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GREEN HYDROGEN AND ITS ROLE IN THE ENERGY TRANSITION

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Content

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- Hydrogen chemistry and physics, hydrogen derivatives
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- Electrolysers their technical and economic parameters role in balancing the variable renewable energy
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- Summary – developing the supply and demand of hydrogen

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Green Hydrogen and Decarbonization

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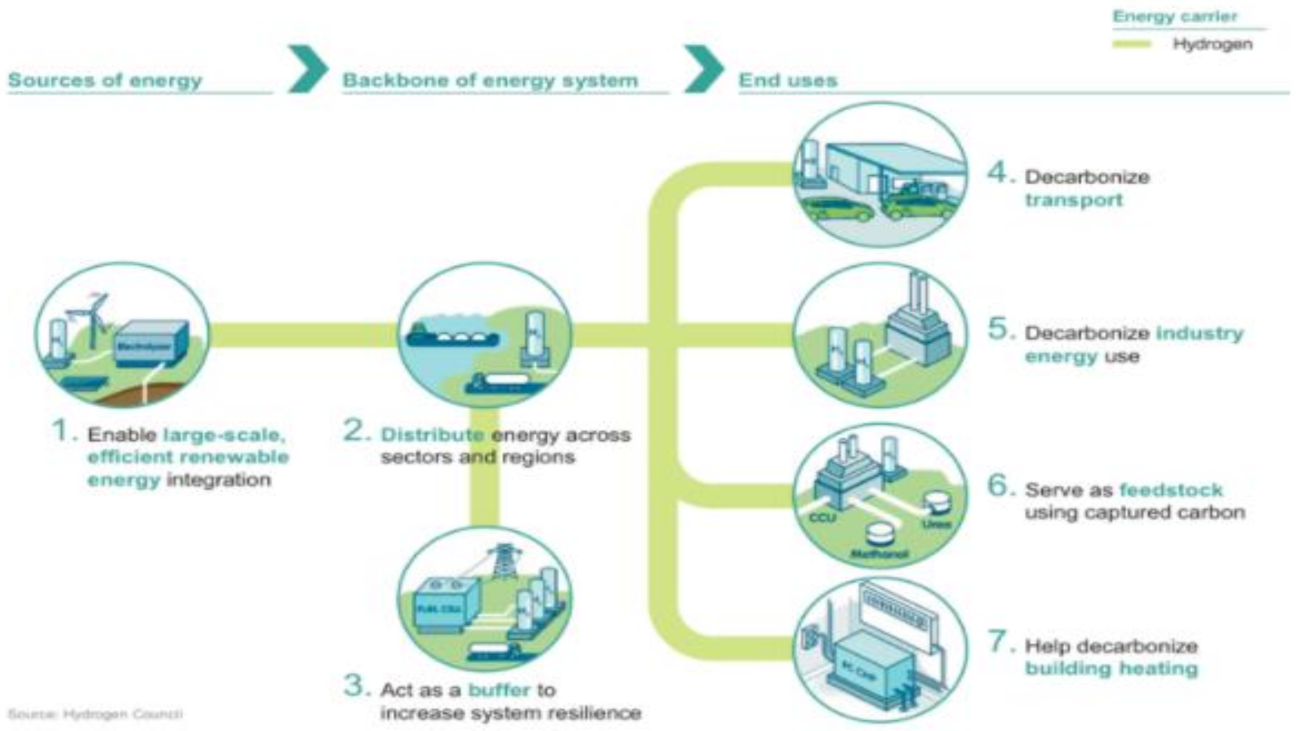
The obvious disastrous effects of climate change urge mankind for decisive action and hydrogen is a crucial part of it.
With international efforts the **green hydrogen obtained through electrolysis powered by renewable electricity from hydropower, water, solar and wind, is going to become an affordable and convenient agent for the storage, transportation, and use of renewable energy in various forms in different sectors of the economy**



The path to Net Zero is still there but accelerated and coordinated action is a **"Fierce Urgency"**
Hydrogen has to assure 4% of cumulative CO_2 reduction by 2050
Source: IEA

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Why hydrogen?

1. **Clean Energy Carrier:** Hydrogen can be produced from renewable wind, solar, and hydroelectric power, through electrolysis. It can store and transport clean energy.
2. **Decarbonizing Industries:** Hydrogen can replace fossil fuels in oil refining steel and cement production, where it's challenging
to electrify the processes. This substitution can significantly reduce carbon emissions from these sectors.
3. **Clean Transportation:** Hydrogen fuel cells can power vehicles, including cars, buses, trucks, and trains. Hydrogen fuel cell vehicles offer a longer driving range and shorter refueling time compared to battery electric vehicles, making them suitable for heavy-duty transport.
4. **Energy Storage:** Hydrogen can be stored and used as a backup energy source during high demand or low renewable energy
production. It can store large amounts of energy for long periods and thus complement batteries.
5. **Heating and Power Generation:** Hydrogen can be used in fuel cells to generate electricity and heat for residential, commercial, and industrial applications. This can be particularly useful in places where natural gas infrastructure is already established.
6. **Grid Balancing:** Hydrogen production in electrolysers and the reverse process in fuel cells can be used for balancing the demand and supply on the grid.

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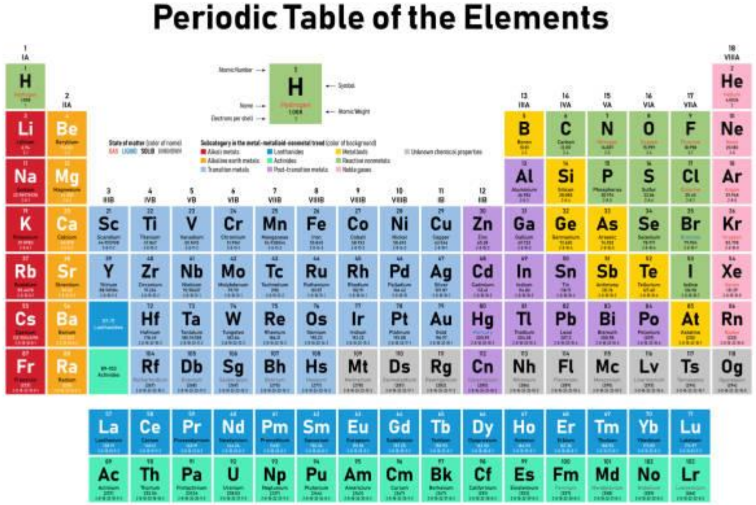
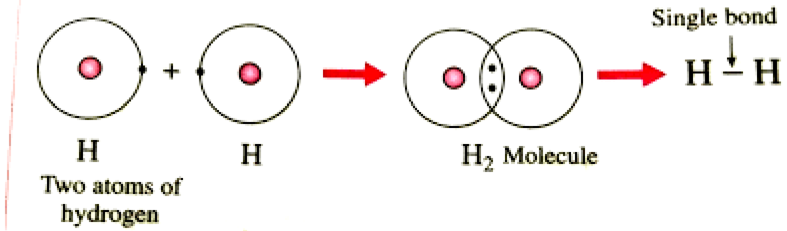
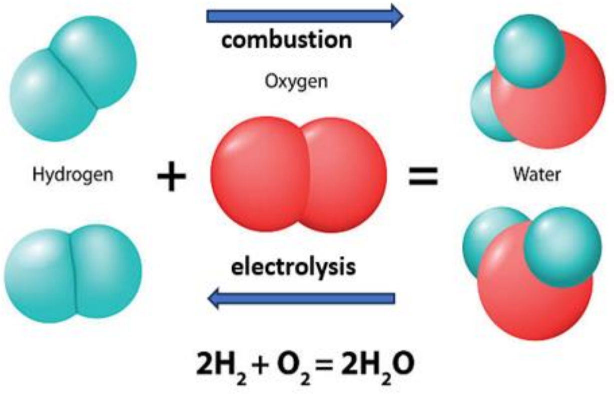
Hydrogen physics & chemistry

