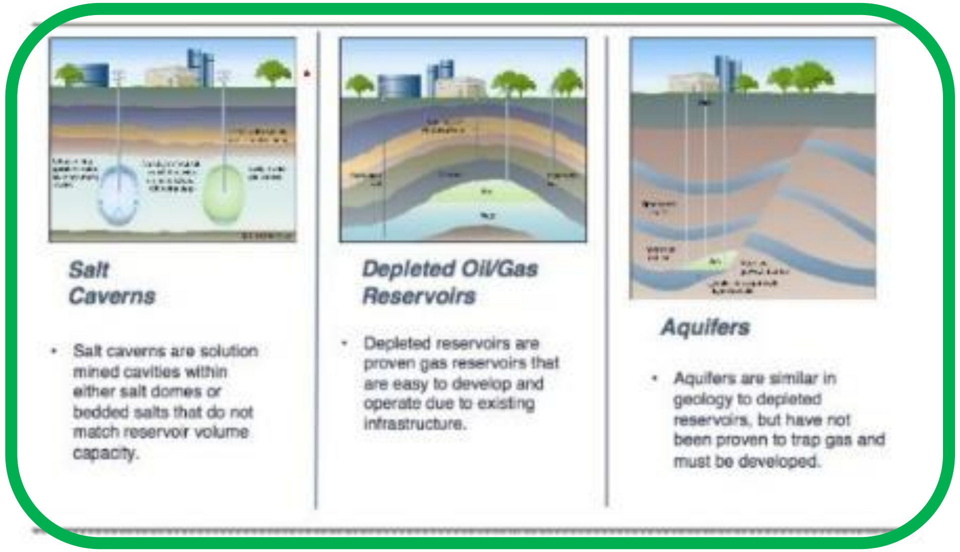
Hydrogen storage

- Several types of storage

Maturity scale



LOHC
(liquid organic hydrogen carriers)



Hydrogen storage

- **Hydrogen storage options**
  - The storage technology needs to be selected as a function of the application (size & duration of storage, use of hydrogen) and of the location

	Gaseous state				Liquid state			Solid state
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	LOHCs	Metal hydrides
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: BloombergNEF. Note: [1] Benchmark levelized cost of storage (LCOS) at the highest reasonable cycling rate (see detailed research for details). LOHC – liquid organic hydrogen carrier.

Extra cost due to state transformation needed: consumes energy and requires installations

Hydrogen transport and distribution

- **Hydrogen transport options**
  - The transport option needs to be selected as a function of the application, the distance and the location

<0.1 USD/kg | 0.1–1 USD/kg | 1–2 USD/kg | >2 USD/kg

		Costs				
		Distribution		Transmission		
		0–50 km	51–100 km	101–500 km	>1,000 km	>5,000 km
Pipelines[1]	Retrofitted	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/Subsea transmission pipelines	N/A
	New	City grid	Regional distribution pipelines	Onshore transmission pipelines	Onshore/Subsea transmission pipelines	N/A
Shipping	LH_2	N/A	N/A	N/A	LH_2 ship	LH_2 ship
	NH_3[2]	N/A	N/A	N/A	NH_3 ship	NH_3 ship
Trucking	LOHC[2]	N/A	N/A	N/A	LOHC ship	LOHC ship
	LH_2 trucking	Distribution truck LH_2	Distribution truck LH_2	Distribution truck LH_2	N/A	N/A
	Gaseous trucking	Distribution truck CH_2[3]	Distribution truck CH_2[3]	Distribution truck CH_2[3]	N/A	N/A

