SH2E/eGHOST

SPRING

SCHOOL

Hydrogen production technologies

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OUTLINE

1. **Introduction**
2. **Hydrogen production: overview of the different production routes**
3. **Focus on the electrolysis technologies**
4. **Comparison of the different technologies**
5. **Conclusion**

1. Introduction

Hydrogen usages

Usage in 2022

“Industrial” H_2

- World ≈ 95 Mt/yr
- Europe ≈ 8.2 Mt/yr

- **Chemistry (ammonia)**
- **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

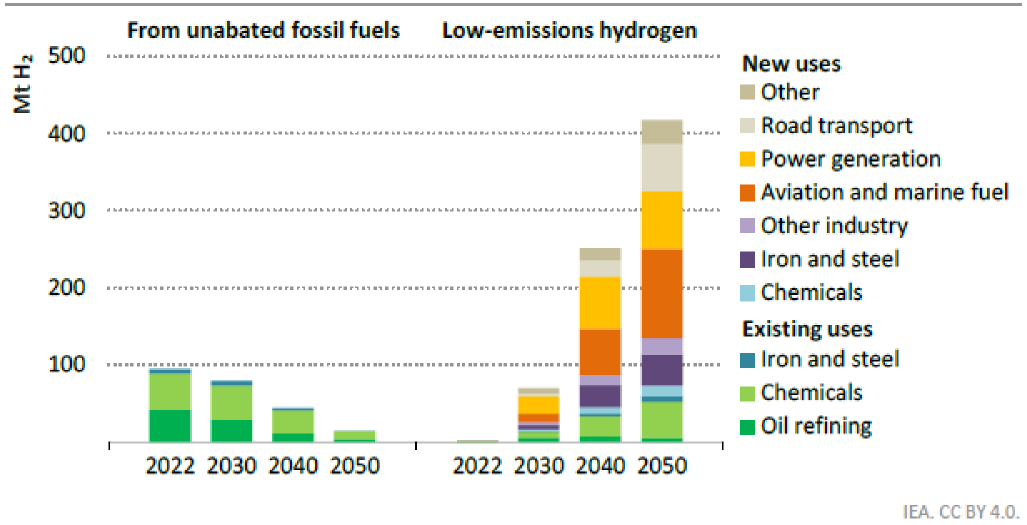
Decarbonization of industrial process :

- 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

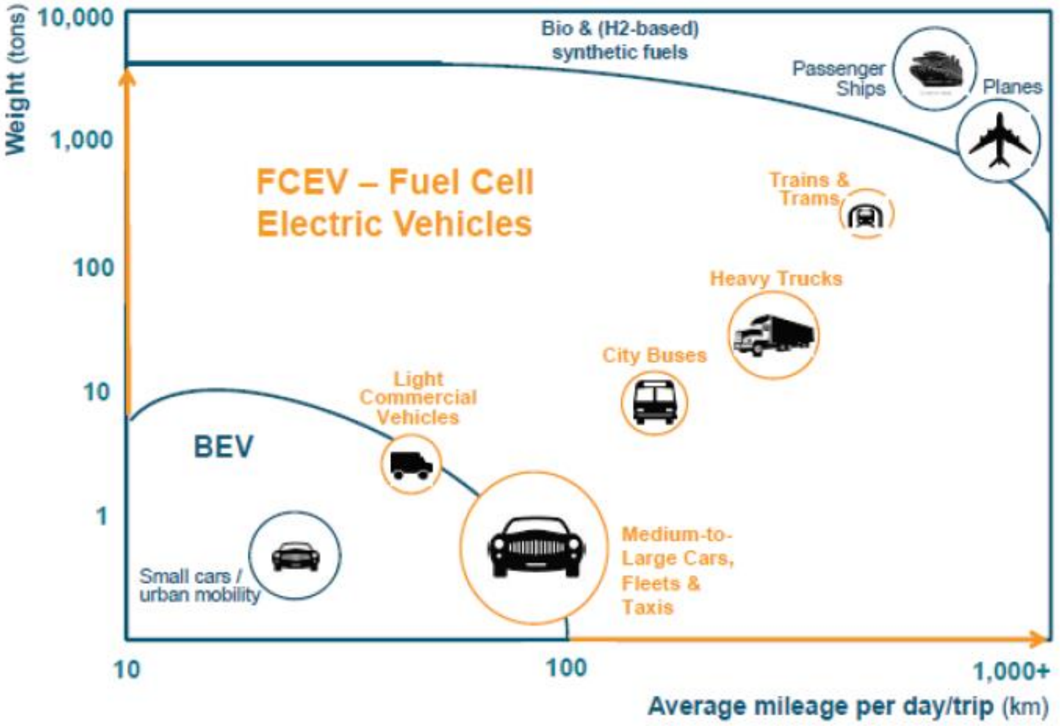
Source : IEA, NetZero Roadmap (2023)

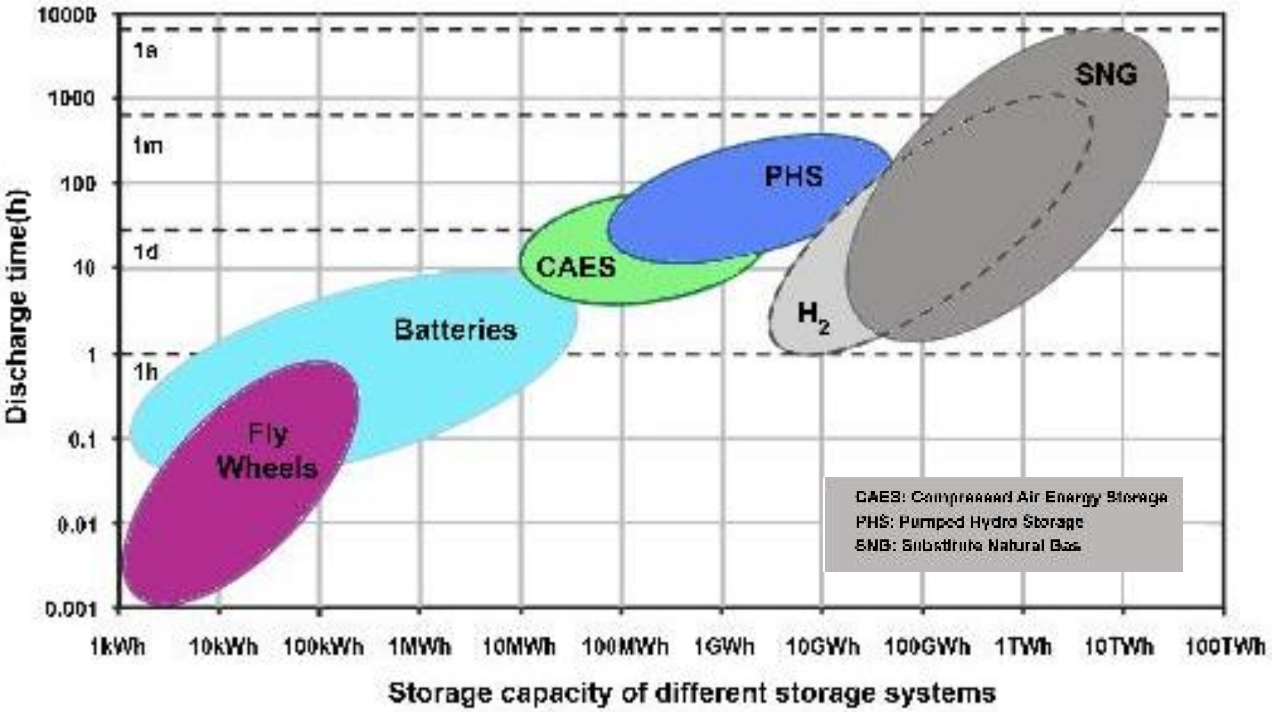
H_2 Needs x5 until 2050

Complementarity of hydrogen and batteries

- Complementarity of H_2 and batteries
  - For transportation
    - H_2 benefit for:
      - long distance
      - Quick refill

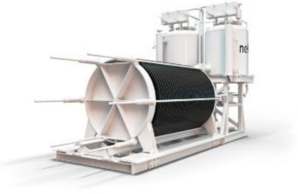
- For electricity storage
  - H_2 benefit:
    - large capacity
    - long time
    - long distance





Hydrogen value chain

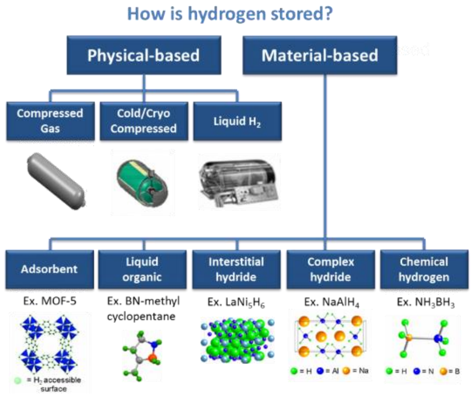
Production | Storage & distribution | Conversion | Decarbonization of usages

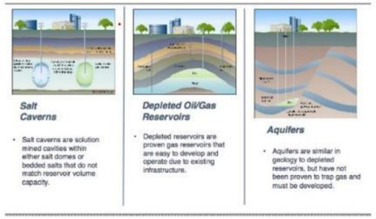


Source: NEL

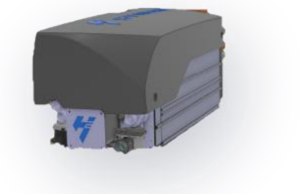
Electrolysis

Other production routes





Storage

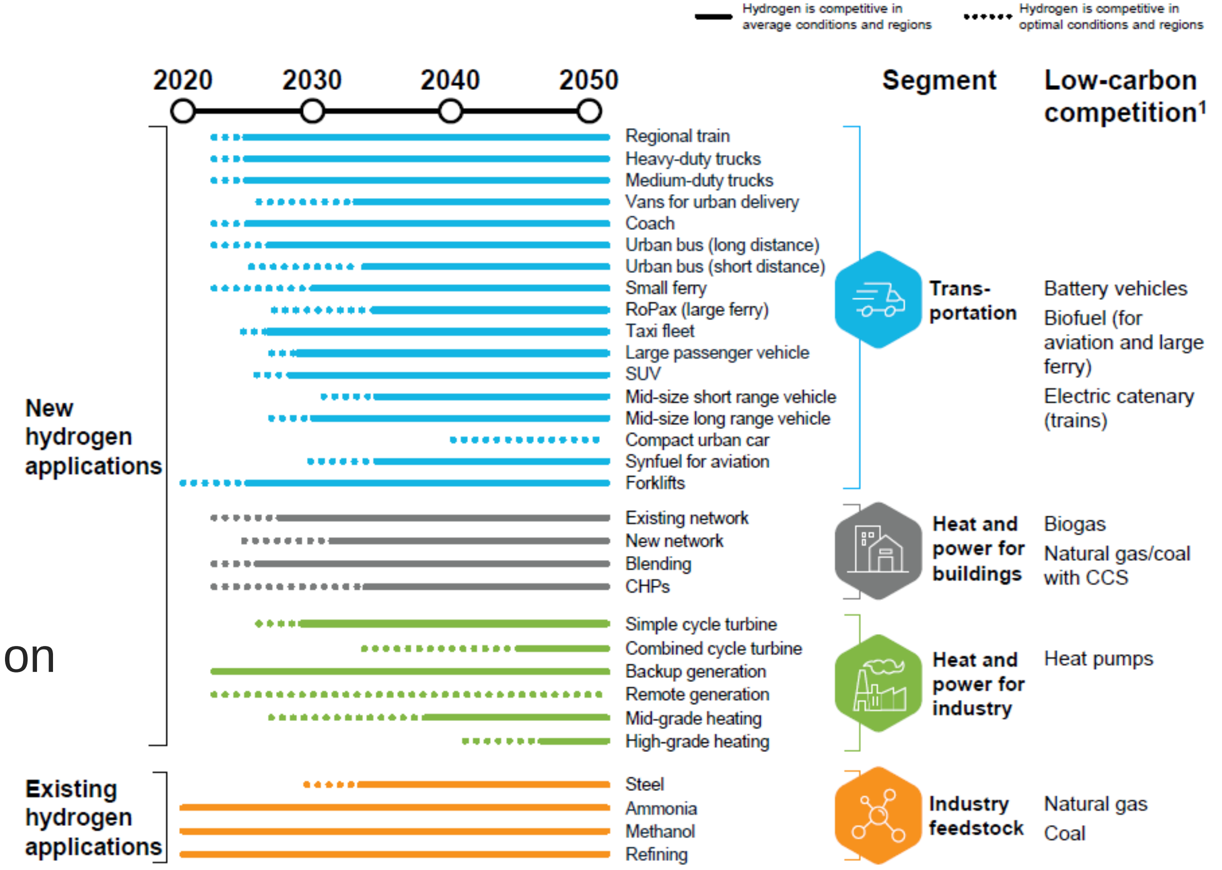


Source: SYMBIO

Fuel cell

Source: Toyota

Internal combustion engines

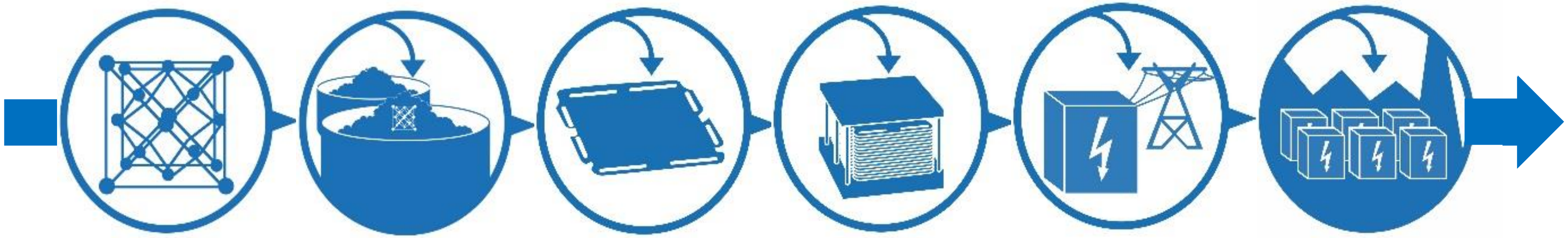


1. In some cases hydrogen may be the only realistic alternative, e.g. for long-range heavy-duty transport and industrial zones without access to CCS

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

Hydrogen value chain

Production → Storage & distribution → Conversion → Decarbonation of usages



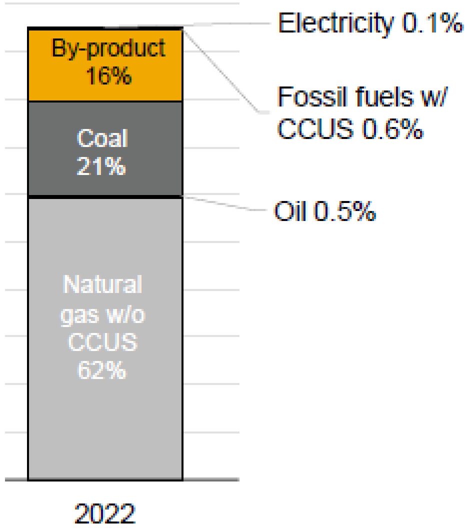
- Development and optimisation
- From materials to systems through components and key technology bricks

2.