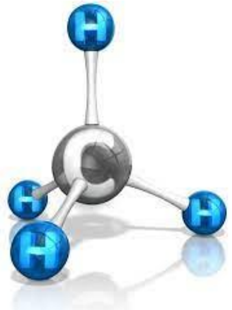






+ 33.3 kWh/kg H_2

- (50-55) kWh/kg H_2



Methane CH_4 9.8 kWh/Nm^3

Hydrogen H_2 - 3 kWh/Nm^3

1/3 of volumetric energy density compared to NG

Hydrogen today and its role in future energy system

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Pre-pandemic

Production

Total H_2 – 113MT/a

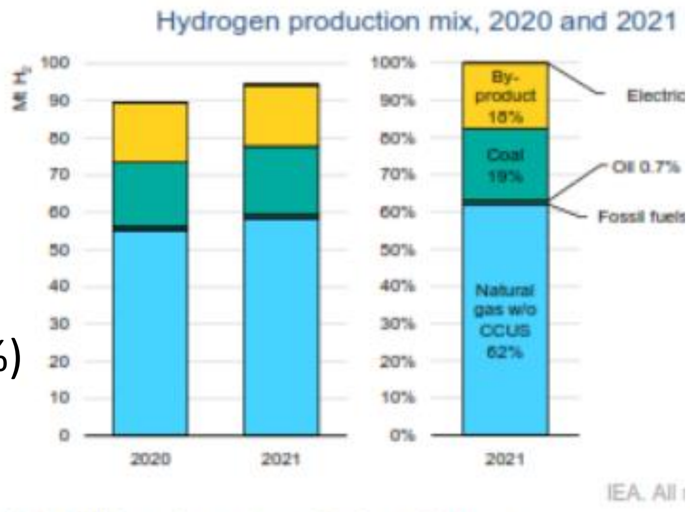
Use

43MT –ammonia and methanol (37%)

38MT – oil refineries (33%)

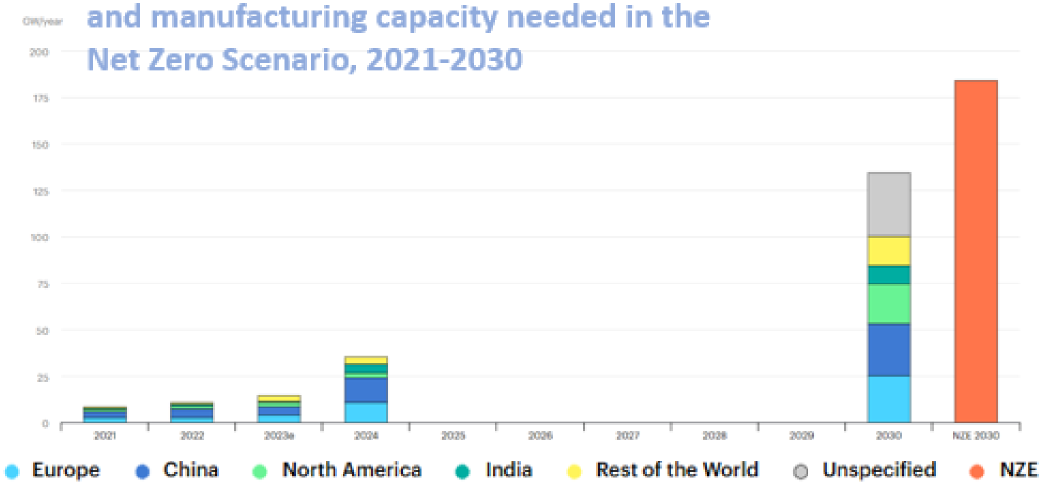
13MT – steel production (11%)

21MT – other (18%)



Note: CCUS = carbon capture, utilisation and storage.

Announced electrolyser manufacturing capacity by region and manufacturing capacity needed in the Net Zero Scenario, 2021-2030



Source: Electrolysers - Energy System - IEA

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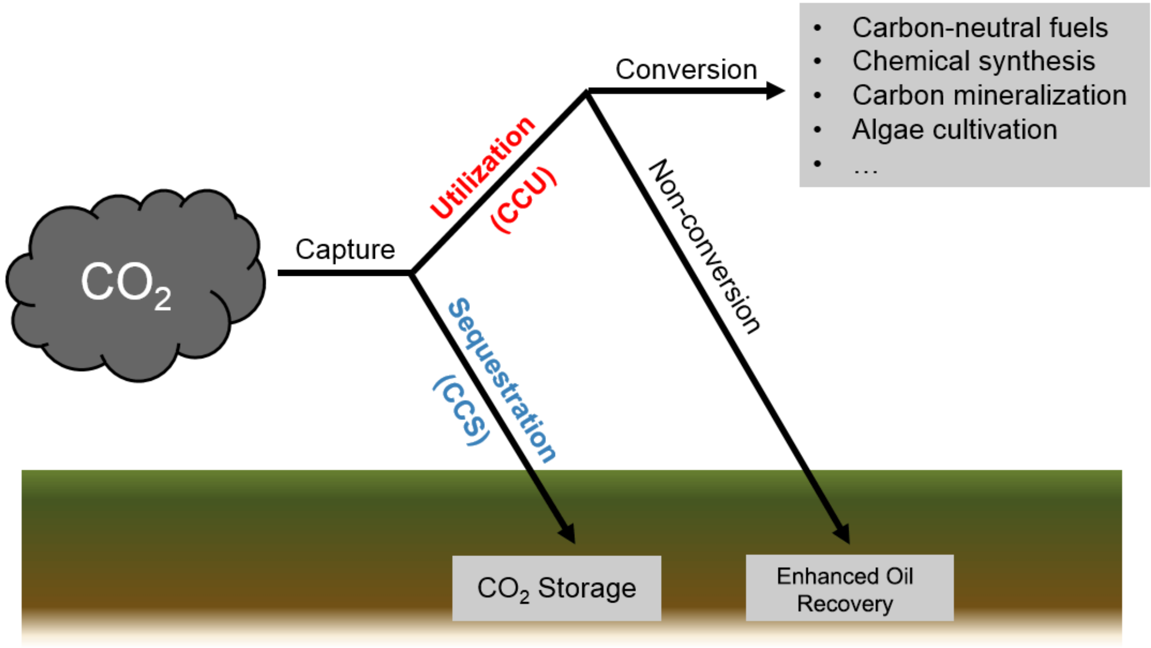
Methane Steam reforming is the main current source of hydrogen

- Produced CO_2 adds to climate change Carbon Capture Utilization and Storage is needed CCUS.