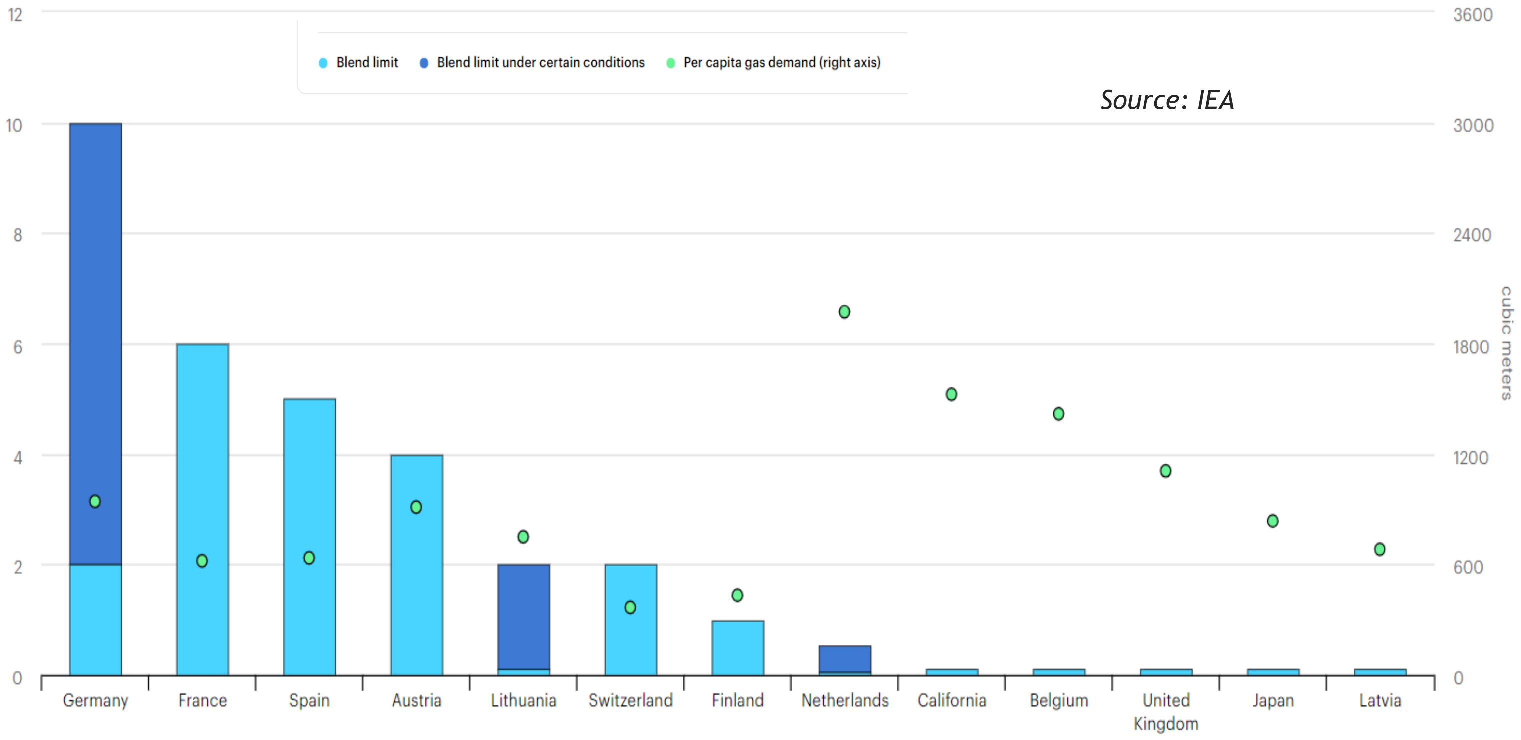
1. Assuming high utilization
2. Including reconversion to H_2; LOHC cost dependent on benefits for last mile distribution and storage
3. Compressed gaseous hydrogen

- **Hydrogen pipelines are cheaper than electricity transmission lines**
  - Can transport 10 times the energy at one-eighth the cost associated with electricity transmission line

Source: Hydrogen Insights Report, Hydrogen Council, 2021

Hydrogen transport and distribution

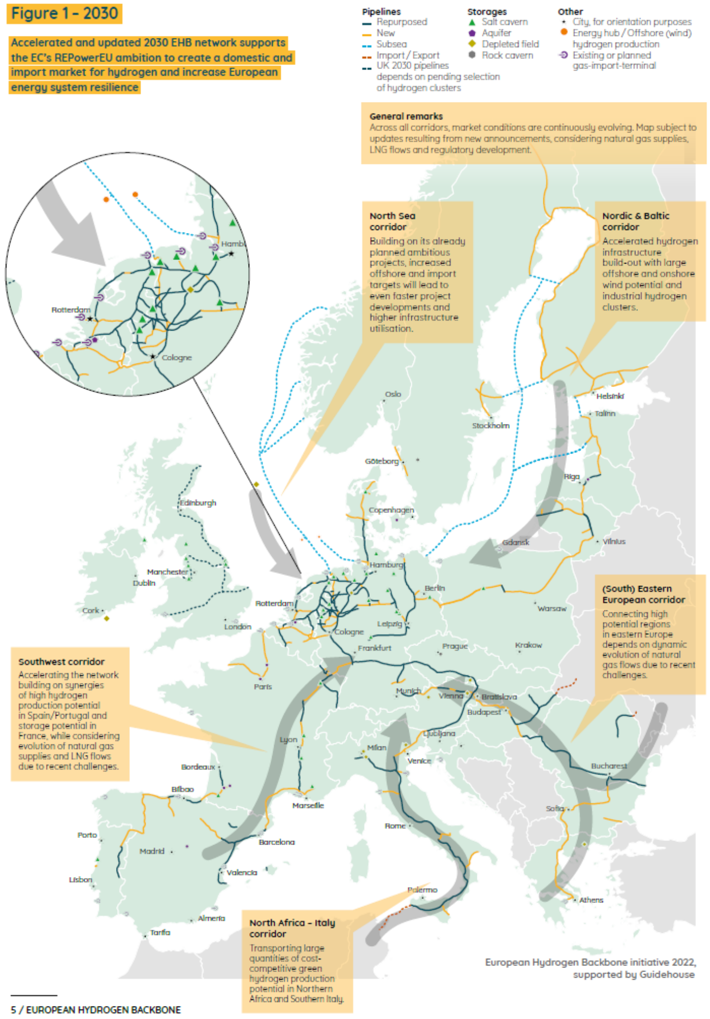
- Growing interest in using H_2 blend in natural gas
  - Maximum threshold depends on countries
  - Validations performed up to 20%



- Pure H_2 pipelines exist: ~ 2500 km in USA, ~ 2000 km in Europe, dedicated to industrial purposes