H2 production: overview of the different production routes

Hydrogen production routes

Currently: Fossile H_2



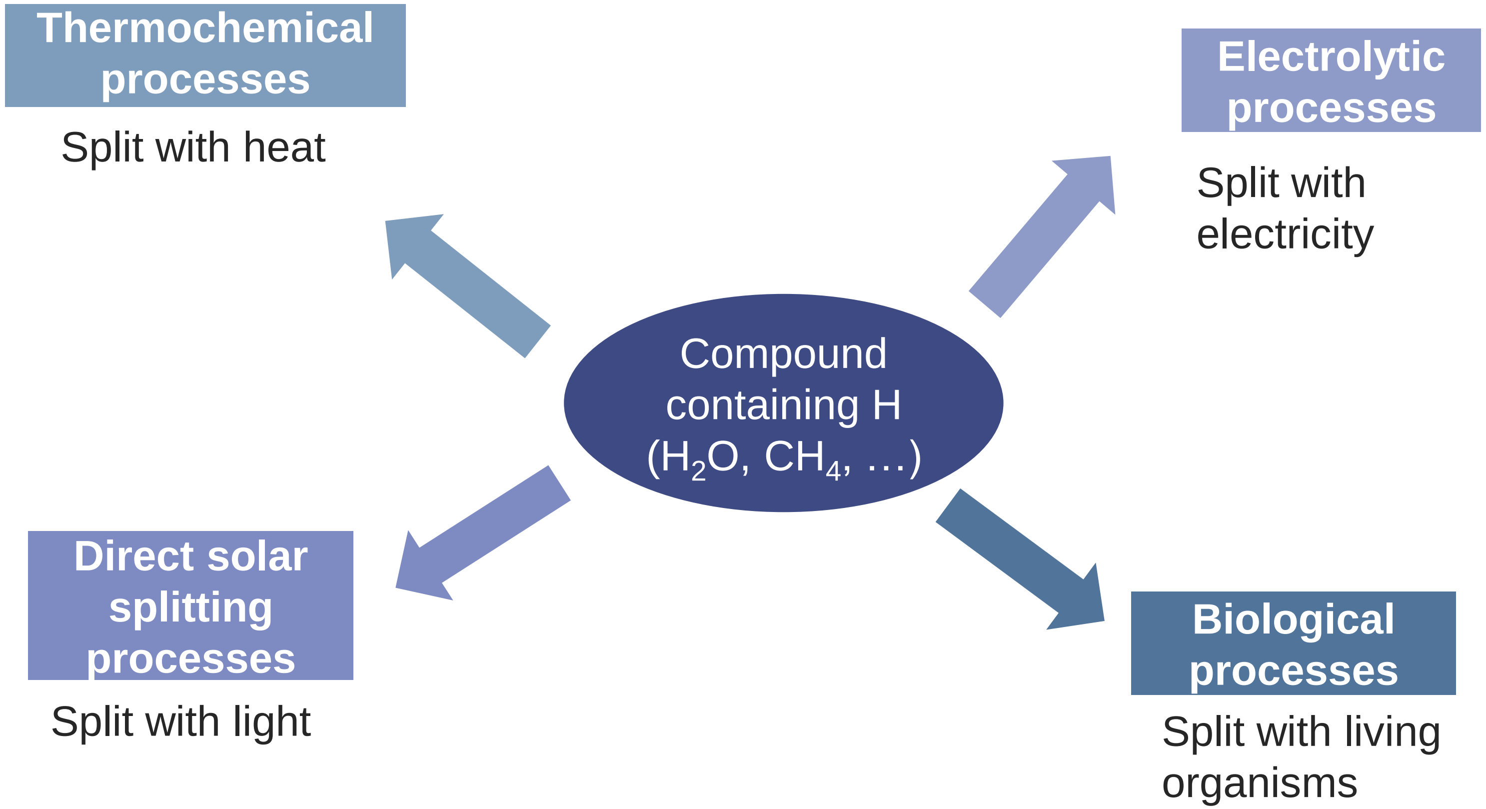
≈ 11-19 kg of CO_2 per kg of H_2

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

Electrolytic processes
Split with electricity

Direct solar splitting processes
Split with light

Biological processes
Split with living organisms

- Native hydrogen…

Hydrogen production routes

Thermochemical processes: split with heat

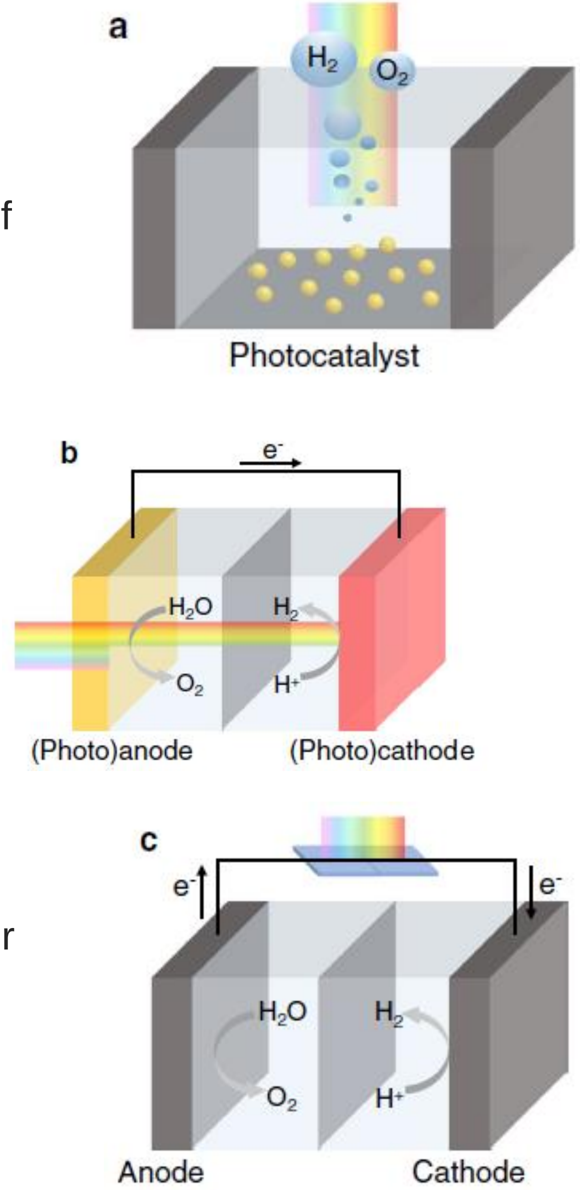
Need for CO_2 capture and storage (CCUS) if fossile considered…

- Gasification of coal or biomass: Coal or biomass is heated to high T (~900-1200°C) in the presence of steam, producing syngas (H_2, CO, CO_2) → WGS to transform CO to CO_2 → separation of H_2
- Reforming of methane (fossile or biogenic)
  - Steam methane reforming (SMR): Methane is heated to high T (700-1000°C) in the presence of steam, producing syngas (H_2, CO, CO_2) → WGS to transform CO to CO_2 → separation of H_2
  - Autothermal Methane Reforming: Methane is heated to high T (950-1050°C) in the presence of air (and steam), producing syngas (H_2, CO, CO_2) → WGS to transform CO to CO_2 → separation of H_2
  - Dry reforming of methane: methane is heated to high T (1000°C) in the presence of CO_2, which produces a mixture of hydrogen and carbon monoxide CO → WGS to transform CO to CO_2 → separation of H_2
- Partial oxidation of (fossile or biogenic) methane: Methane is heated to high T (800-1200°C) in the presence of air, producing a mixture of hydrogen, carbon dioxide, and carbon monoxide.
- Pyrolysis of methane or biomass:
  - Methane decomposes into 2 H_2 and solid carbon, without CO_2 emissions
  - Thermal pyrolysis: T=1000-1200°C
  - Catalytic pyrolysis: T=800-1000°C
  - Plasma pyrolysis: T up to 2000°C
  - In the case of biomass: This results in the production of gaseous components (methane and hydrogen for use as fuel), liquid components (oil and hydrocarbons for use as biofuel) and a solid and stable component: biochar
- Thermal or thermochemical separation of water:
  - Thermal separation: consists of heating the water to a very high T, around 4000°C, the T at which the water decomposes into hydrogen and oxygen.
  - Thermochemical separation: uses a series of chemical reactions to separate hydrogen from oxygen. This process is more efficient than thermal separation and uses lower temperatures (~1200°C)

Hydrogen production routes

Direct solar splitting processes: split with light

- Photocatalytic (PC) water splitting:
  - Use of photocatalysts (e.g. TiO_2) for a direct decomposition of water into H_2 and O_2 using light
- Photoelectrochemical (PEC) water splitting:
  - Use of light to decompose water into H_2 and O_2 using a photoelectrochemical cell (using semiconductors and electrocatalysts)
- Photovoltaic-electrochemical (PV-EC) water splitting:
  - Couples locally a photovoltaic device and a water electrolyser



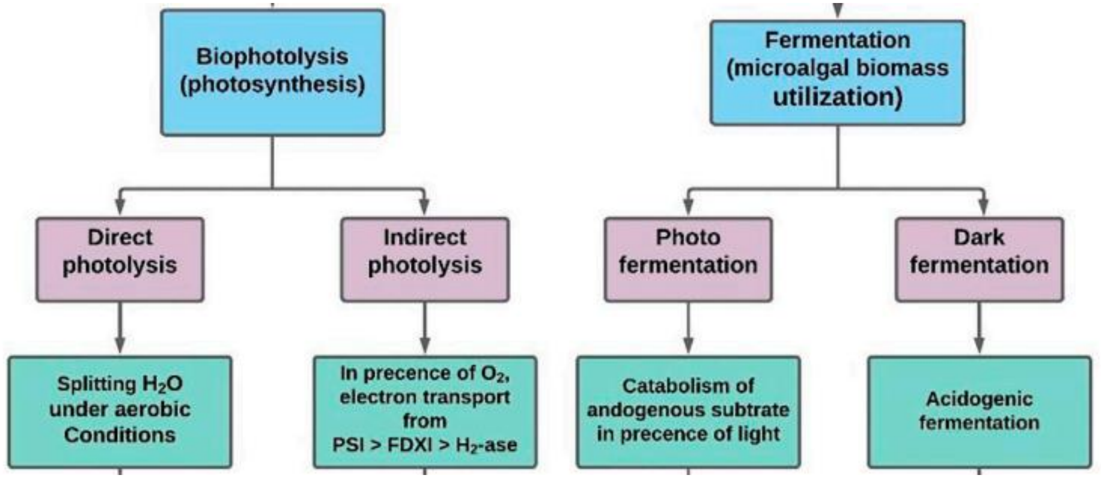
Source: Zheng et al. Carbon Neutrality (2023) 2:23
https://doi.org/10.1007/s43979-023-00064-6

In all cases, efficiency is currently very low…
1-15%

Hydrogen production routes

Biological processes: split with living organisms

- Biophotolysis:
  - Use of photosynthetic microorganisms for a decomposition of water into O_2 and subsequently hydrogenase enzyms convert electrons and protons in excess into H_2
- Fermentation :
  - Biological process: microorganisms (bacteria) to consume and digest biomass and release hydrogen