Methane Steam reforming

$$CH_4 + H_2O \leftrightarrow CO + 3H_2$$
$$CO + H_2O \leftrightarrow CO_2 + H_2$$
$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$$



Hydrogen Production methods and hydrogen palette

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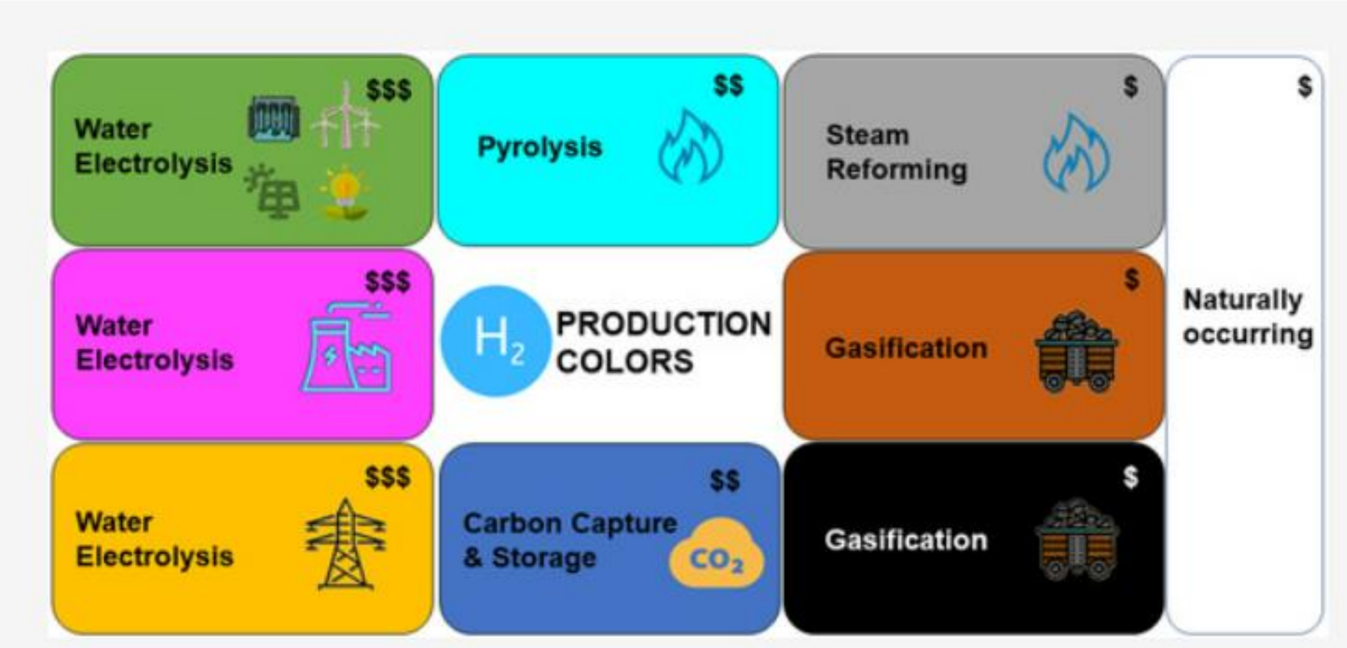
Colour	Fuel	Process	Products
Brown/Black	Coal	Steam reforming or gasification	$H_2 + CO_2$ (released)
White	N/A	Naturally occurring	H_2
Grey	Natural Gas	Steam reforming	$H_2 + CO_2$ (released)
Blue	Natural Gas	Steam reforming	$H_2 + CO_2$ (% captured and stored)
Turquoise	Natural Gas	Pyrolysis	$H_2 + C$ (solid)
Red	Nuclear Power	Catalytic splitting	$H_2 + O_2$
Purple/Pink	Nuclear Power	Electrolysis	$H_2 + O_2$
Yellow	Solar Power	Electrolysis	$H_2 + O_2$
Green	Renewable Electricity	Electrolysis	$H_2 + O_2$

Source: The many colours of hydrogen | Sustainable NI



Source: Gases | Free Full-Text | The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production (mdpi.com)

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Low-Emission Hydrogen Projects Globally

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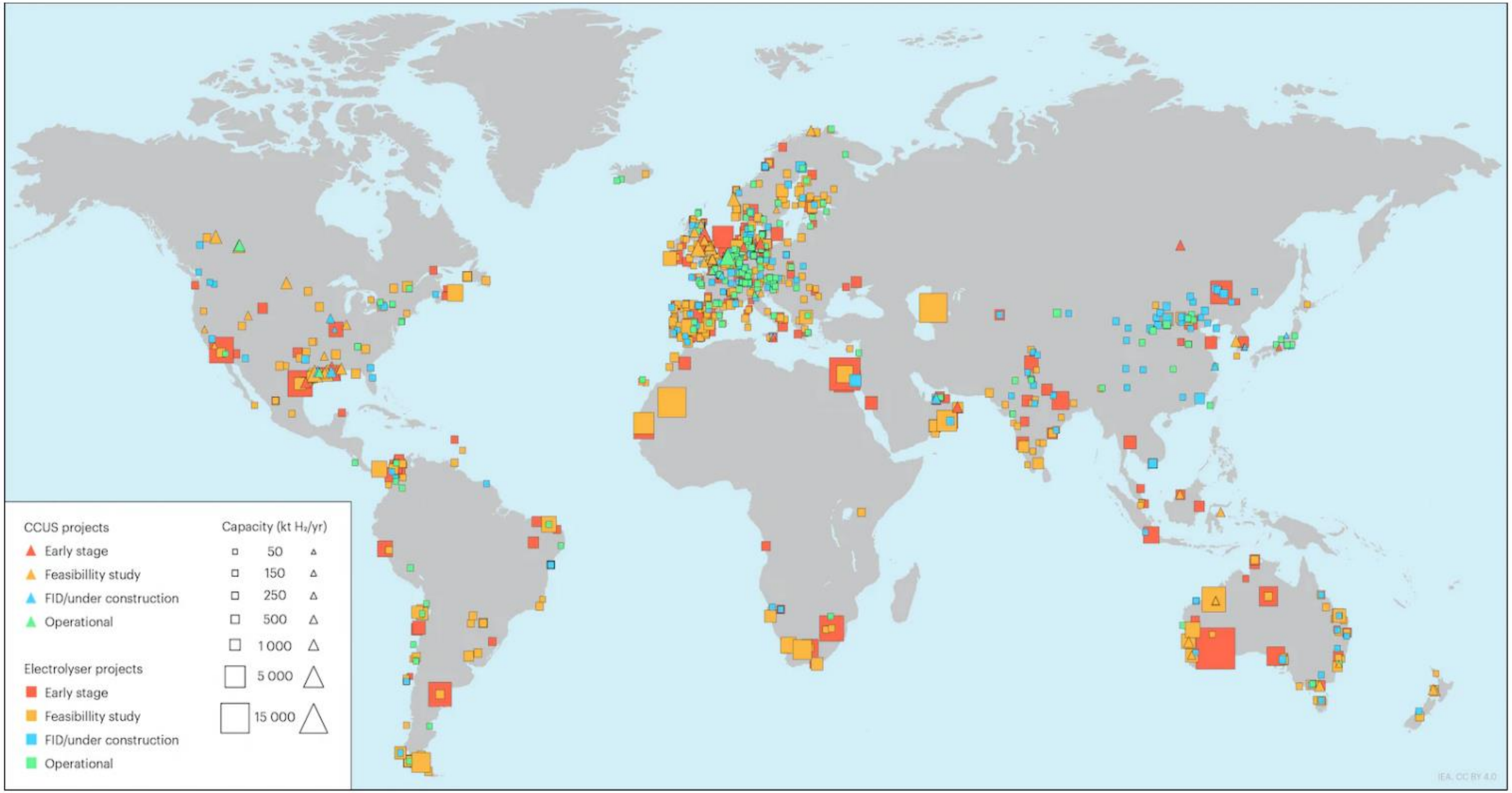