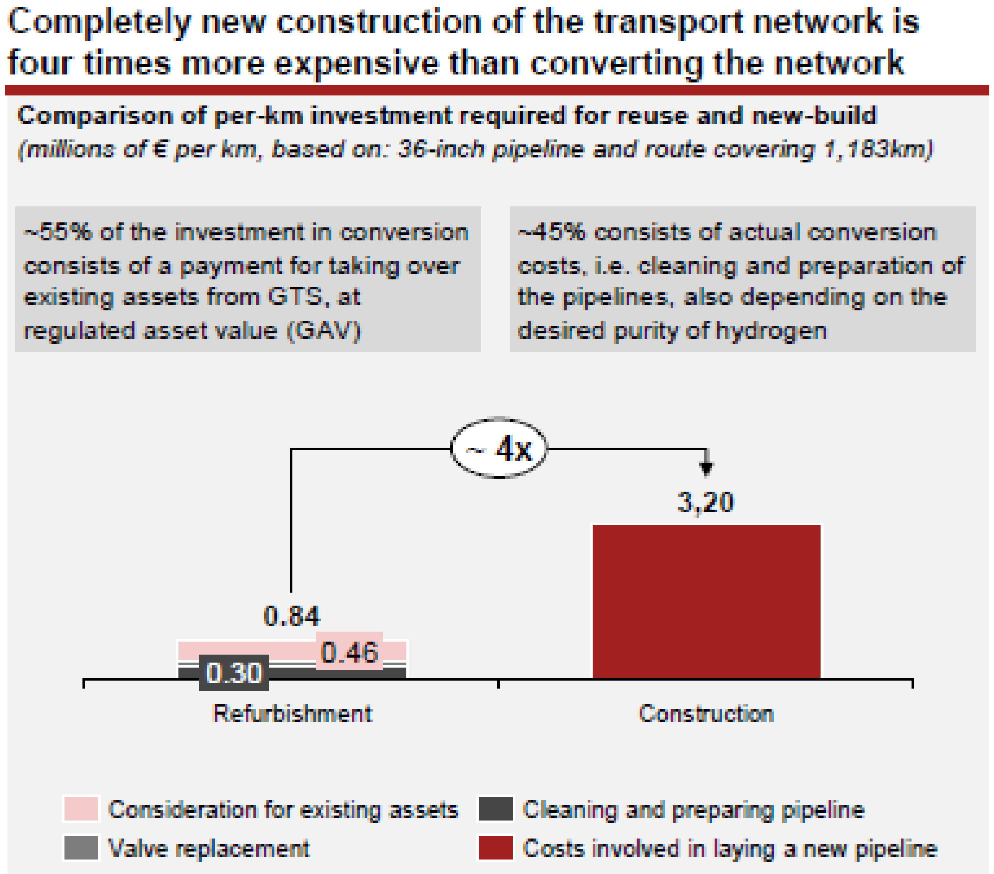
Hydrogen transport and distribution

- European Hydrogen Backbone plan for 2040: 53000 km
  - 69% retrofitted
  - 31%: new



Source: EHB

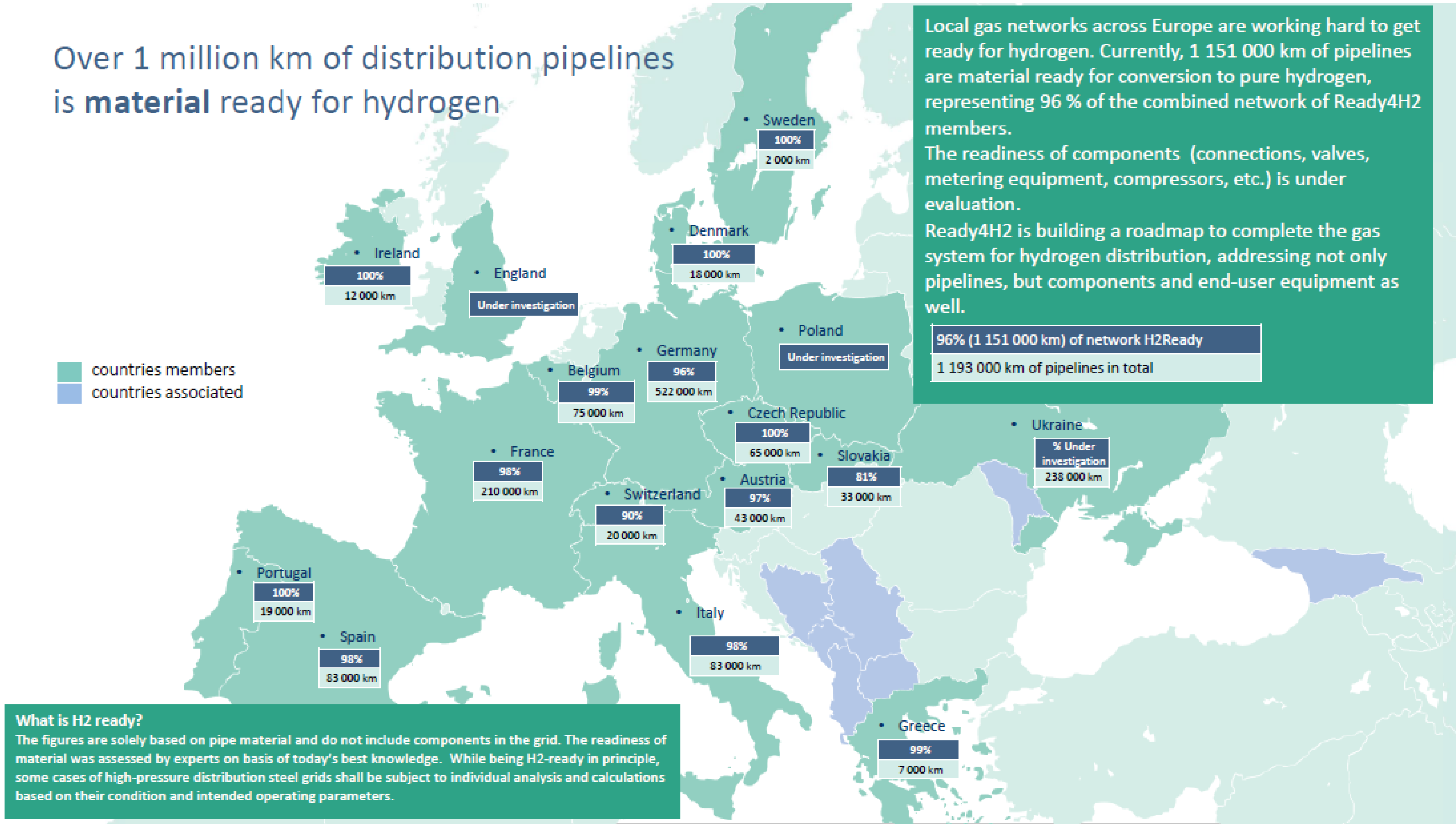
- Retrofitting of transport network more cost efficient
  - Investment 4X expensive with new pipes
  - Cost to transport 1kg H_2 over 1000 km with 900 mm pipe
    - ~ 0,11 € with retrofitted pipe
    - ~ 0,30 € with new pipe