Source: S. Ahmed et al., doi: 10.3389/fenrg.2021.753878

3. Focus on electrolysis technologies

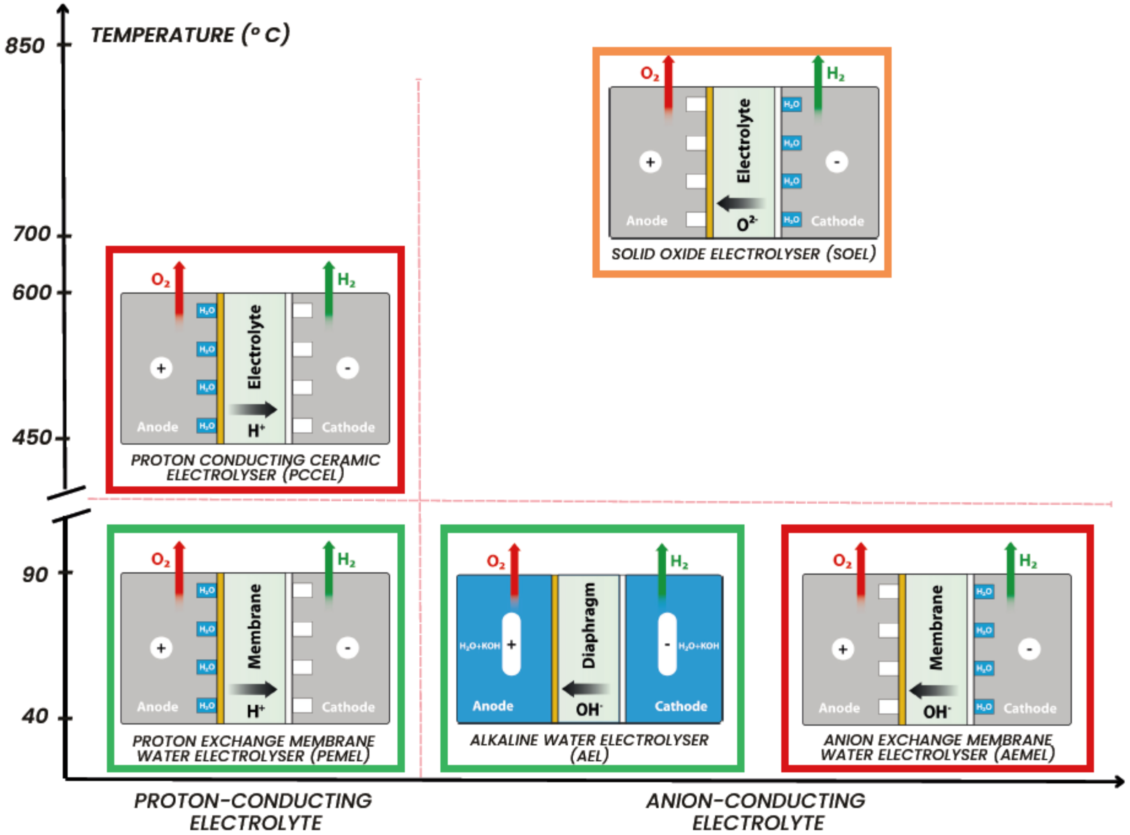
Hydrogen production routes

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



Niveaux de maturité
Maturity levels

🟩 industriel
industrial

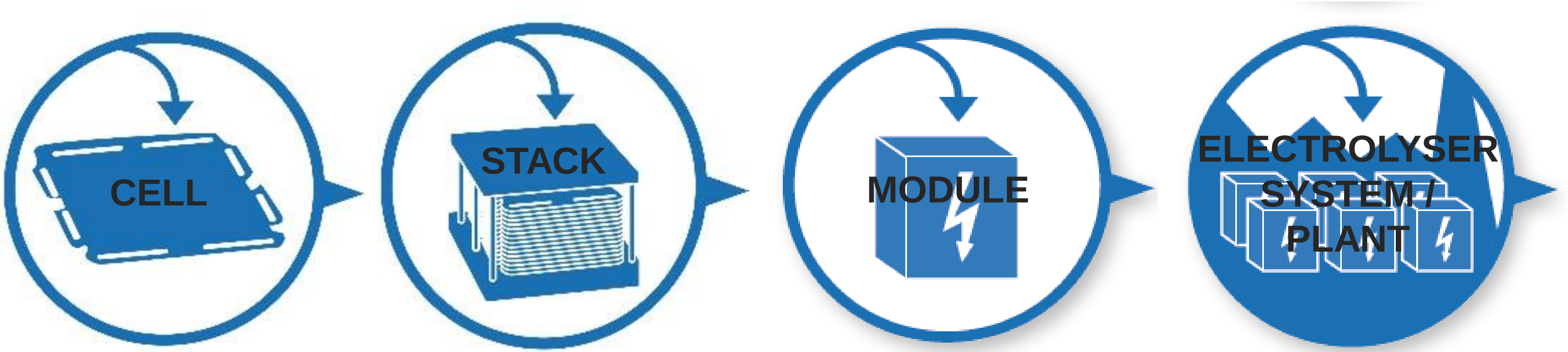
🟧 pré-industrialisation
pre-industrialisation

🟥 en développement
under development

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

Hydrogen production by electrolysis

- **Modular technologies**



CELL

STACK

MODULE

ELECTROLYSER SYSTEM / PLANT

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

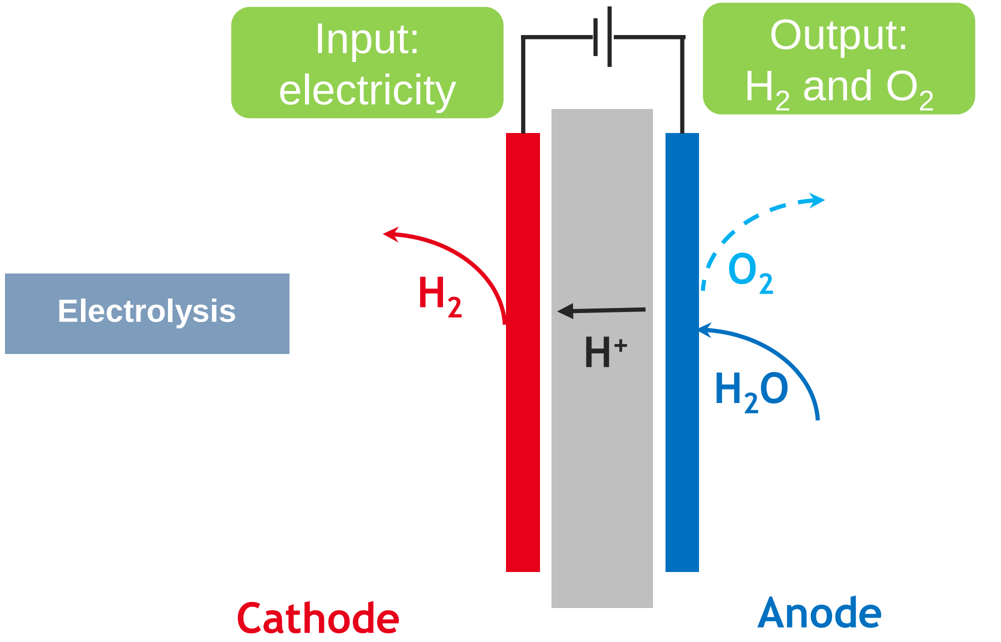
Integration of modules into an **electrolysis system/plant** including all Balance of Plant components = electrolyser

Can/will include several modules into the electrolysis system/plant

Hydrogen production by electrolysis

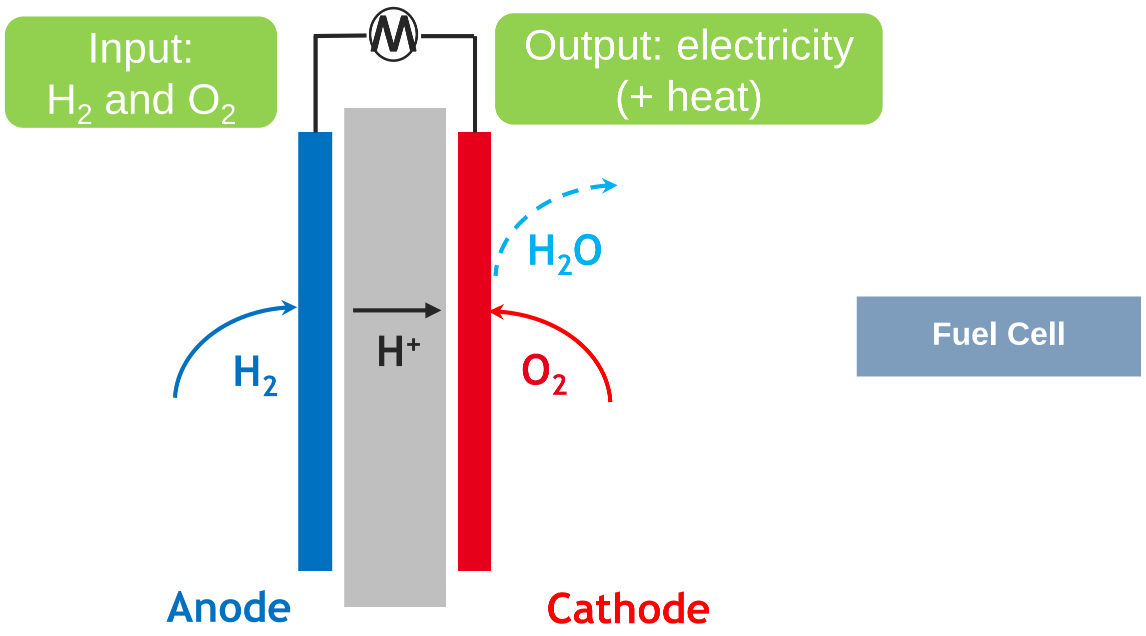
- **Principle of electrolysis**

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



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

$H_20 \rightarrow 2H^+ + 2e^- + ½\ O_2$



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

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

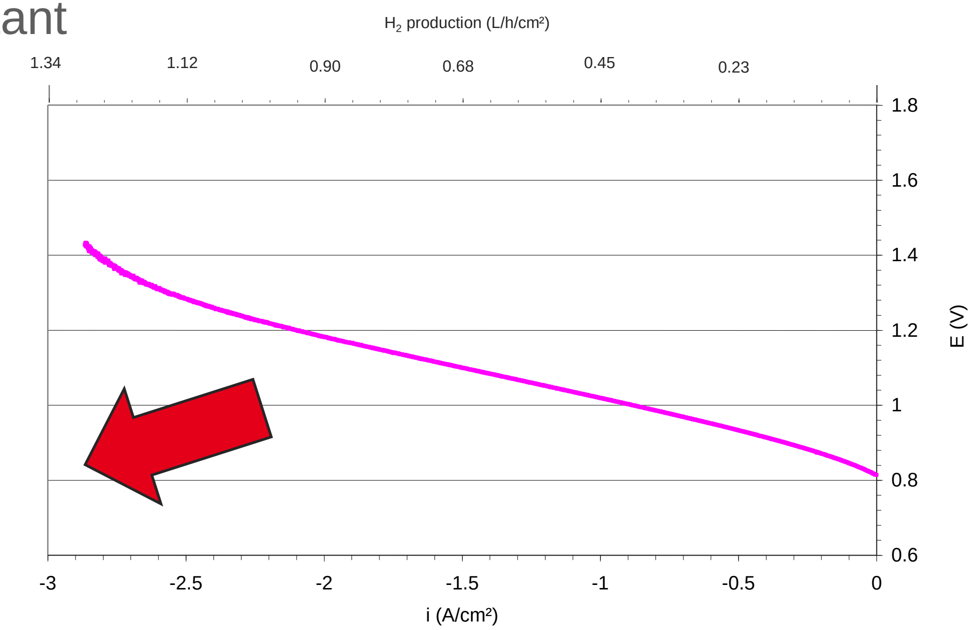
Exemple for PEMEL and PEMFC

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 :**

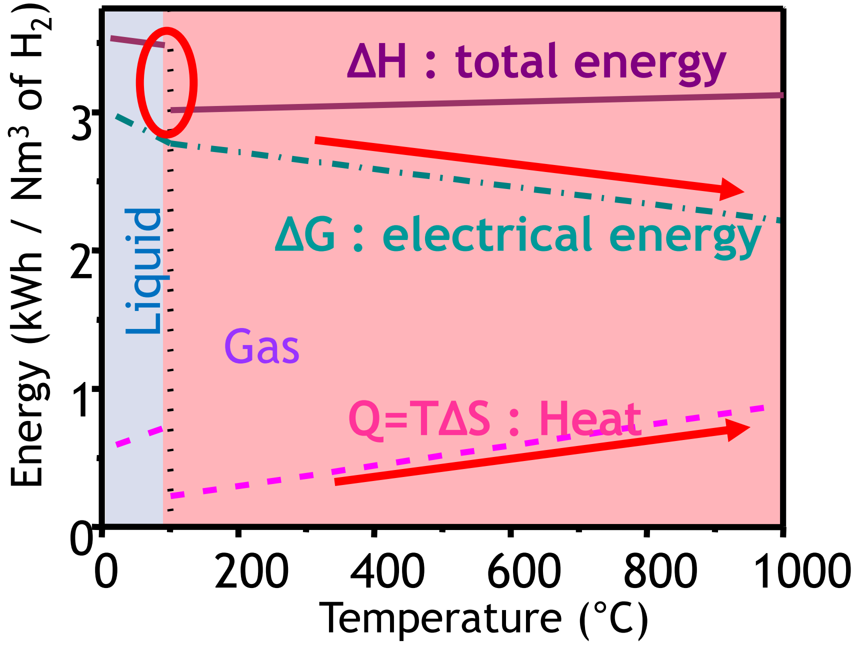
$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

    - 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: $H_2O\ (l) \rightarrow H_2\ (g) + ½\ O_2\ (g)$ $\Delta H° = 285.84$ kJ/mol
    - High T: $H_2O\ (g) \rightarrow H_2\ (g) + ½\ O_2\ (g)$ $\Delta H° = 250$ kJ/mol
  - Different energy needs:



$\Delta H = \Delta G + T\Delta S$

Energy gain with gas phases

ΔH almost constant ~ 250 kJ/mol

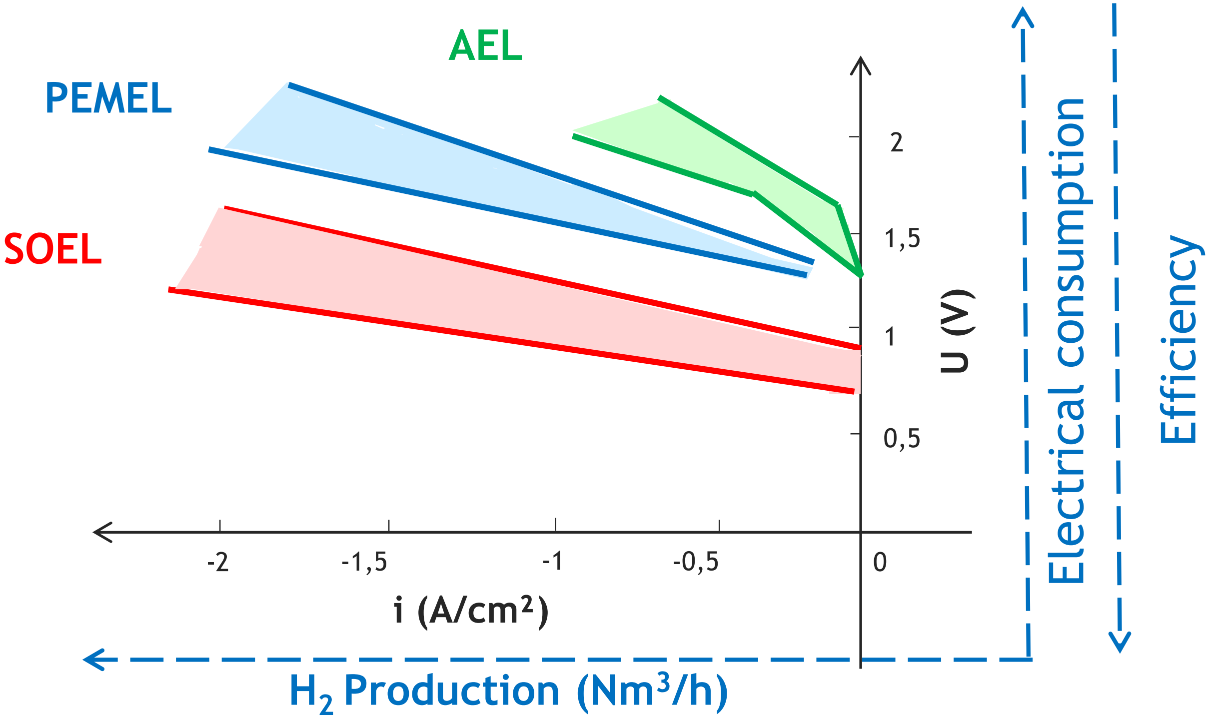
ΔG decreases with T
TΔS increases with T