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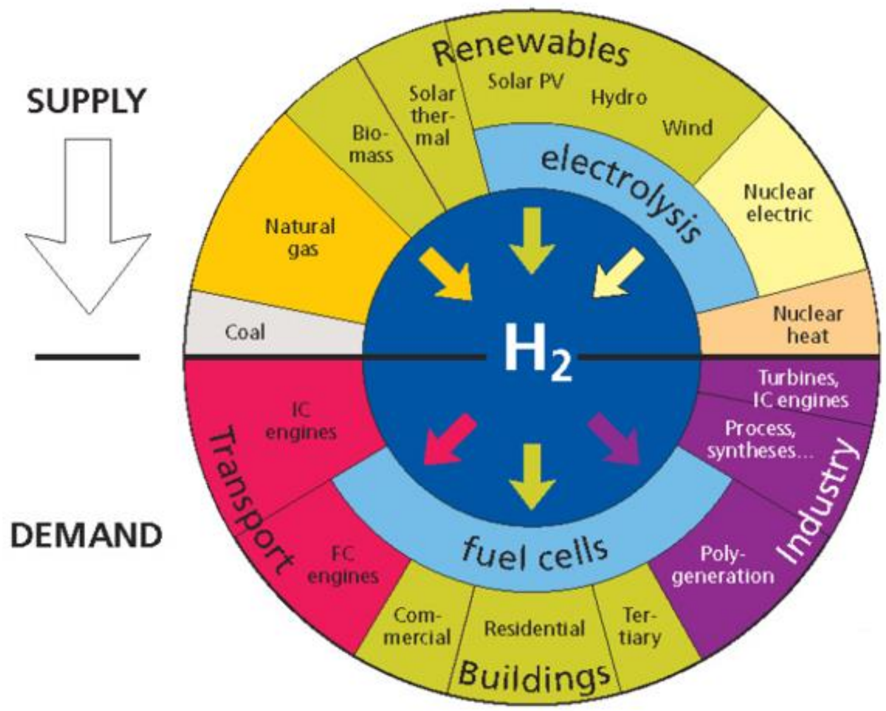
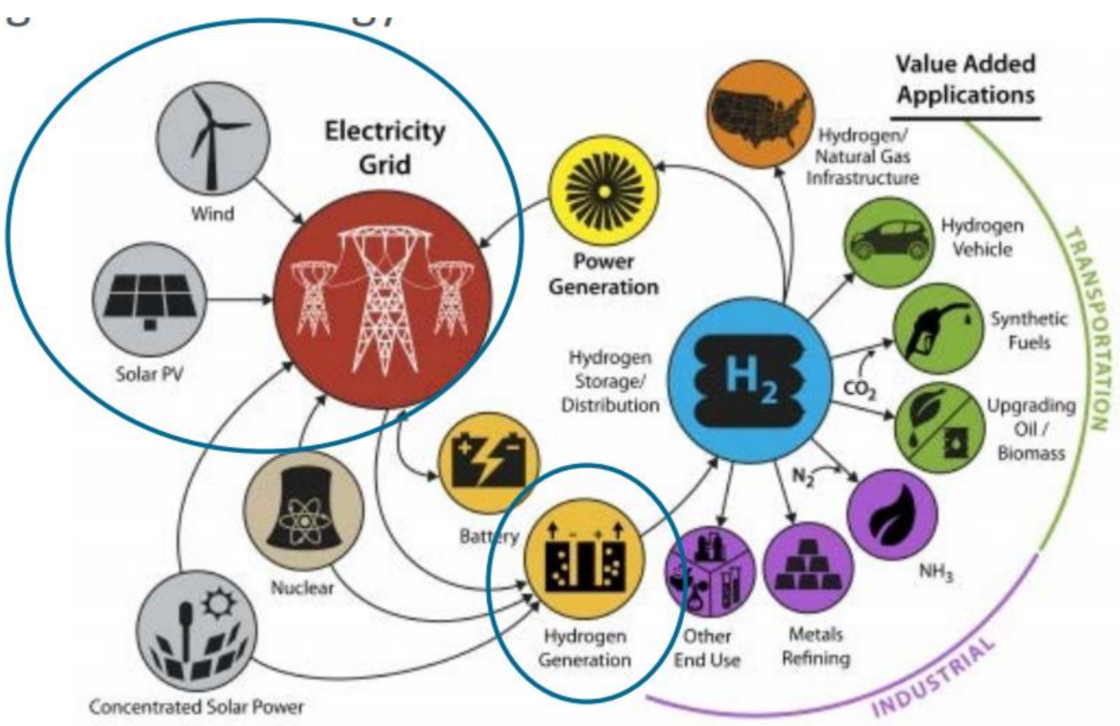
Deployment of hydrogen for decarbonization a systemic task