Source: Hyway

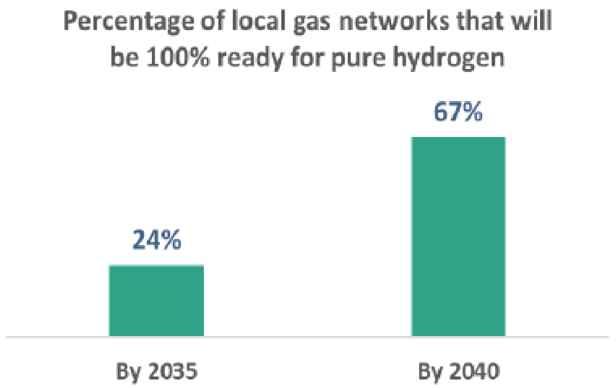
Hydrogen transport and distribution

- > 1 million km distribution pipelines material ready for H2



Source: ReadyforH2

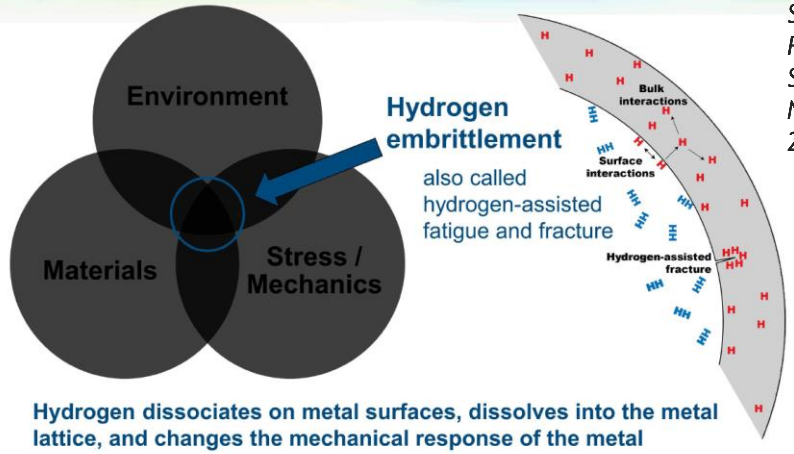
- Distribution network readiness plan for pure H_2 (including all components)



*The network readiness includes the readiness of the pipe material, all components (connections, valves, metering equipment, compressors, etc.) and the end user equipment

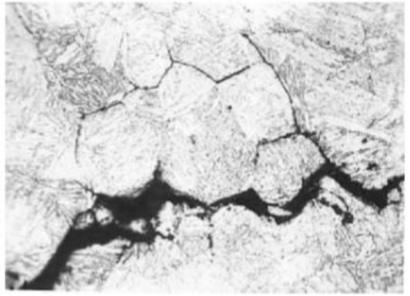
Hydrogen transport and distribution

- **Hydrogen embrittlement (HE) issues**

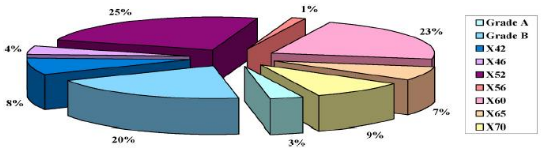


Source: J. Ronevich, Sandia Nat. Lab, 2019

- On hydrogen tanks (metallic parts)
- On pipelines



Barthélémy, 1st ESSHS, 2006



- This issue does not preclude material from usage but necessitates proper design
  - Material selection:
    - Ni, C content, other addition elements (Ti) in steels
    - A wide range of steels have the same fatigue crack growth in gaseous hydrogen
    - Materials less/not sensitive to HE: Cu, Al, Stainless steels
  - Welding techniques:
    - Many welds behave the same way as bulk materials