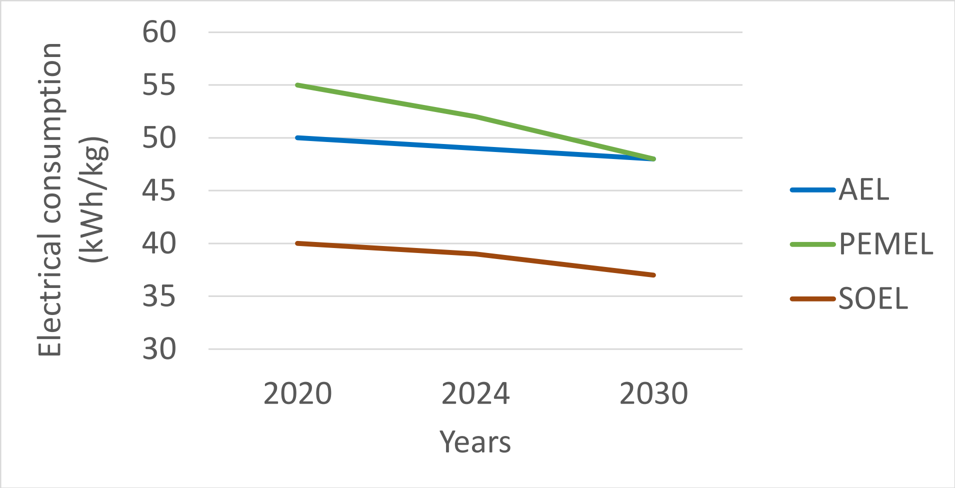
- **Low T: energy = 85% electricity / 15% heat**
- **High T: energy = 70% electricity, 30% heat**

Hydrogen production by electrolysis

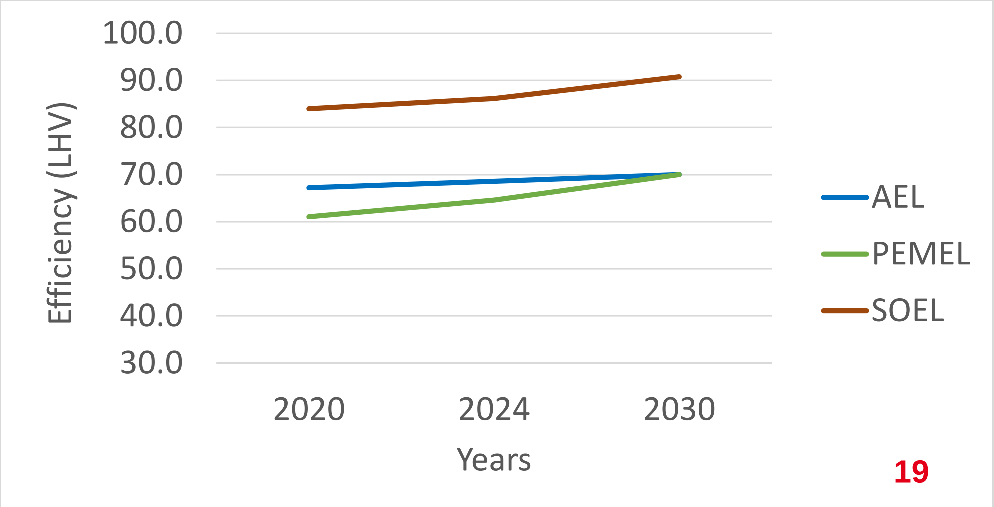
- **Overview of the different technologies**

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





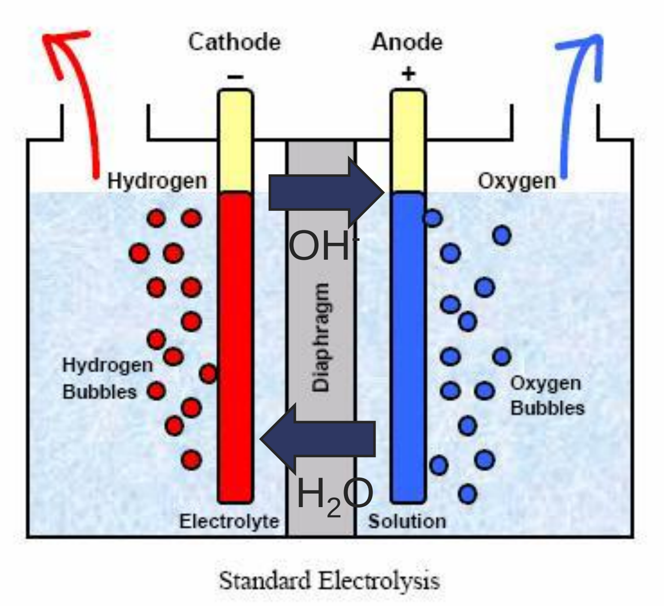
- low T electrolysis : 50 to 55 kWh/kg
- high T electrolysis (SOEL): 40 kWh/kg
- Both will tend to decrease by 2030 but gap remains



Presentation of the different electrolysis technologies

- **Alkaline Electrolysis (AEL)**
- General principle

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



Standard Electrolysis

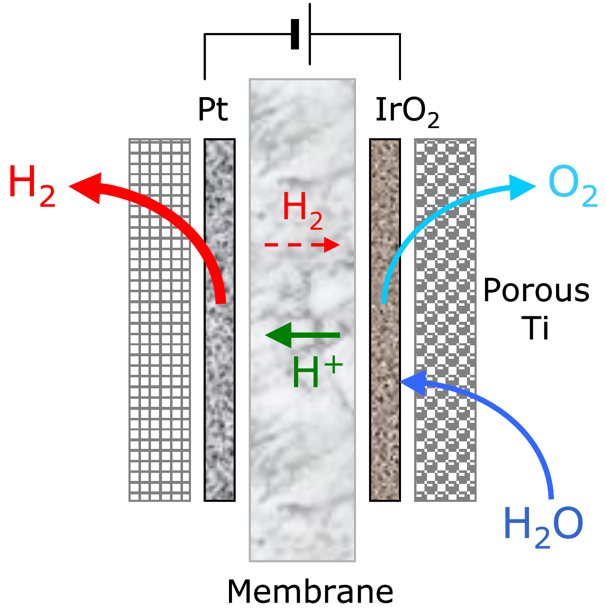
Anode (+):
$2OH^- \rightarrow H_2O + 2e^- + ½ O_2$

Charge carrier: OH^-
Electrolyte: liquid - KOH

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

Presentation of the different electrolysis technologies

- **Proton Exchange Membrane Water Electrolysis (PEMEL)**
- General principle



Cathode

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

Anode

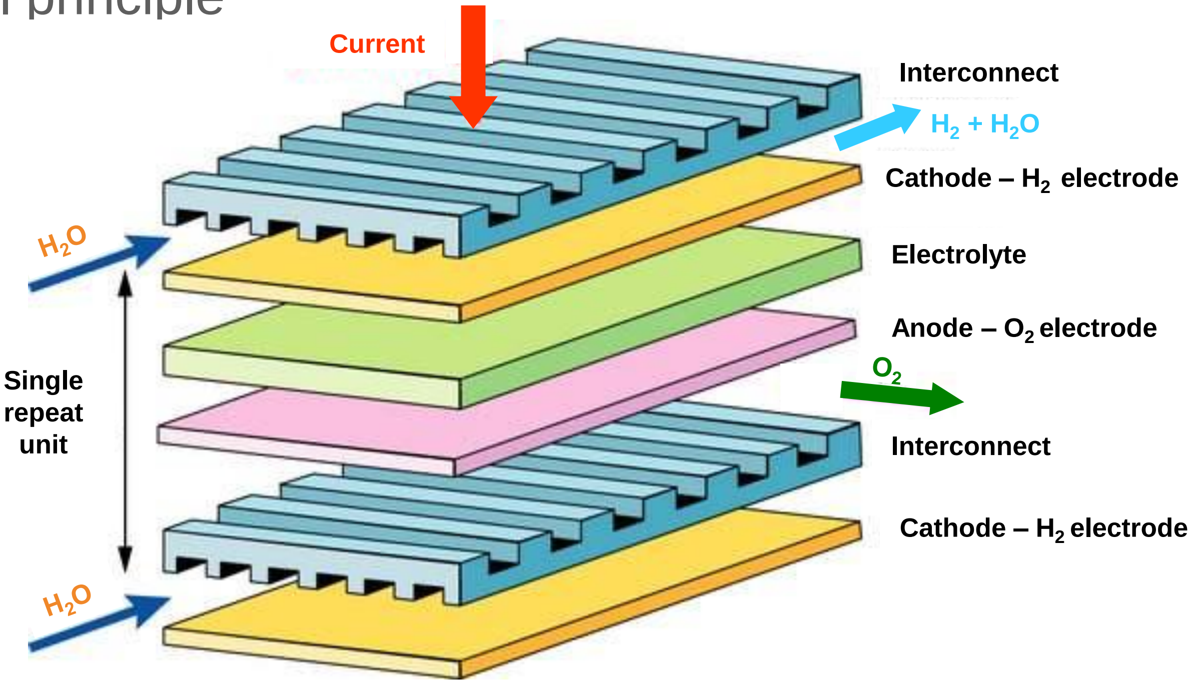
$H_20 \rightarrow 2H^+ + 2e^- + ½\ O_2$

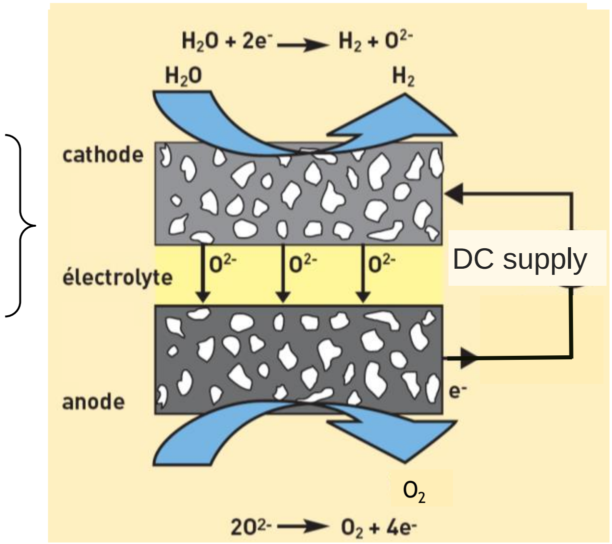
Charge carrier: H^+
Electrolyte: solid - polymer

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

Presentation of the different electrolysis technologies

- **Solid Oxide Electrolysis (SOEL)**
- General principle





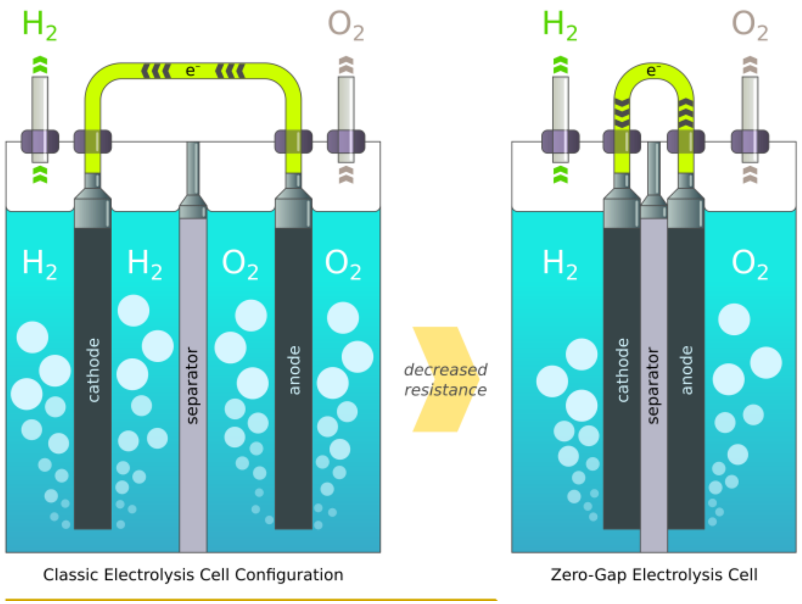
Charge carrier: O^{2-}
Electrolyte: solid - ceramic

Usual operating temperature: 700-850°C
Usual operating pressure: 1 bar, pressurized demonstrated at small scale (up to 30 bar)

Design and materials

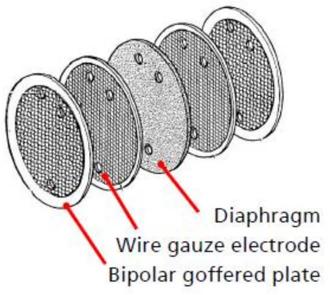
- **Alkaline Electrolysis (AEL)**
- Design