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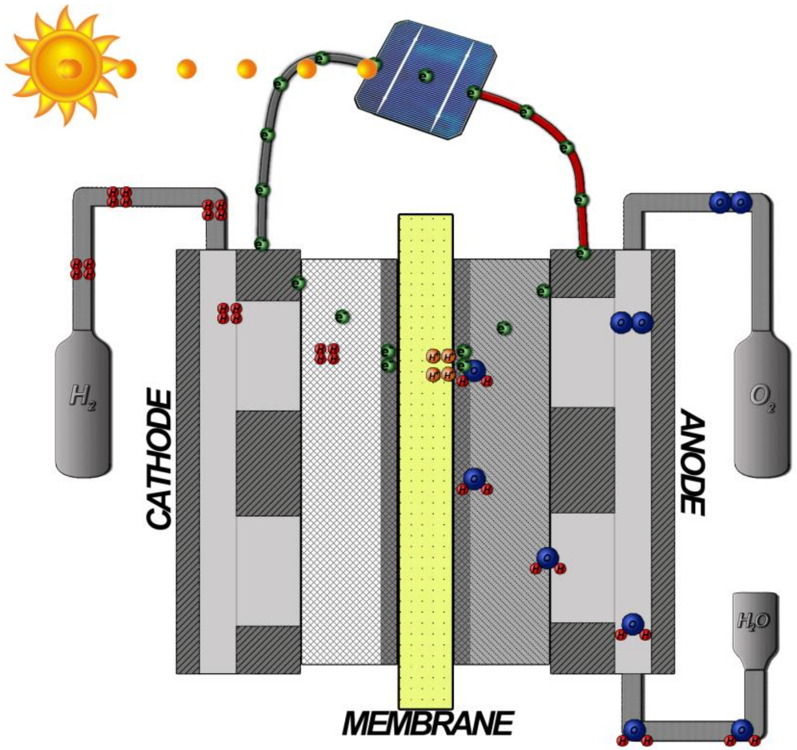
Electrolysis

Alkaline Electrolyser

PEM Electrolyser



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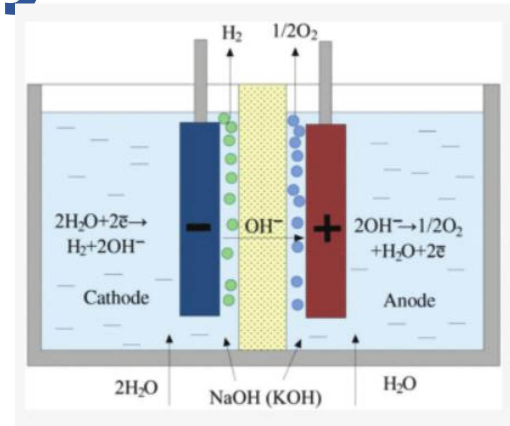
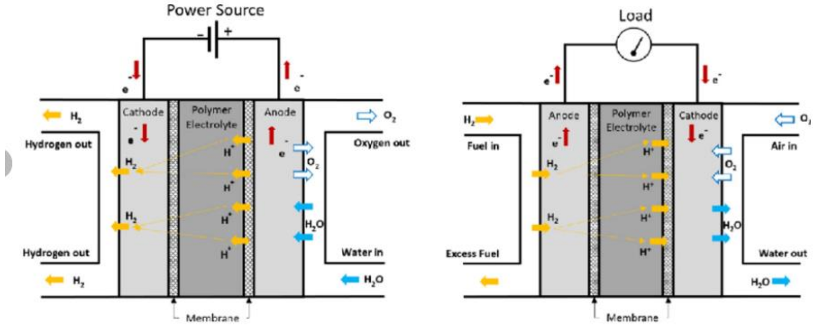
Electrolyzers

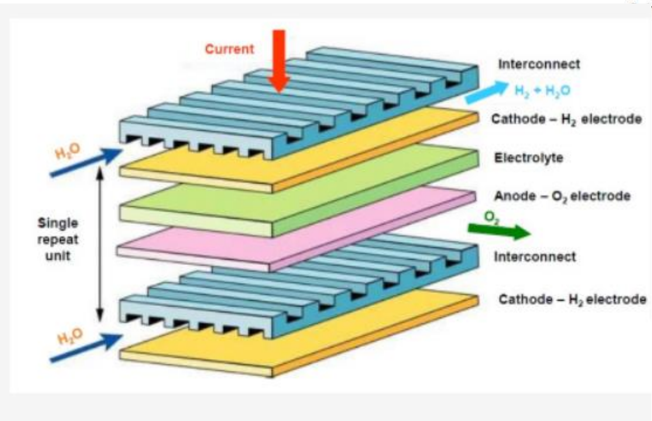


- Alcaline electrolyzers
  - Proven



hematics of PEM devices: electrolyzer (left) and fuel cell (right).

- Proton Exchange Membrane PEM
  - Flexible reversible



- Sodium Oxide fuel cells
  - High temperature
  - Higher efficiency

Fuel Cell Types

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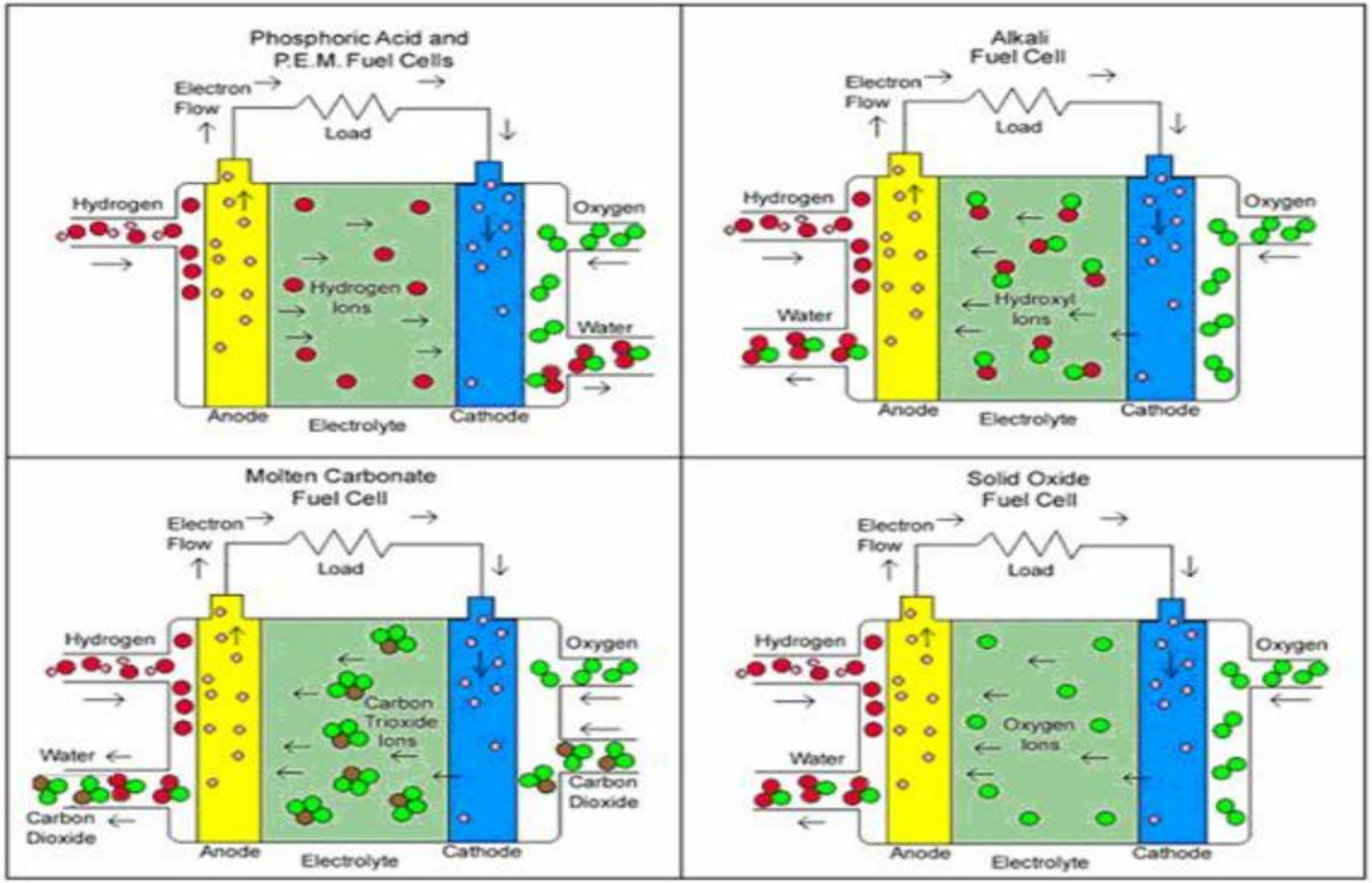