- **Network transport heterogeneous**
  - Various grades (C-Mn), with different mechanical behaviours
  - Different ages: 80 years to recent
  - Importance of operating window: P, T
    - Effect of pressure level
      - Not much on fatigue crack growth
      - Visible on fracture resistance
  - Mitigation strategies can exist
    - Coatings
    - Impurities

Source: Pluvinage (2021)

4. Nuclear hydrogen

Interest of hydrogen production using nuclear energy

- **To decarbonize the current hydrogen consumption of 97 million tonnes:**
  - would require 4 850 TWh of low-carbon electricity
- **In the future: > 400 million tonnes in 2050**
  - will require 20 000 TWh of low-carbon electricity
- **➔ Need to have huge amounts of low carbon electricity**

■ < USD 2/kg ■ USD 2-3/kg ■ USD 3-4/kg ■ > USD 4/kg ⬚ Viable medium-term (<2030)

LCOE	Capex electrolyser USD 750/kW					USD 500/kW					USD 250/kW				
UDD 0/MWh	5.7	2.8	1.9	1.4	1.1	4.2	2.1	1.4	1.1	0.9	2.8	1.4	0.9	0.7	0.6
USD 10/MWh	6.1	3.3	2.4	1.9	1.6	4.7	2.6	1.9	1.5	1.3	3.2	1.9	1.4	1.2	1.0
USD 20/MWh	6.6	3.8	2.8	2.4	2.1	5.2	3.0	2.3	2.0	1.8	3.7	2.3	1.9	1.6	1.5
USD 30/MWh	7.1	4.2	3.3	2.8	2.5	5.6	3.5	2.8	2.5	2.2	4.2	2.8	2.3	2.1	2.0
USD 40/MWh	7.5	4.7	3.8	3.3	3.0	6.1	4.0	3.3	2.9	2.7	4.6	3.2	2.8	2.6	2.4
USD 50/MWh	8.0	5.2	4.2	3.7	3.5	6.5	4.4	3.7	3.4	3.2	5.1	3.7	3.2	3.0	2.9
USD 100/MWh	10.3	7.5	6.5	6.1	5.8	8.9	6.7	6.0	5.7	5.5	7.4	6.0	5.6	5.3	5.2
Load factor	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%

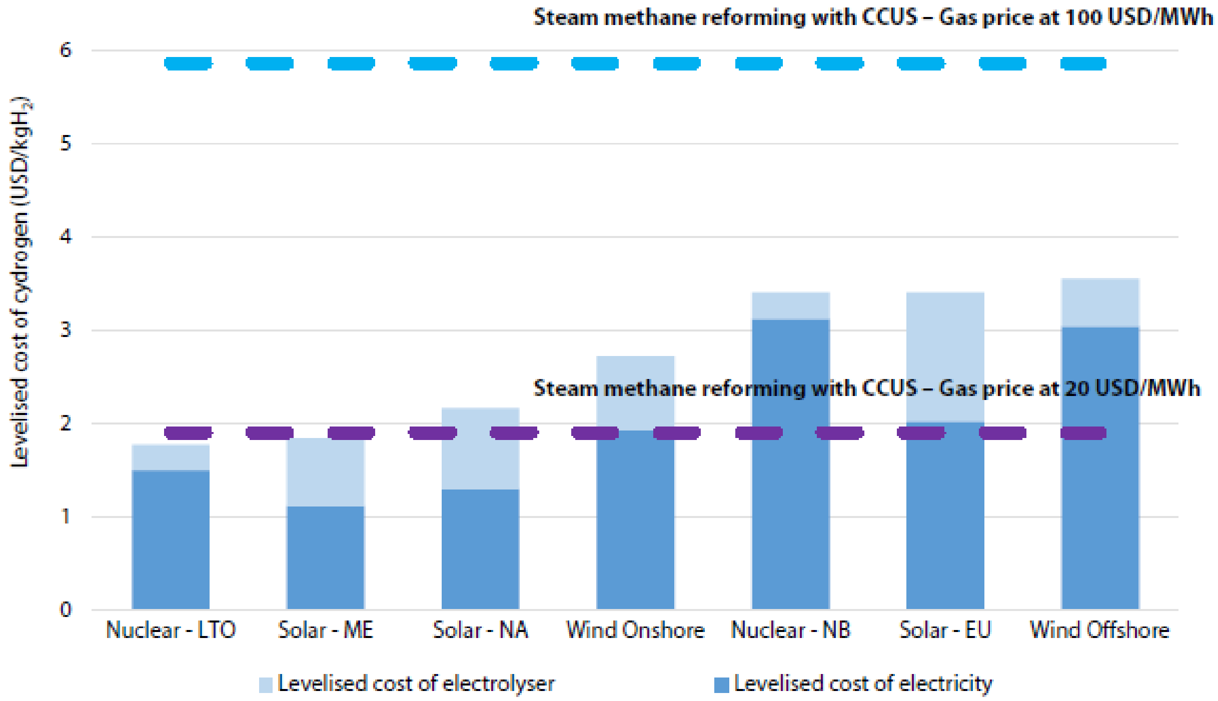
- **Nuclear electricity:**
  - Low-carbon content
  - Base load production (no fluctuation compared to renewable electricity sources)