- 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
  - Conditions to achieve small bubbles



Classic Electrolysis Cell Configuration

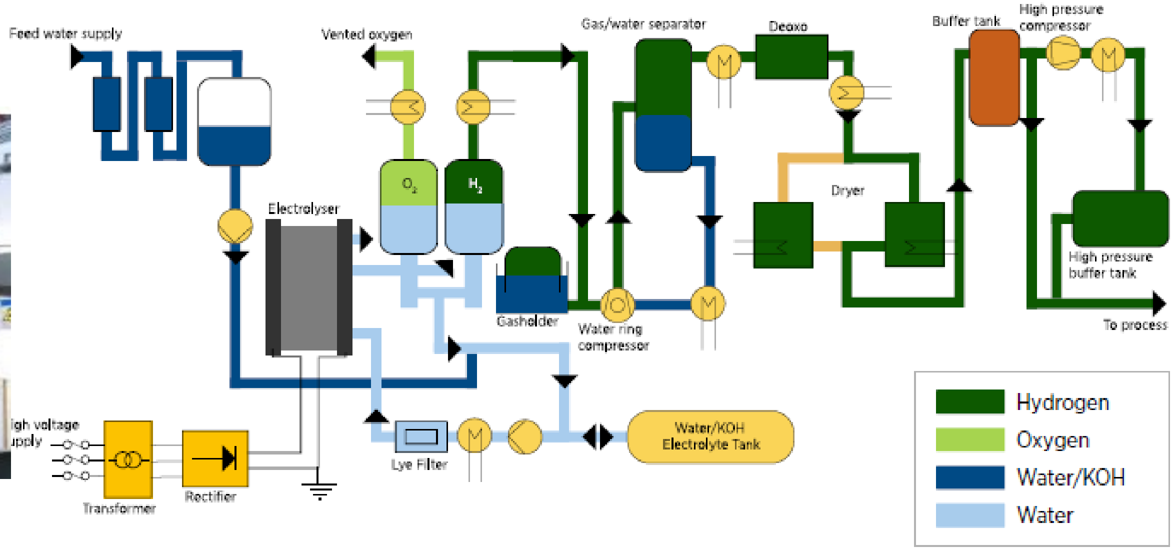
Zero-Gap Electrolysis Cell



Schematic of a Lurgi electrolysis cell

McPhy stack

John Cockrill installation



Source: IRENA Scaling up electrolysers to meet the 1.5°C climate goal, 2020

Design and materials

- **Alkaline Electrolysis (AEL)**
- Materials

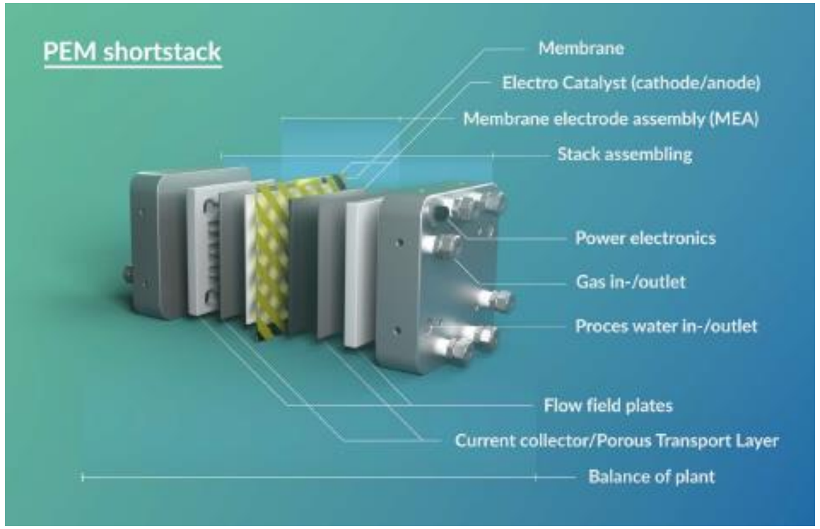
Component	Material
Cathode	Raney-Nickel in various forms (Ni-Al, Ni-Zn) NiMo (MoNi4 + MoO2)
Anode	Ni-X (X=Co,Fe) Oxide Hydroxides: Ni(OH)2, NiOOH + dopants
Membrane / Separator / diaphragm	Zirfon perl materials ZrO2 and polyphenylene sulfide
Electrolyte	KOH 30wt%
Bipolar plate	Ni-coated Steel, nickel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

- EU targets: decrease the use of CRM as catalysts while increasing performance
- ➔ Work to achieve:
  - Higher catalytic activity by new catalyst compositions/ morphologies
  - Increased catalyst utilization by optimized electrode structures

Unit	SoA	Targets	
	2020	2024	2030
mg/W	0.6	0.3	0

Design and materials

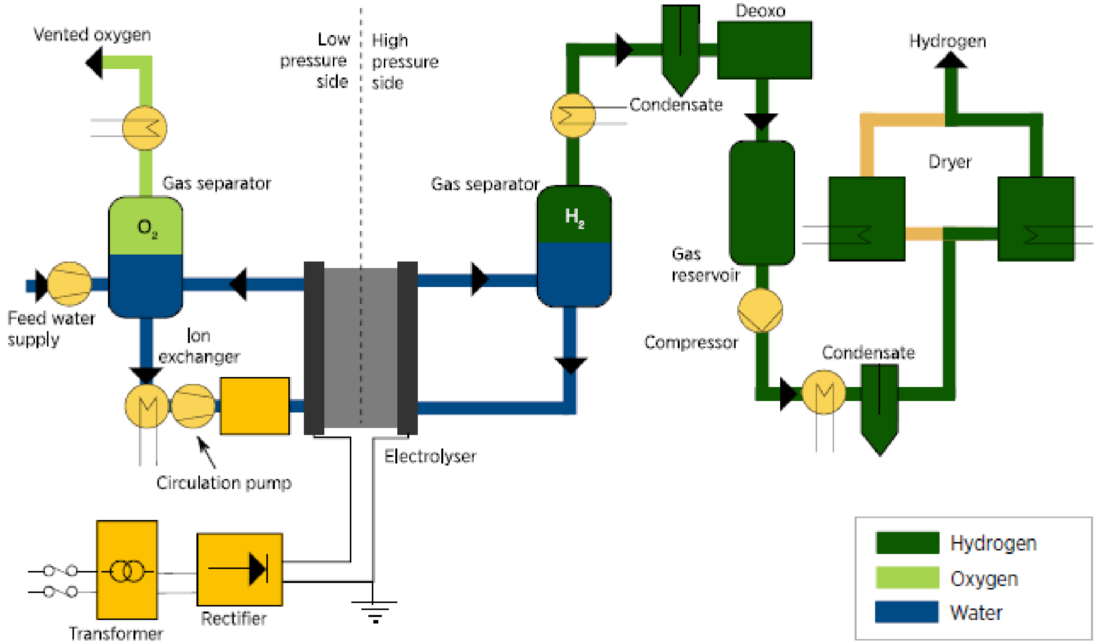
- **Proton Exchange Membrane Water Electrolysis (PEMEL)**
- Design



- To improve performance
  - Membrane as thin as possible (< 200 µm)
  - Catalysts as active as possible (PGM)

Silyzer 300 – PEM Module Array

Siemens installation with 24 stacks



Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Source: IRENA Scaling up electrolysers to meet the 1.5°C climate goal, 2020

Design and materials

- **Proton Exchange Membrane Water Electrolysis (PEMEL)**
- Materials

Component	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

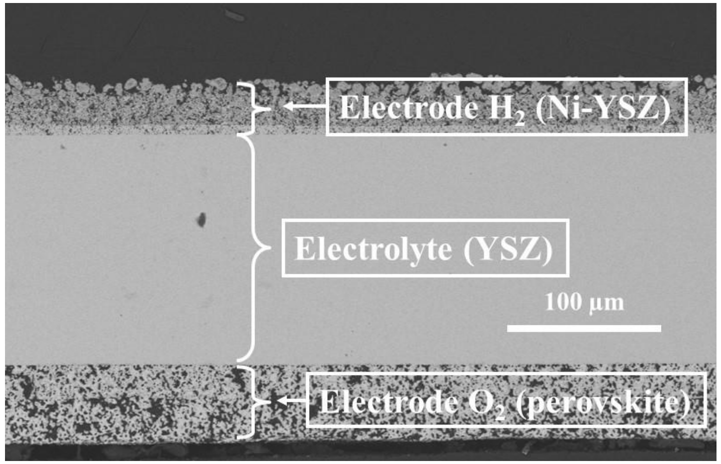
- EU targets: decrease the use of CRM as catalysts (PGM, Platinum group metals)
- But they most probably always be needed
- ➔ Work to achieve:
  - Higher catalytic activity by new catalyst compositions/ morphologies
  - Increased catalyst utilization by optimized electrode structures

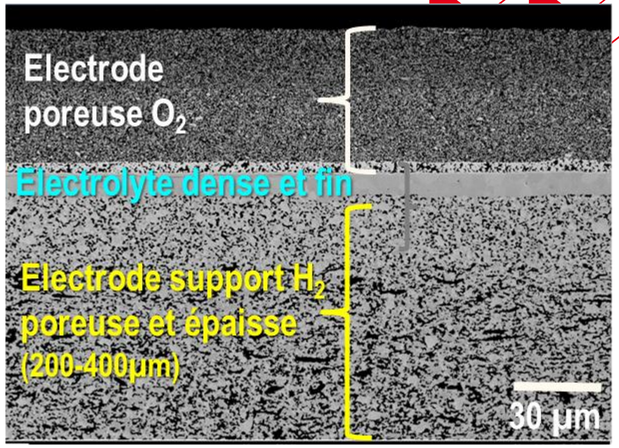
Unit	SoA	Targets	
	2020	2024	2030
mg/W	2.5	1.25	0.25

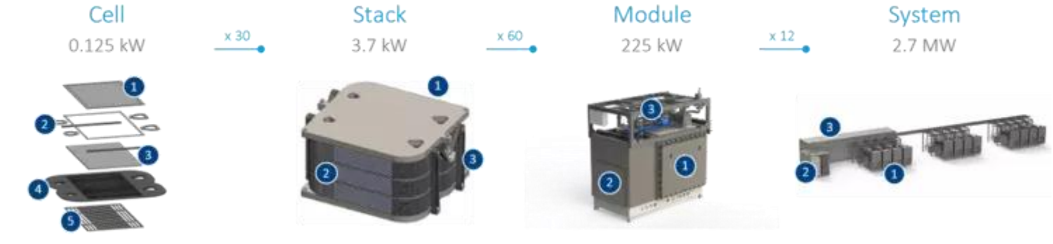
Design and materials

- **Solid Oxide Electrolysis (SOEL)**
- Design

  - To improve performance
    - Thin electrolyte (< 10 µm)
    - Electrode materials with improved conductivity







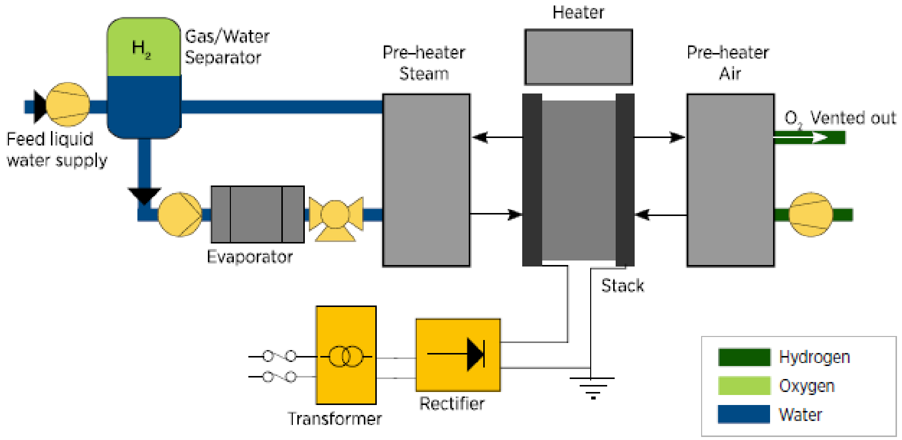
① Membrane electrode assembly
② Glass sealing
③ Nickel foam
④ Sheet metal cassette
⑤ Cathode contact

① End plates
② Cells
③ Stack tensioning

① Stack unit
② Gas processing unit (GPU)
③ Supply and discharge unit (SDU)

① Block (= 4 modules)
② Fluid interface unit (FIU)
③ Power electronics

Sunfire stack, module and system



Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Source: IRENA Scaling up electrolysers to meet the 1.5°C climate goal, 2020

Design and materials

- **Solid Oxide Electrolysis (SOEL)**
- Materials

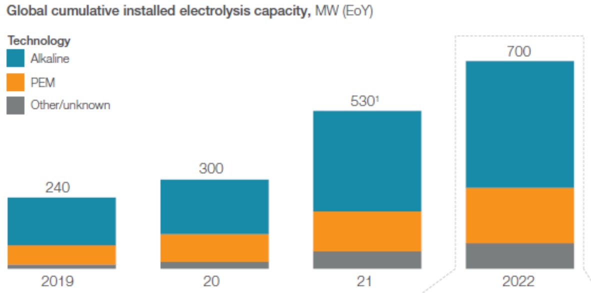
Component	Material
Cathode	Ni-YSZ
Anode Diffusion barrier layer	Perovskite: $(La_{0.60}Sr_{0.40})_{0.95}Co_{0.20}Fe_{0.80}O_{3-X}$ Gadolinia doped ceria
Separator / diaphragm	/
Electrolyte	YSZ (ZrO_2 doped with Y_2O_3)
Bipolar plate	Ferritic stainless steel, often coated with Co
Porous transport layer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

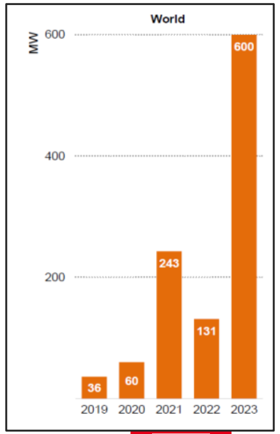
- No noble catalysts
- Some rare earth elements

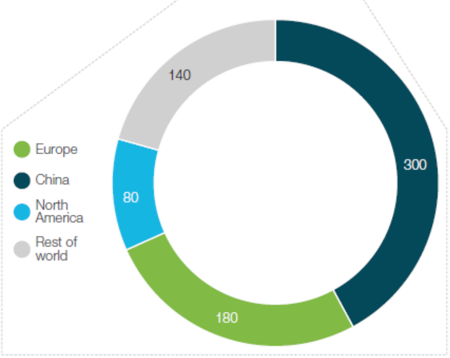
Current status

- 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.