Types of Electrolyzers

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	Temperature °C	Electrolyte	Plant size		Efficiency	Purity H_2	System costs	Lifespan	Maturity level
Alkaline Electrolysis (AE)	60 – 80	Potassium-hydroxid	0.25 – 760 $Nm^3\ H_2/h$	1.8 – 5,300 kW	65 – 82 %	99.5% – 99.9998 %	1,000 – 1,200 €/kW	60,000 – 90,000 h	Commercially used in industry for the last 100 years
Proton Exchange Membrane Electrolysis (PEM)	60 – 80	Solid state membrane	0.01 – 240 $Nm^3\ H_2/h$	0.2 – 1,150 kW	65 – 78 %	99.9% – 99.9999 %	1,900 – 2,300 €/kW	20,000 – 60,000 h	Commercially used for medium and small applications (<300 kW)
Anion Exchange Membrane Electrolysis (AEM)	60 – 80	Polymer membrane	0.1 – 1 $Nm^3\ H_2/h$	0.7 – 4.5 kW	N/A	99.4%	N/A	N/A	Commercially available for limited applications
Solid Oxide Electrolysis (SOE)	700 – 900	Oxide ceramic	Until now at experimental stage in laboratories		85% (lab)	N/A	N/A	approx 1,000 h	Experimental stage

E4tech 2014; IEA 2015b; own diagram

Hydrogen uses

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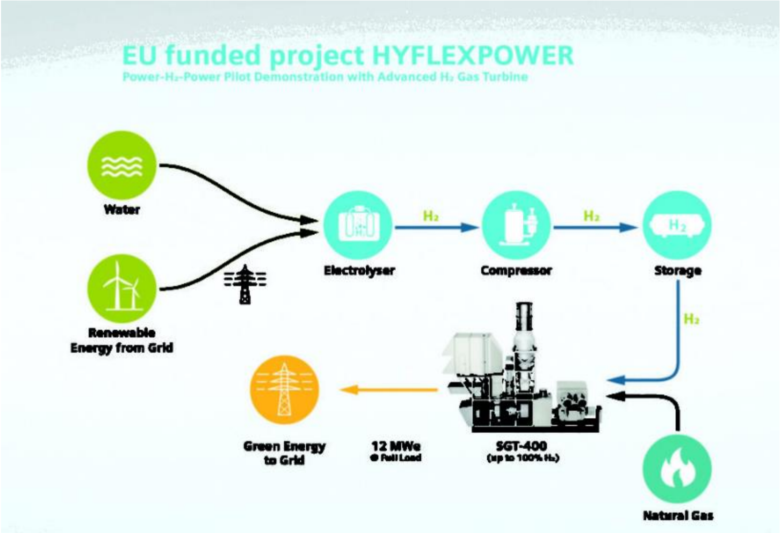
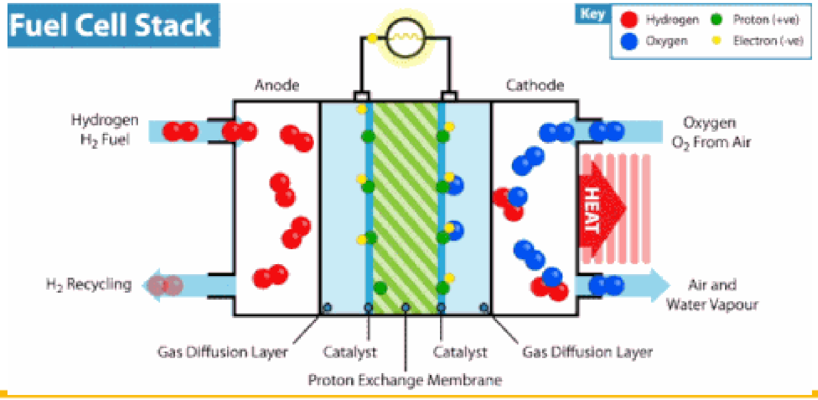
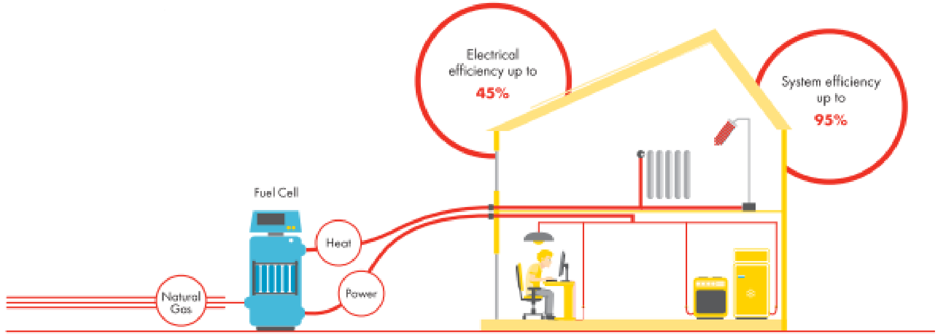