  ➔ possibility to operate the electrolyser at high load factor = beneficial for ROI
  - High power reactors: source of a lot of electricity at a same place, dispatchable

  ➔ possibility to minimize the transport cost

- **Nuclear heat available:**
  - Interest for SOEL technology
  - Also for thermochemical cycles…

Interest of coupling nuclear energy and electrolysis



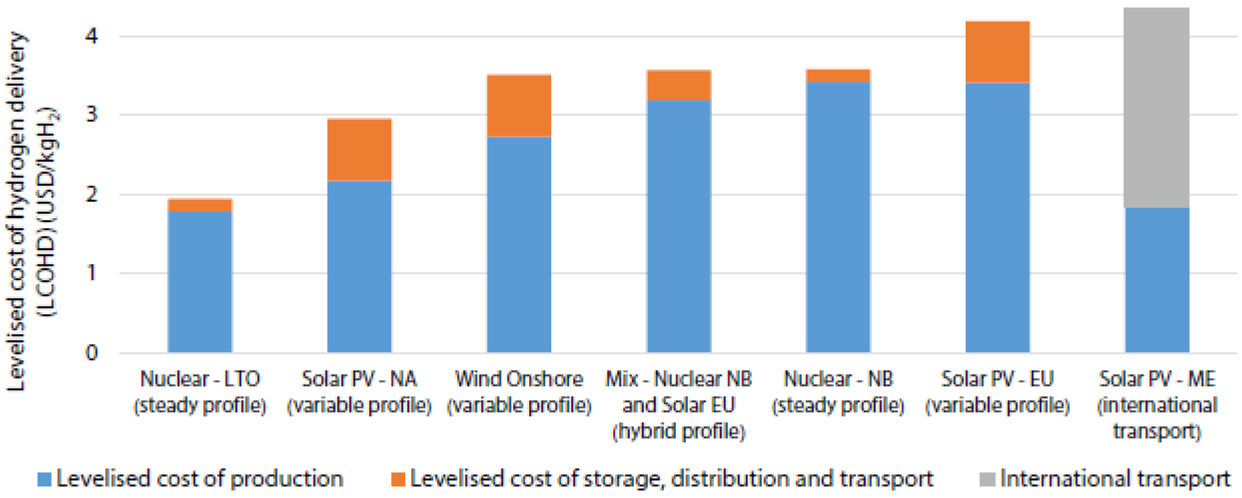
Note: LTO = Long-term operation; NA = North America; NB = New build; EU = European Union; ME = Middle East.

Source: OECD NEA report The Role of Nuclear Power in the Hydrogen Economy (2022)

- Potential for competitivity with fossile H2 at long term
- Interest of synergies between nuclear and renewable systems such as solar PV

➔ leveraging nuclear steadiness and solar PV low-cost electricity, such mixed systems optimise both hydrogen cost of production and delivery.

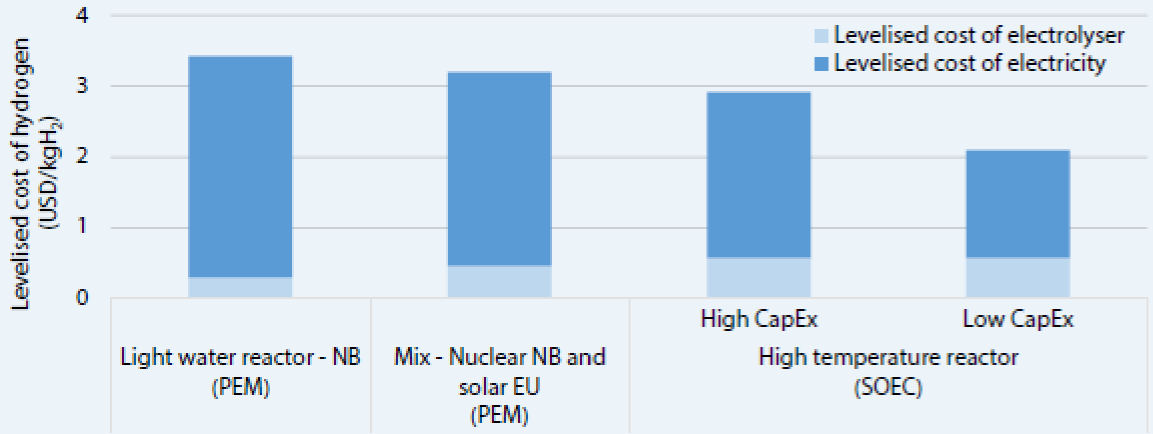
Figure ES2: The levelised cost of hydrogen delivery (LCOHD) for different electricity sources



Note: LTO = Long-term operation; NA = North America; NB = New build; EU = European Union; ME = Middle East.