Global cumulative installed electrolysis capacity, MW (EoY)





Source: H2 Council 2023 & IEA 2024

In only 10 years electrolyser capacity increased 500× and funding per MW installed reduced 100×

- installed in a steelmaking plant in Austria

- at Nouryon's Delfzijl site, The Netherlands, to produce green methanol
- 8 t/day of H_2 produced


Project: Don Quichote
Place: Belgium
Date: 2011
Electrolyser: Hydrogenics
Funding: 5.0 m€

Project: Haeolus
Place: Norway
Date: 2017
Electrolyser: Hydrogenics
Funding: 5.0 m€

Project: H2future
Place: Austria
Date: 2016
Electrolyser: Siemens
Funding: 12 m€

Project: Djewels
Place: The Netherlands
Date: 2018
Electrolyser: McPhy
Funding: 11 m€

0.15 MW
1.2 MW
2.5 MW
3.2 MW
6.0 MW
10 MW
20 MW → 60MW
3x100 MW

Project: Hybalance
Place: Denmark
Date: 2014
Electrolyser: Hydrogenics
Funding: 8.0 m€

Project: Demo4grid
Place: Austria
Date: 2016
Electrolyser: IHT
Funding: 2.9 m€

Project: Refhyne
Place: Germany
Date: 2017
Electrolyser: ITM
Funding: 10 m€

Green Deal Projects:
- Refhyne II
- GreenHyScale
- GreenH2Atlantic

Date: 2021
Funding: =30 m€

PEMEL
AEL

~2030: 100 GW scale

- H2 for transportation
- 230 Nm³/h of hydrogen (+/- 500 kg/day)

- installed in a refinery in Germany
- 4 t/day of H_2 produced)

Source: Clean H2 JU

Current status

- **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

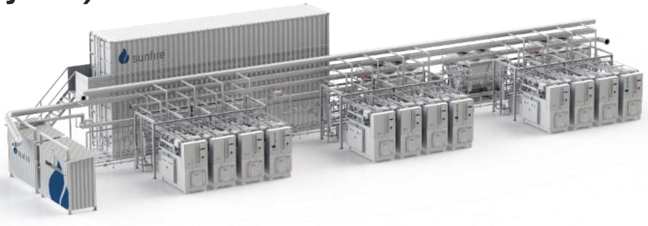
2020 720 kW SOEL installed in August 2020 on the steel plant (Grinhy 2.0)

- 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

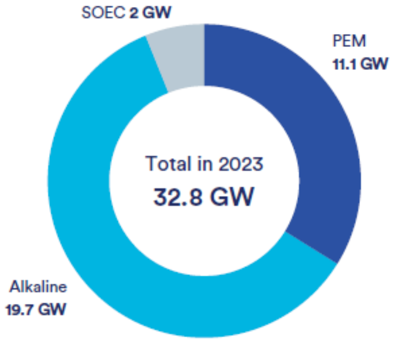


Current status

- **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
    - = 2 x 100 GW electrolysis

- **➔ 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
- 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 2023: total manufacturing capacity = 32.8 GW

Figure 29: Global Nameplate Electrolyzer Manufacturing Capacity[58]

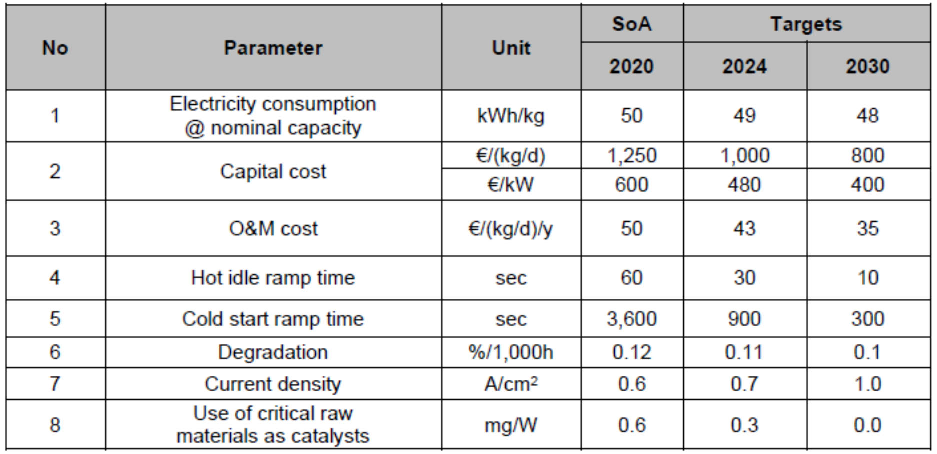



Solid Oxide Electrolysis: A Technology Status Assessment

Trend of development

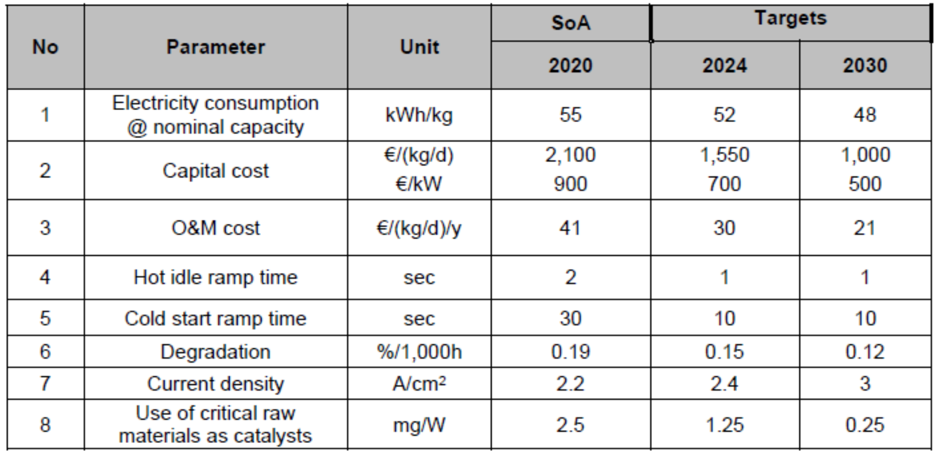
- Still some work on AEL, PEMEL, SOEL to meet the key performance indicators

Table 2: KPIs for Alkaline Electrolysis (AEL)



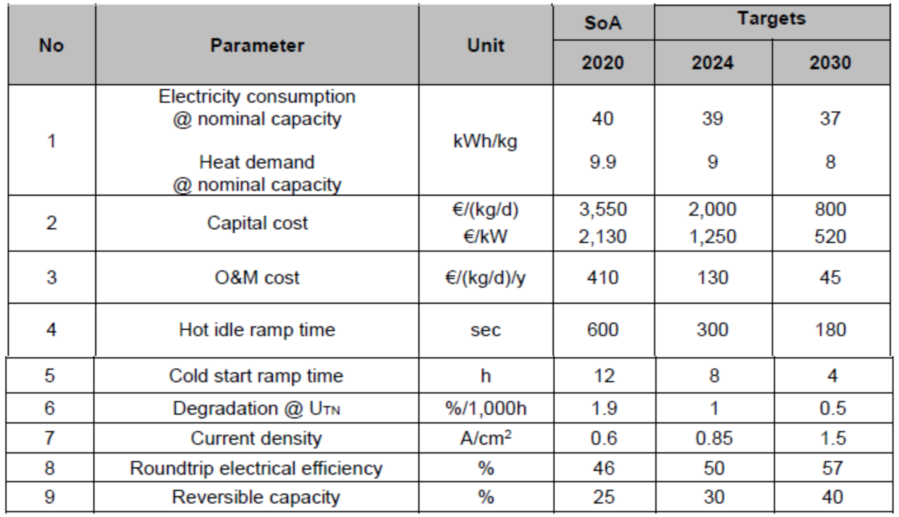
No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity	kWh/kg	50	49	48
2	Capital cost	€/(kg/d)	1,250	1,000	800
		€/kW	600	480	400
3	O&M cost	€/(kg/d)/y	50	43	35
4	Hot idle ramp time	sec	60	30	10
5	Cold start ramp time	sec	3,600	900	300
6	Degradation	%/1,000h	0.12	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)

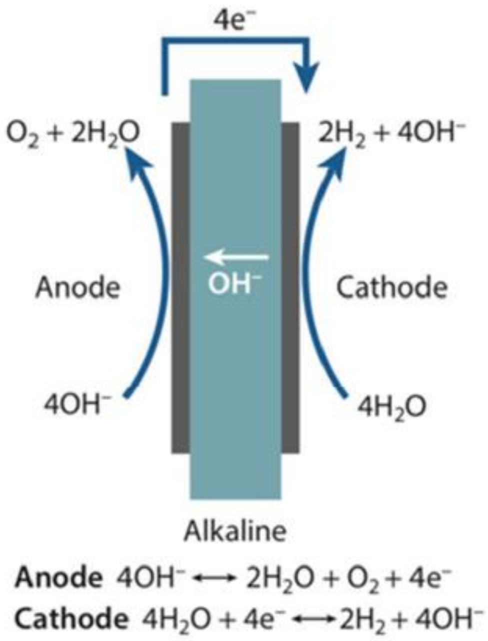


No	Parameter	Unit	SoA	Targets	
			2020	2024	2030
1	Electricity consumption @ nominal capacity Heat demand @ nominal capacity	kWh/kg	40 9.9	39 9	37 8
2	Capital cost	€/(kg/d) €/kW	3,550 2,130	2,000 1,250	800 520
3	O&M cost	€/(kg/d)/y	410	130	45
4	Hot idle ramp time	sec	600	300	180
5	Cold start ramp time	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

- Work on emerging technologies: AEMEL

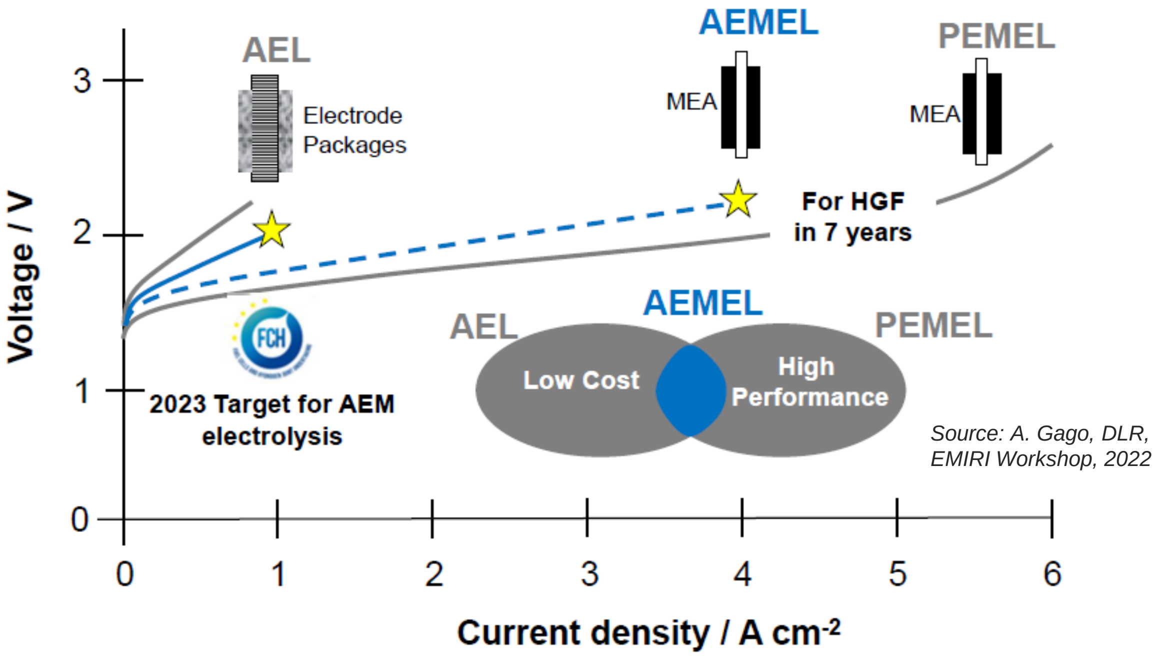


Source: K. Ayers et al., Rev. Chem. Biomol. Eng. 10 (2019) 219-239

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



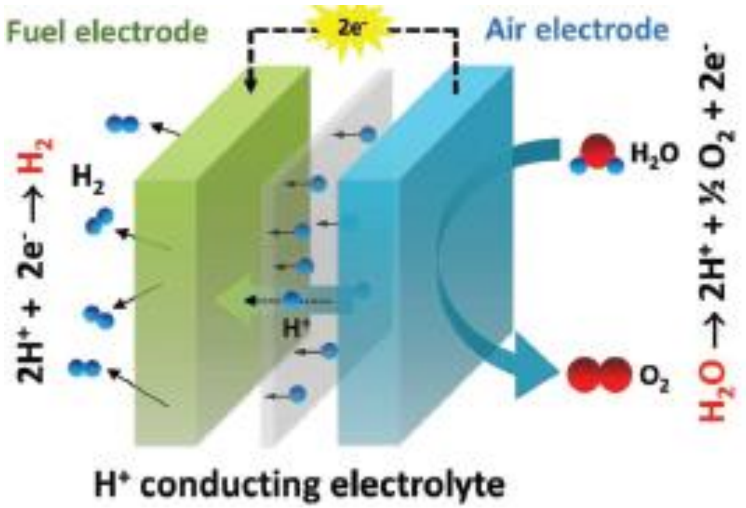
Source: A. Gago, DLR, EMIRI Workshop, 2022