- Electricity generation
  - Cofiring of gas turbines and engines

- Electricity and heat for homes and industries





Fuel Cell characteristics

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Fuel cell type	Temperature range °C	Electrical performance	Fuel	Efficiency η_{el} (H_i)	Investment costs USD/kW_{el}	Life expectancy (h)	Market development	Application
AFC	60 – 90	Up to 250 kW	H_2	50 – 60%	200 to 700	5,000 to 8,000	Established for decades, but limited to specialised applications	Space travel, submarines
PEMFC	50 – 90 (LT) up to 180 (HT)	From 500 W to 400 kW	H_2, gas, syngas, biogas, methanol (external reforming)	30 – 60% (depending on size and application)	3,000 to 4,000 (stationary) ~500 (mobile)	60,000 (stationary) 5,000 (mobile)	Early market / mature leading fuel cell type	Vehicle drivetrains, space travel, micro + block-type CHP, backup power
PAFC	160 – 220	Up to several 10 MW	H_2, gas, syngas, biogas, methanol (external reforming)	30 – 40%	4,000 to 5,000	30,000 to 60,000	Mature (low volume)	Decentralised power generation, block-type CHP
MCFC	600 – 700	From a couple of 100 kW to several MW	H_2, gas, syngas, biogas, methanol (internal reforming)	55 – 60%	4,000 to 6,000	20,000 to 40,000	Early market / market introduction (especially for bigger plants)	Power plants (base load), CHP (process heat/steam)
SOFC	700 – 1,000	From a couple of kW to several MW	H_2, gas, syngas, biogas, methanol (internal reforming)	50 – 70%	3,000 to 4,000	up to 90,000	Mature (volumes rising)	Power plants, CHP (process heat/steam), micro + block-type CHP

Wagner 1996; Dienhart/Hassmann 1993, updated with IEA 2015b, EA NRW 2017 [www.brennstoffzelle-nrw.de] and own additions

https://hydrogeneurope.eu/sites/default/files/shell-h2-study-new.pdf

1.4 MW Fuel Cell in Germany

Natural gas powered 1.4-MW fuel cell designed by Dresden-based FuelCell Energy Solutions
- NG reforming to produce H_2
- an electrical efficiency of 47%.
- 11.2 GWh of electricity and 6 GWh of heat about 60% of the total energy requirements for [FRIATEC's] production processes,"
- Process heat of up to $400C^0$—used as steam, hot water, in the industrial production processes.
- overall efficiency of more than 90%.

E.On and FuelCell Energy Solutions
Manheim, Germany.

https://www.powermag.com/europe-gets-first-mw-scale-industrial-fuel-cell-power-plant/

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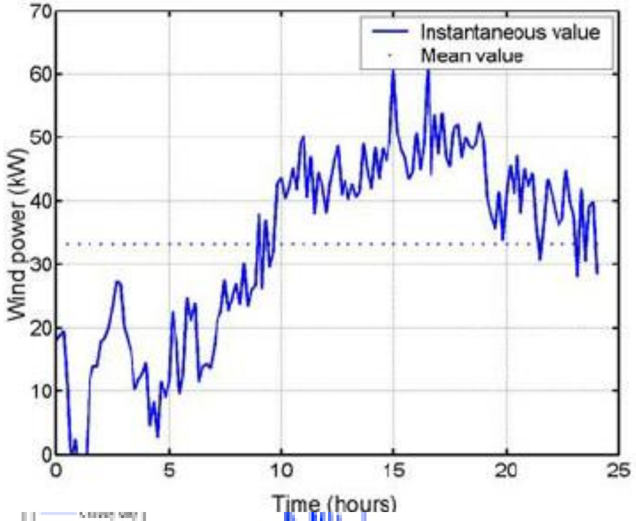
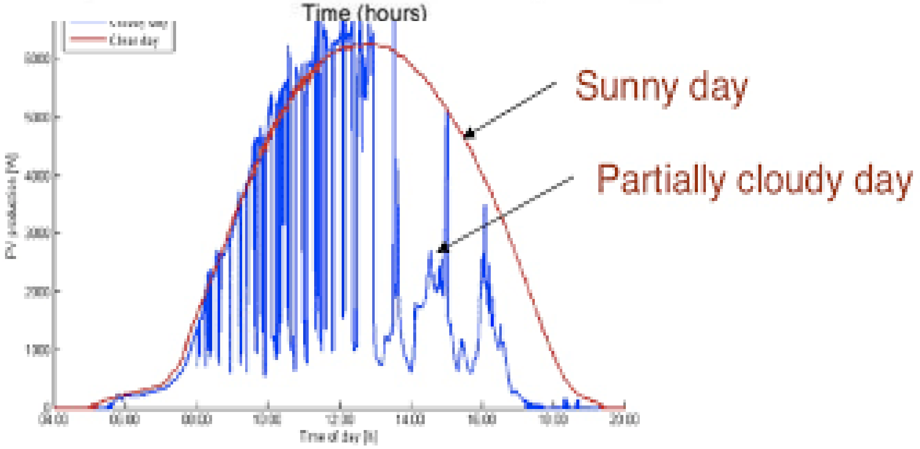
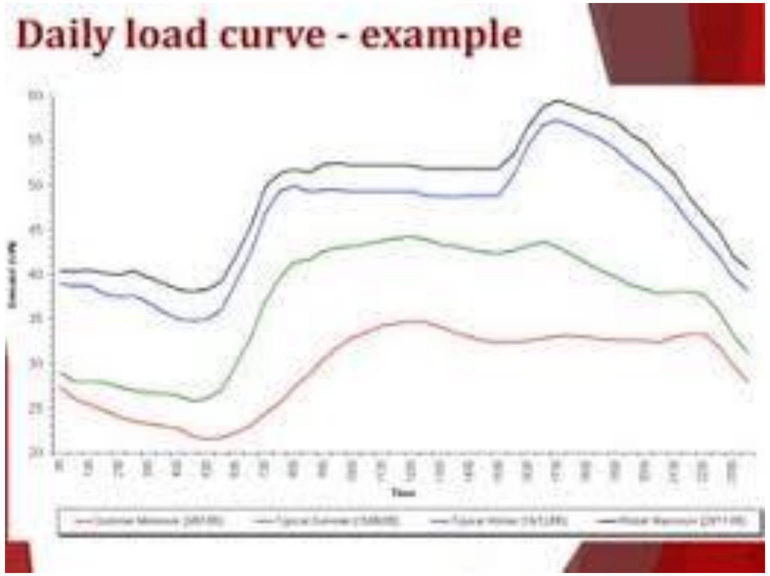
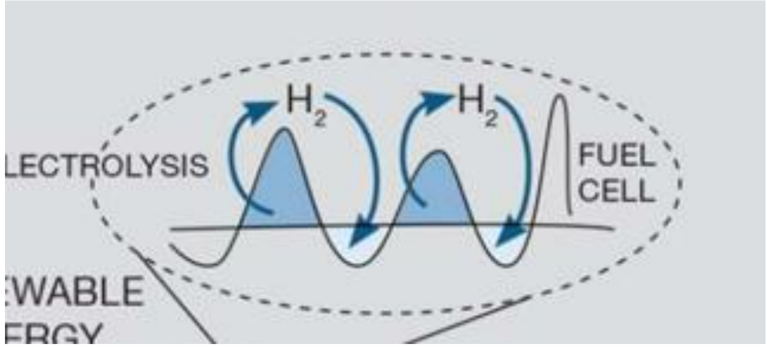
Accommodation of Solar and Wind Generation into the Grid