Interest of coupling nuclear energy and electrolysis

Figure 2.2: **Levelised cost of hydrogen for different nuclear configurations**



Note: It is possible to operate a LWR-SOEC system, although the overall system efficiency would be slightly lower than with the HTR-SOEC configuration. PEM = proton exchange membrane; SOEC = solid oxide electrolyser cell; HTR = high-temperature reactor; Solar EU = Solar European Union; NB = New build.

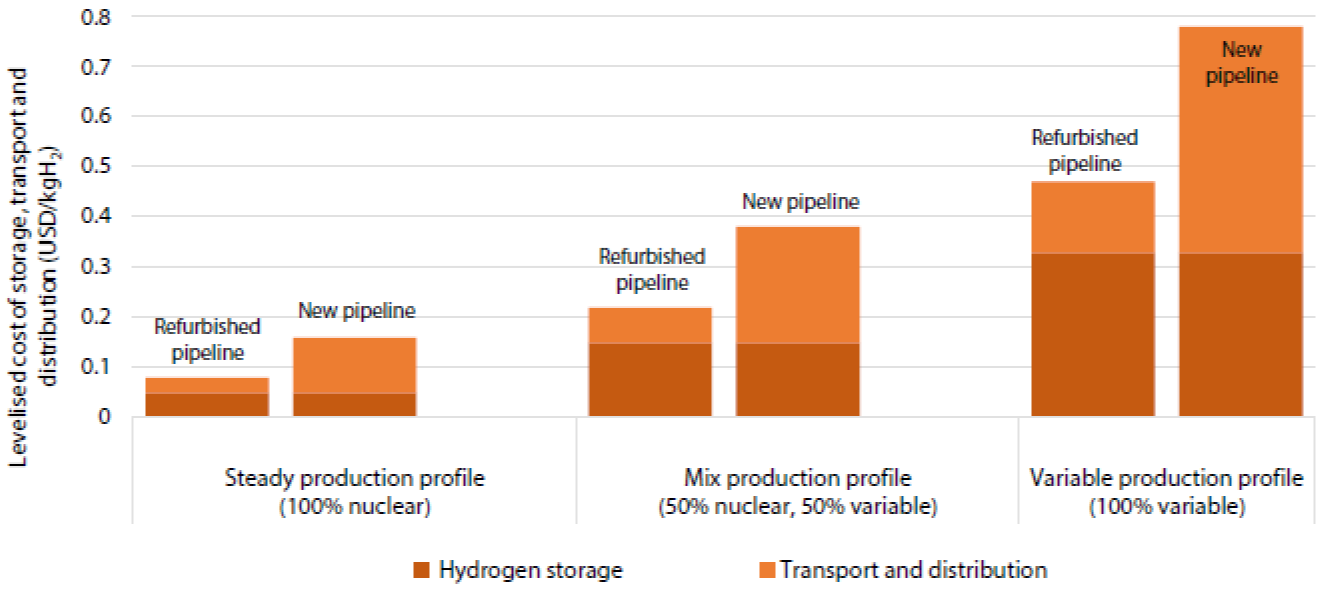
Source: OECD NEA report The Role of Nuclear Power in the Hydrogen Economy (2022)

- Interest of high temperature reactor providing heat to SOEL technology which presents a higher efficiency

➔ 0.5-1.0 $\$/kg_{H2}$ saved

Interest of coupling nuclear energy and electrolysis

Figure 2.6: **Levelised cost of storage, transport and distribution for different production profiles**