	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

4. Comparison of the different technologies

Hydrogen production routes

- Comparison based on a few indicators:
  - TRL
  - Carbon footprint
  - Energetic efficiency
  - Cost of H_2 produced
  - Could also consider other indicators:
    - Accessibility to the ressource: but less data available…
    - 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

Thermochemical processes: split with heat

- Synthesis based on a few indicators
  - Need for CO_2 capture and storage (CCUS) if fossile considered for C footprint improvement:
    - impact on TRL (↓), efficiency (↓) and cost (↑)
  - Methane pyrolysis promising
  - Use of biomass : quite a good option, but competition with other usages of biomass (to produce biofuels for instance)
  - Thermochemical water splitting: less promising considering those indicators

	TRL	C footprint (kg_{CO2e}/kg_{H2})	Energetic efficiency (LHV)	Cost ($\$/kg_{H2}$)
Coal gasification	9	20	50%	1 - 3
Steam methane reforming (SMR)	9	11	57-75%	1 - 3
Partial oxidation of methane	9	~11	55-75%	?
Autothermal methane reforming	6	~11	60-75%	1 - 3
Fossile with CCUS	6-9	6,5-2,5	50-70%	1,5 - 3,6
Biomass gasification	8	<1	50%	1 - 3
Pyrolysis of methane	3-8	3-4	60-90%	~ 3.5
Pyrolysis of biomass	3-8	-6 to 1	Low	?
Thermochemical splitting of water	4	X	20-45%	4 - 10

Hydrogen production routes

- Synthesis based on a few indicators
  - Low TRL technologies: still some work to do…

Direct solar splitting processes: split with light

	TRL	C footprint (kg_{CO2e}/kg_{H2})	Energetic efficiency (LHV)	Cost ($/$kg_{H2}$)
Photocatalytic (PC) water splitting	3	<1	<1%	10
Photoelectrochemical (PEC) water splitting	4	<1	4-10%	8.5
Photovoltaic-electrochemical (PV-EC) water splitting	6	?	10-15%	6

Biological processes: split with living organisms

	TRL	C footprint ($kg_{CO2e}/kg_{H}2$)	Energetic efficiency (LHV)	Cost ($/$kg_{H2}$)
biophotolysis	3	? But low	4%	?
fermentation	6	? But low	5-30%	7 - 10

Hydrogen production routes

Electrolytic processes: split with electricity

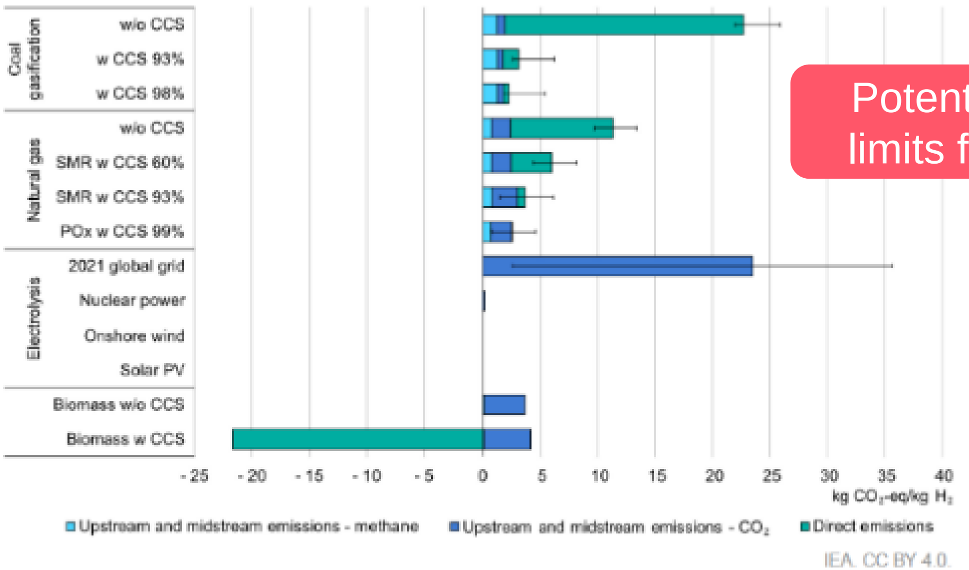
- Synthesis based on a few indicators
  - Impact of electricity (source and price) on C footprint and cost of H2 produced

	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%	?

Hydrogen production routes

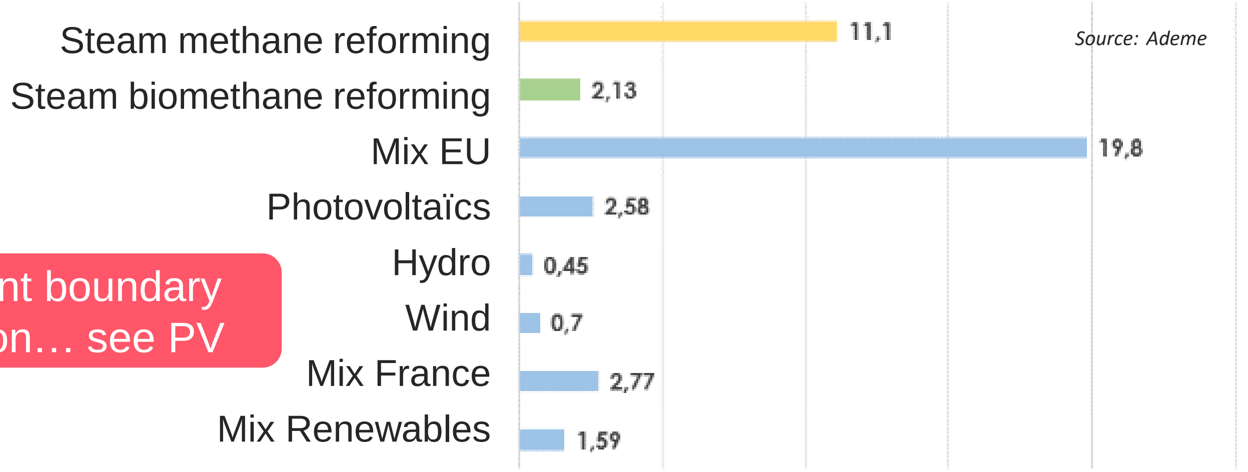
- **Carbon footprint ($\mathrm{kg_{CO_2}e/kg_{H_2}}$):** between <1 and >20 !

Figure 3.15 Comparison of the emissions intensity of different hydrogen production routes, 2021



Source: Global Hydrogen Review, International Energy Agency (IEA), 2023

Potentially different boundary limits for evaluation… see PV

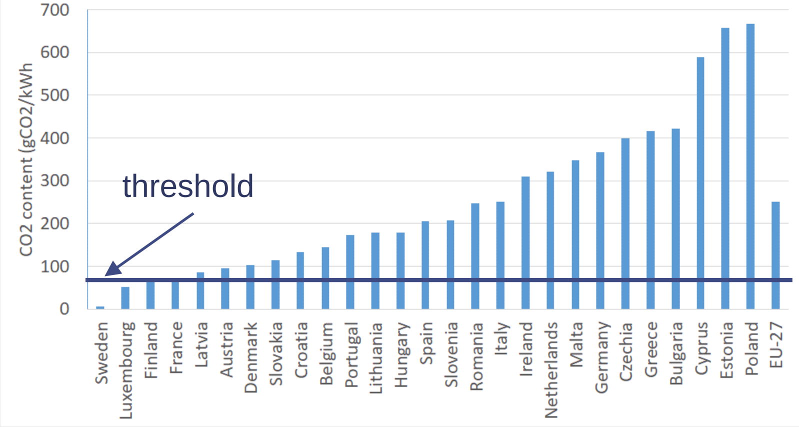


Source: Ademe

Low carbon hydrogen : **<3,38 $\mathrm{kg_{CO_2e}/kg_{H_2}}$**

- It requires electricity C content **< 67 $\mathrm{g_{CO_2}/kWh}$**
- Only 4 countries in EU have an electricity mix meeting this threshold

Carbon footprint of electricity in EU in 2022



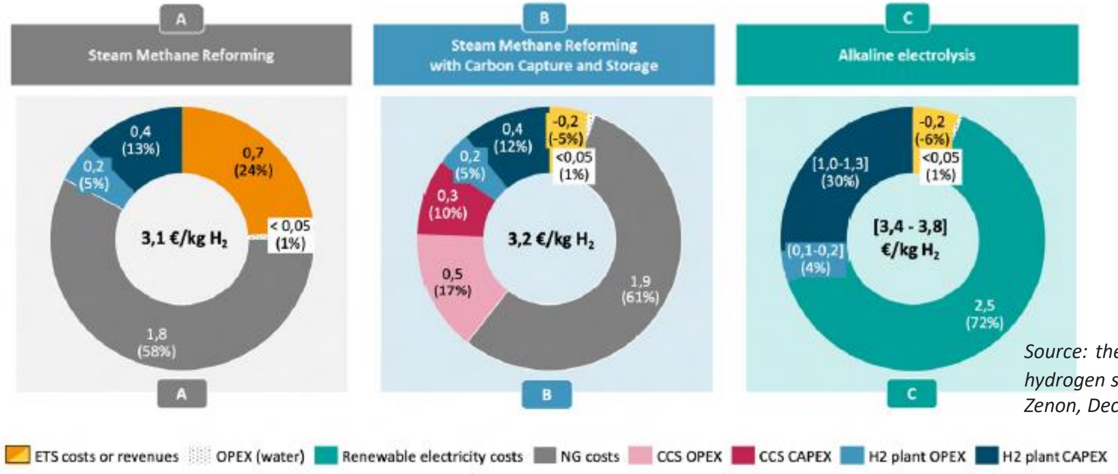
Source: European Environment agency

Carbon footprint:

- Depends on the process
- For electrolysis: depends on electricity origin
  - below 2.6 $\mathrm{kg_{CO_2}/kg_{H_2}}$ if renewable or nuclear
  - As high as 13.7 $\mathrm{kg_{CO_2}/kg_{H_2}}$ considering EU electricity mix (2022 value for EU-27)

Hydrogen production routes

- H_2 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

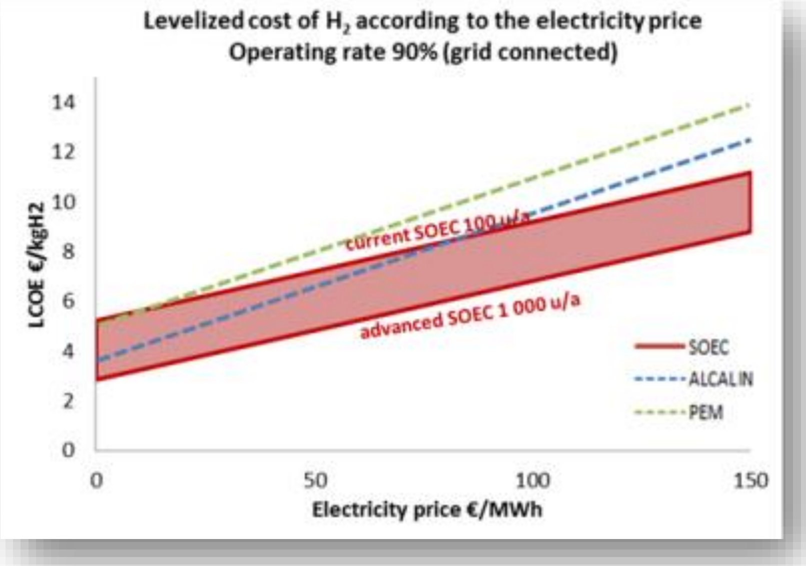
Price of natural gas:

- Impact on SMR 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.

Price of electricity:

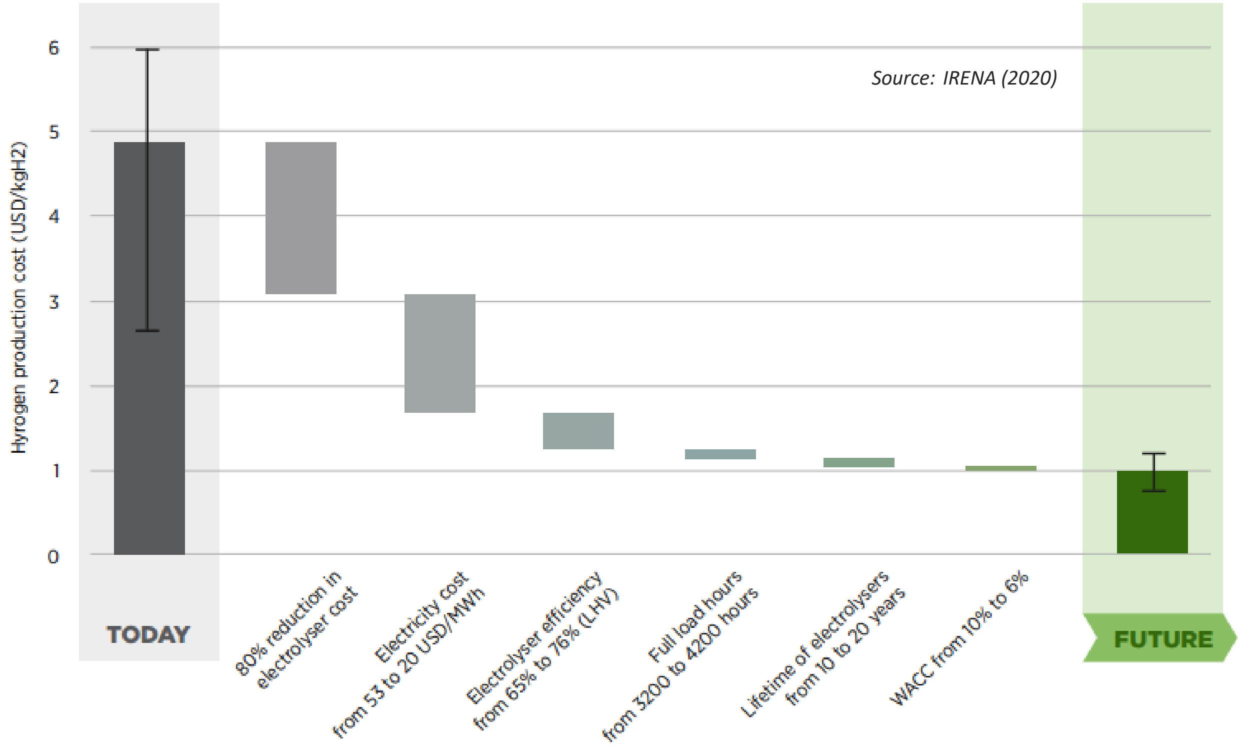
- Impact on electrolytic H_2 cost
  - If electricity 2 times more expensive, H_2 50% more expensive
  - H_2 produced with higher efficiency technology (SOEL) less sensitive



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

Hydrogen production routes

- **H_2 cost**
  - Other key parameters to be taken into account, optimised
    - CAPEX, efficiency, load factor, lifetime



Source: IRENA (2020)

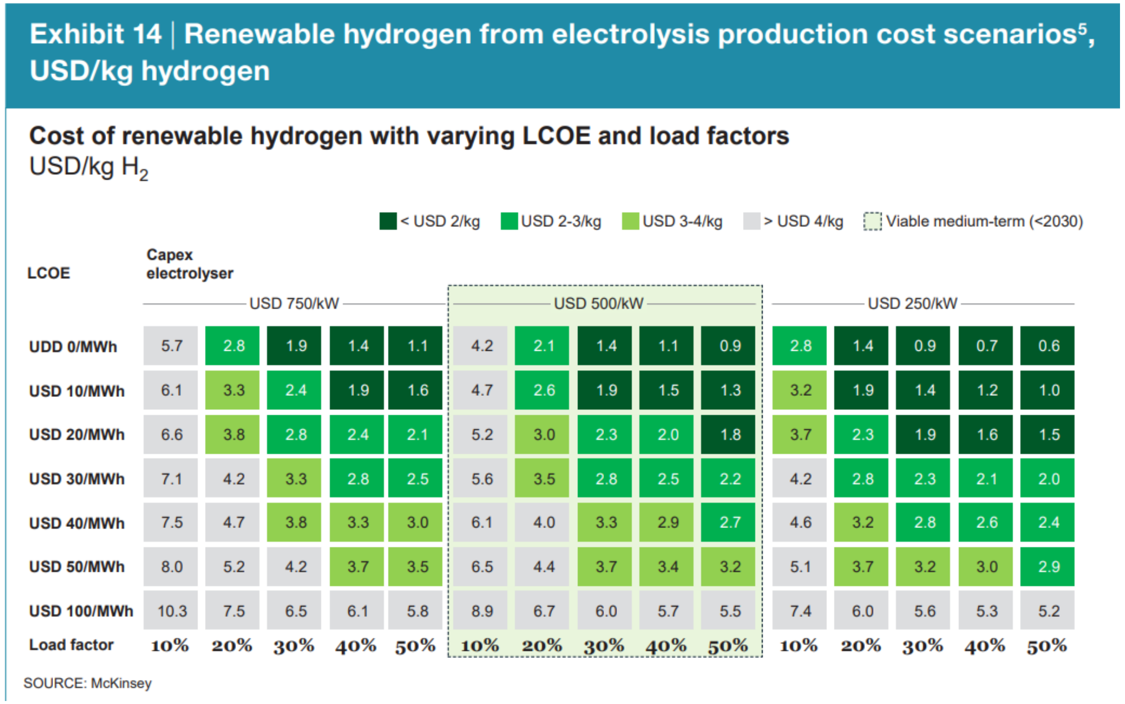


Exhibit 14 | Renewable hydrogen from electrolysis production cost scenarios[5], USD/kg hydrogen

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)

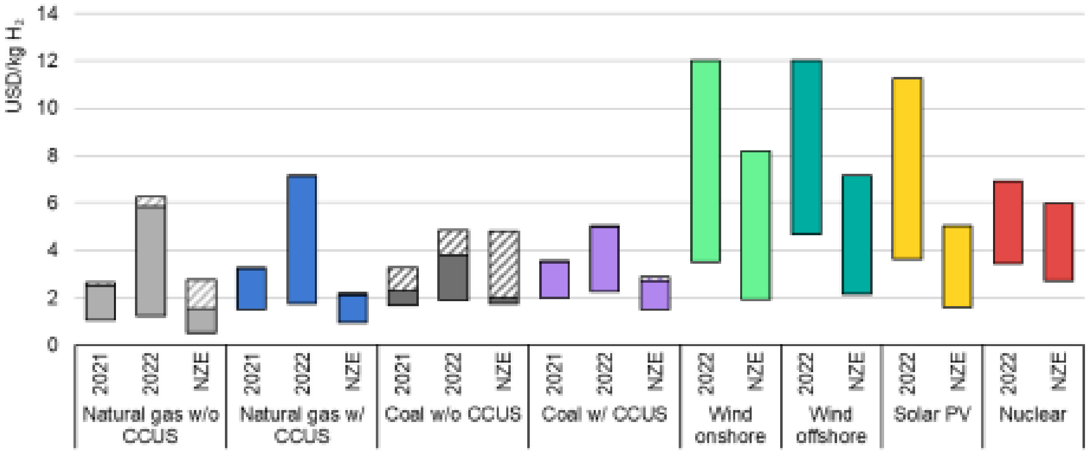
LCOE / **Capex electrolyser**	USD 750/kW					USD 500/kW					USD 250/kW				
UDD 0/MWh	5.7	2.8	1.9	1.4	1.1	4.2	2.1	1.4	1.1	0.9	2.8	1.4	0.9	0.7	0.6
USD 10/MWh	6.1	3.3	2.4	1.9	1.6	4.7	2.6	1.9	1.5	1.3	3.2	1.9	1.4	1.2	1.0
USD 20/MWh	6.6	3.8	2.8	2.4	2.1	5.2	3.0	2.3	2.0	1.8	3.7	2.3	1.9	1.6	1.5
USD 30/MWh	7.1	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

Hydrogen production routes

- **H_2 cost: synthesis**
- Cost in 2021 (before the war in Ukraine)
  - Fossile: 1 to 3 \$/kg H_2 up to 6 \$ (energy crisis)
  - Fossil + CCUS: 1.5 to 3.6 \$/kg H_2
  - Electrolysis: 3.5 to 10 \$/kg H_2
- Depends on the production technologies and the techno-economic hypotheses taken
  - Electrolysis: CAPEX (expected to fall), Electricity price, Electrolyzer load factor
  - Fossil and/or Fossile+CCUS: Cost of gas or coal, Carbon tax, Tax incentive for CO_2 storage, CAPEX if CCUS
- Outlook in 2030
  - Fossile:1 to 5\$/kg H_2
  - Fossil CCUS: 1 to 2\$/kg H_2
  - Electrolysis: 1.8 to 8\$/kg H_2

Figure 3.11 **Levelised cost of hydrogen production by technology in 2021, 2022 and in the Net Zero Emissions by 2050 Scenario in 2030**



IEA. CC BY 4.0.

Notes: CCUS = carbon capture, utilisation and storage; PV = photovoltaic; NZE= Net Zero Emissions by 2050 Scenario in 2030. Solar PV, wind and nuclear refer to the electricity supply to power the electrolysis process. NZE values refer to 2030. Natural gas price is USD 5-15/MBtu for 2021, USD 6-36/MBtu for 2022 and USD 1-8/MBtu for 2030 NZE. Coal price is USD 40-180/tonne for 2021, USD 50-360/tonne for 2022 and USD 30-70/tonne for 2030 NZE. Solar PV electricity cost is USD 22-120/MWh for 2022, USD 13-80/MWh for 2030 NZE, with capacity factor of 12-35%. Onshore wind electricity cost is USD 25-130/MWh for 2022, USD 25-120/MWh for 2030 NZE, with capacity factor of 15-53%. Offshore wind electricity cost is USD 50-225/MWh for 2022, USD 30-125/MWh for 2030 NZE, with capacity factor of 32-67%. The cost of capital is 6%.

The dashed area represents the CO_2 price impact, based on USD 15-140/t CO_2 for the NZE Scenario. More techno-economic assumptions will be made available in a separate forthcoming Annex.

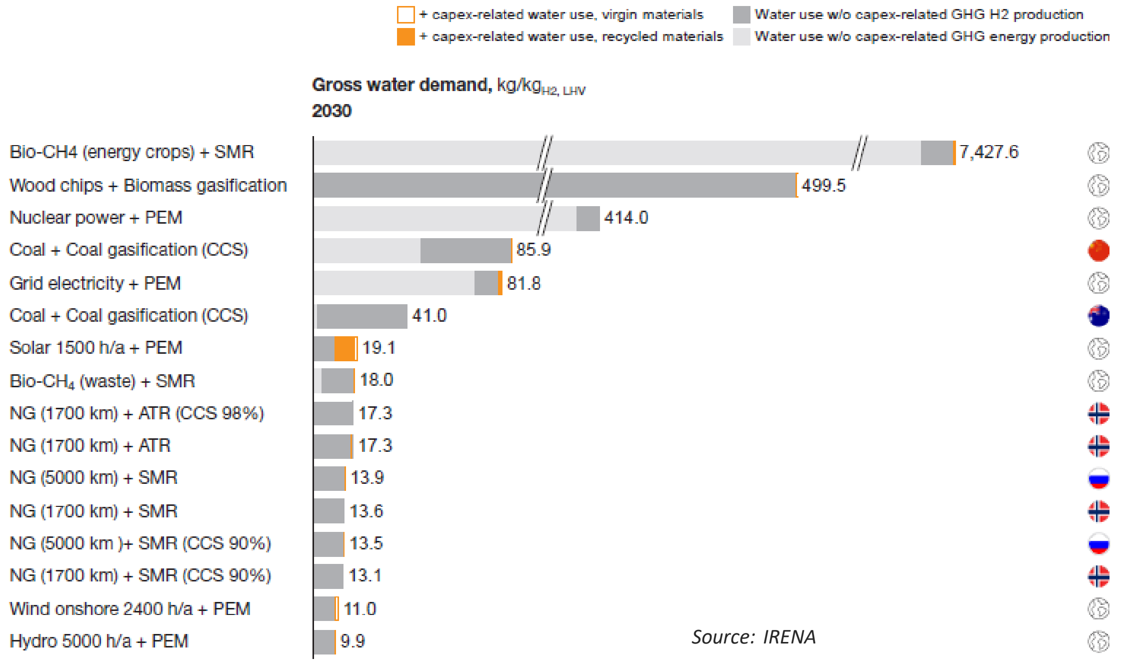
Sources: IEA analysis based on data from McKinsey & Company and the Hydrogen Council; IEA GHG (2014); NREL (2022); IEA GHG (2017); E4Tech (2015); Kawasaki Heavy Industries.

With natural gas prices subsiding from their 2022 highs, renewable hydrogen could become competitive with hydrogen from fossil fuels by 2030.

Source: IEA (2023)

Hydrogen production routes

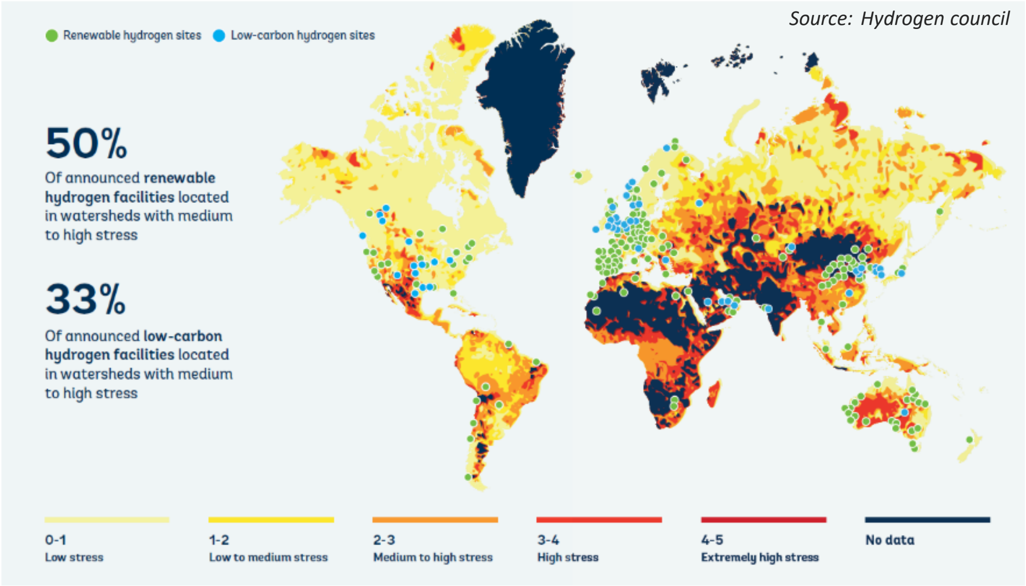
- **Water consumption**
  - Water consumption for all H_2 production technologies
  - Consumption varies between 10 to 19 kg of water per kg of H_2 for low carbon processes.
  - Water consumption indicated for nuclear power is significant but a large part of the water is released into groundwater
  - 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}
    - 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: IRENA

Source: Hydrogen Council, LBST

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



Source: Hydrogen council

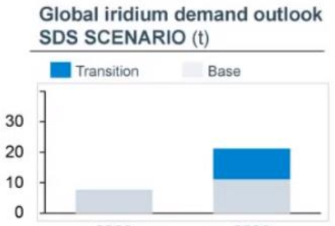
Hydrogen production routes

- **Use of Critical Raw Materials**
- **Case of electrolysis**

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

17-30%
of 2030 platinum demand from FCEVs & hydrogen electrolysers



35-50%
of 2030 iridium demand from hydrogen electrolysers

Source: KU Leuven, Eurometaux, Nov 2022

Source: EU CRM list (2023)

5. Conclusion

Conclusion

- **Hydrogen : expected to play a key role in the future climate-neutral economy**
  - Enabling emission-free transport, heating and industrial processes as well as inter-seasonal energy storage.
- **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 hydrogen 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
    - 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

cea liten

Thank you for your attention

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