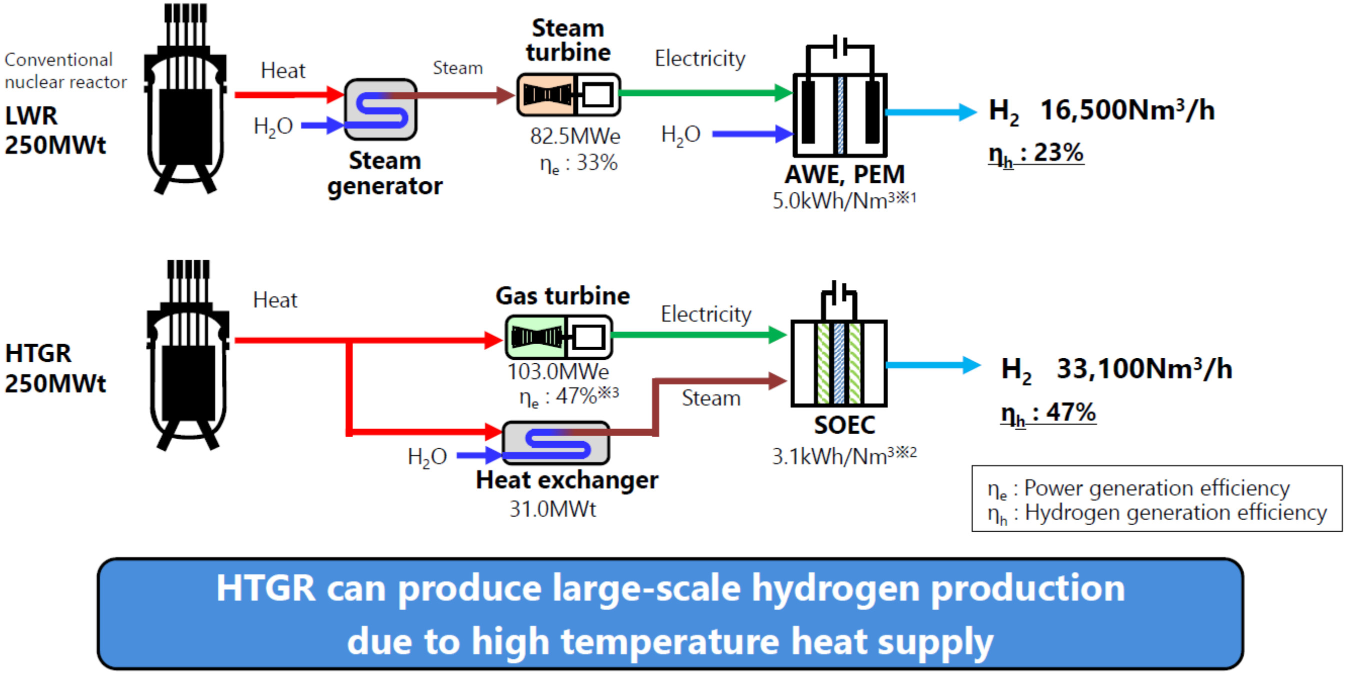


- **At a given electrolyser scale, the larger volume and continuous production of a nuclear based hydrogen value chain allow for a cost-efficient deployment of all infrastructures**

- As a dispatchable large-scale solution, nuclear power would enhance **co-location synergies** with large-scale industrial demand
- **minimising infrastructure costs for hydrogen storage, transport and distribution**.
- Infrastructure costs for a nuclear based value chain ~ 0.16 $/kg_{H2}$ for a 500 MWe system that answers a continuous demand.
- ≠ For variable production: value chain costs are ~ 0.77 $/kg_{H2}$.
- ➔ when value chain costs are added to H2 production costs for different options of electricity generation, **nuclear stands out as a competitive solution**.

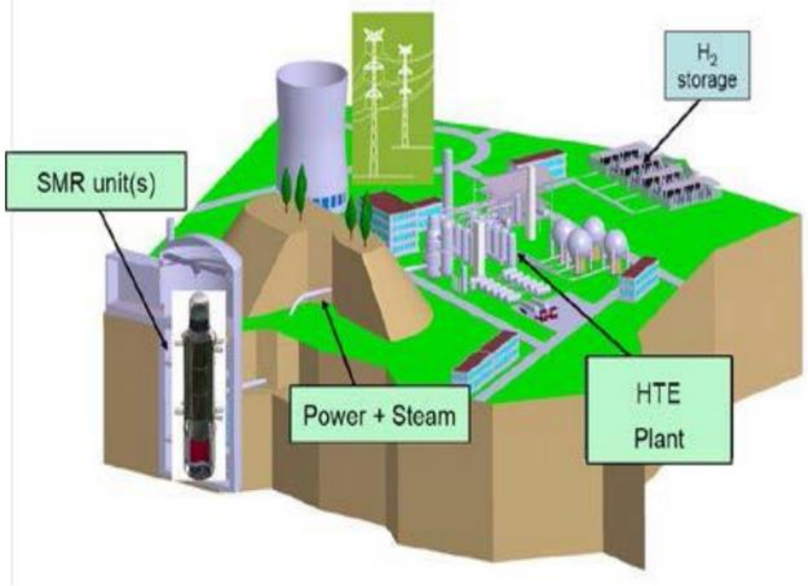
Ongoing studies for H2-NUC coupling

- Different types of reactors:
  - Light Water Reactors (LWR)
  - High-Temperature Gas Reactors (HTGR)
  - Small Modular Reactors (SMR)
- LWR generally considered for PEMEL
- HTGR generally considered for SOEL



Source: N. Sakaba, WHEC2024

- SMR coupling with SOEL also studied



Source: CEA

5. Conclusion

Conclusion

- **Hydrogen : expected to play a key role in the future climate-neutral economy**
  - Enabling emission-free transport, heating & industrial processes, inter-seasonal energy storage
  - If produced with low-carbon electricity (and heat for HT technology) including nuclear energy
- **Share of hydrogen in EU's energy mix is projected to grow from the current less than 2% to 13-14% by 2050**
- **To emphasise its importance and facilitate the scaling up of H_2 applications, it is needed to:**
  - **Scale up** the different technology bricks on the whole value chain
  - Improve its **competitiveness** against other energy carriers
  - With support of **research and innovation** to further increase performance, durability and reliability
    - For more mature technologies
    - For breakthrough technologies
    - From materials to systems
  - Without forgetting other **non technical aspects**
    - Regulation in an international harmonized way
      - Permitting
      - Low carbon H_2 certification
    - Political support:
      - National and international development and deployment plans
      - Financial support: European Hydrogen Bank, Inflation Reduction Act in the USA
    - Use of resources:
      - Critical raw materials, water
      - Circular approach needed

Thank you for your attention