[24-hour wind power profile for Wales Village. | Download Scientific Diagram (researchgate.net)](researchgate.net)

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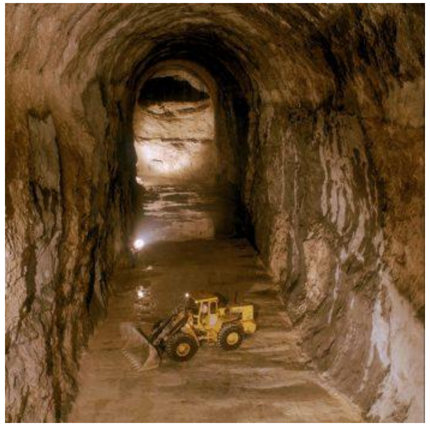
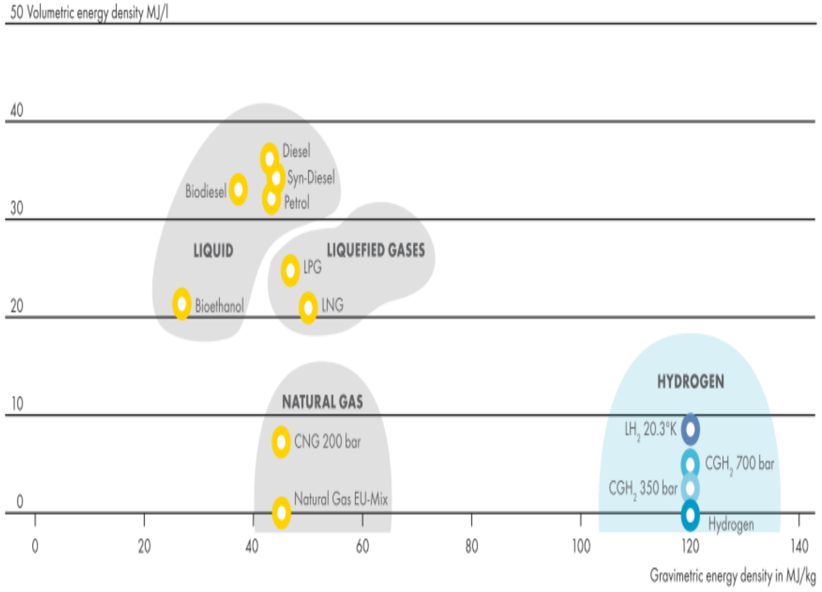
Hydrogen storage and transportation





Geological Storage (Salt caverns)

Storage of compressed hydrogen 500-700bar

Liquefied hydrogen -253^{0}C

Chemical storage - Paladium hydrid 900 times volume of H_2

Ammonia and methanol

https://hydrogeneurope.eu/sites/default/files/shell-h2-study-new.pdf

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Hydrogen Transportation

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COMPRESSED GAS CONTAINERS

At standard conditions (1.013 bar and 0 °C), the density of hydrogen is 0.0899 kg per cubic meter (m3). and 33 kg H 2 / m 3 at 500 bar. Target is 700 bar. TTaargen

Liquid Hydrogen transportation

Temperature -253^{0}C low pressure

www.ebay.com

Transportation by Pipelines

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(2016) Total of 4500 km of pipelines in the world

H_2 blending in gas pipelines

US estimate (5 – 15)% by volume

Germany - 10% by volume.

Obstacles

Higher pressure for pumping

Lower volumetric energy density

Tighter fittings and quality steel are needed

https://hydrogeneurope.eu/sites/default/files/shell-h2-study-new.pdf

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- Deblending costs $(0.5-0.8)/kg   H2SITE estimates
  - point of hydrogen (-253 °C) compared to natural gas (-162 °C)
- The transport of hydrogen in the form of LH_2 may be attractive for users requiring high purity hydrogen.
  - Hydrogen liquefaction and storage are mature technologies
  - approximately 10 kWh/kg equivalent to around 30% of the energy content (lower heating value)

Around 130 kg hydrogen is required as feedstock per tonne of

- methanol.
  - The 113 Mt methanol produced in 2021 globally led to
  - around 15 Mt of hydrogen demand, and virtually 100% of this
  - production was from fossil fuels

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Hydrogen in Transport

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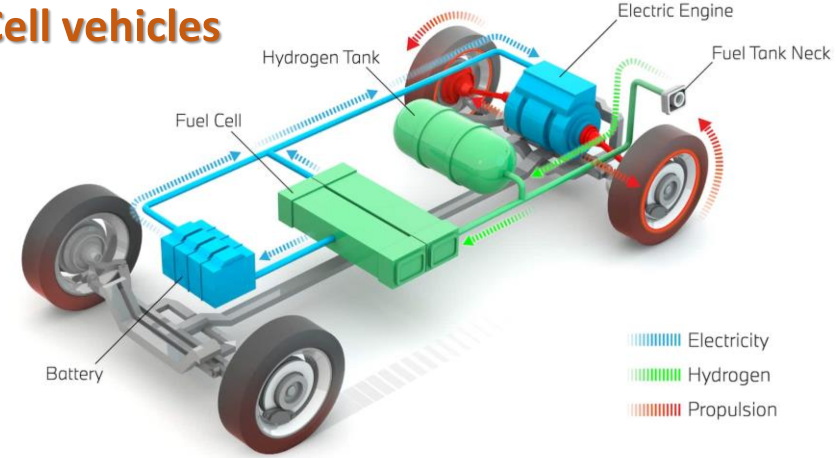
Fuel Cell vehicles



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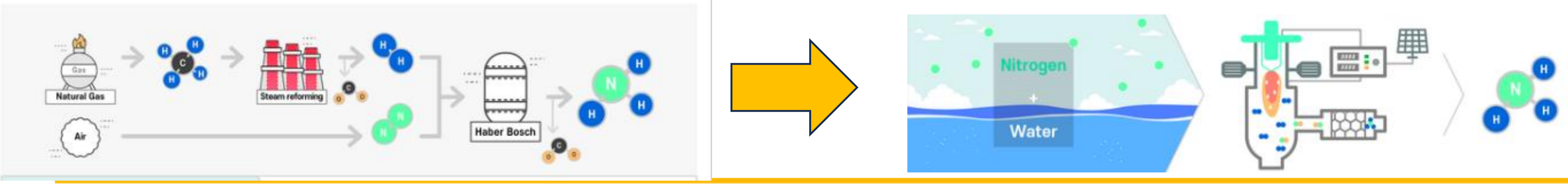
Decarbonization of Industry

- **Steel Industry**
  - DRI – Direct Iron Reduction
  - Hydrogen for heat
- **Cement industry**
  - Cofiring
  - Carbon capture and utilization CCU – profuction of syngas and other fuels
- **Refining**
  - Use of GH_2 for cracking the oil compound molecules
- **Green fertilizer industry**



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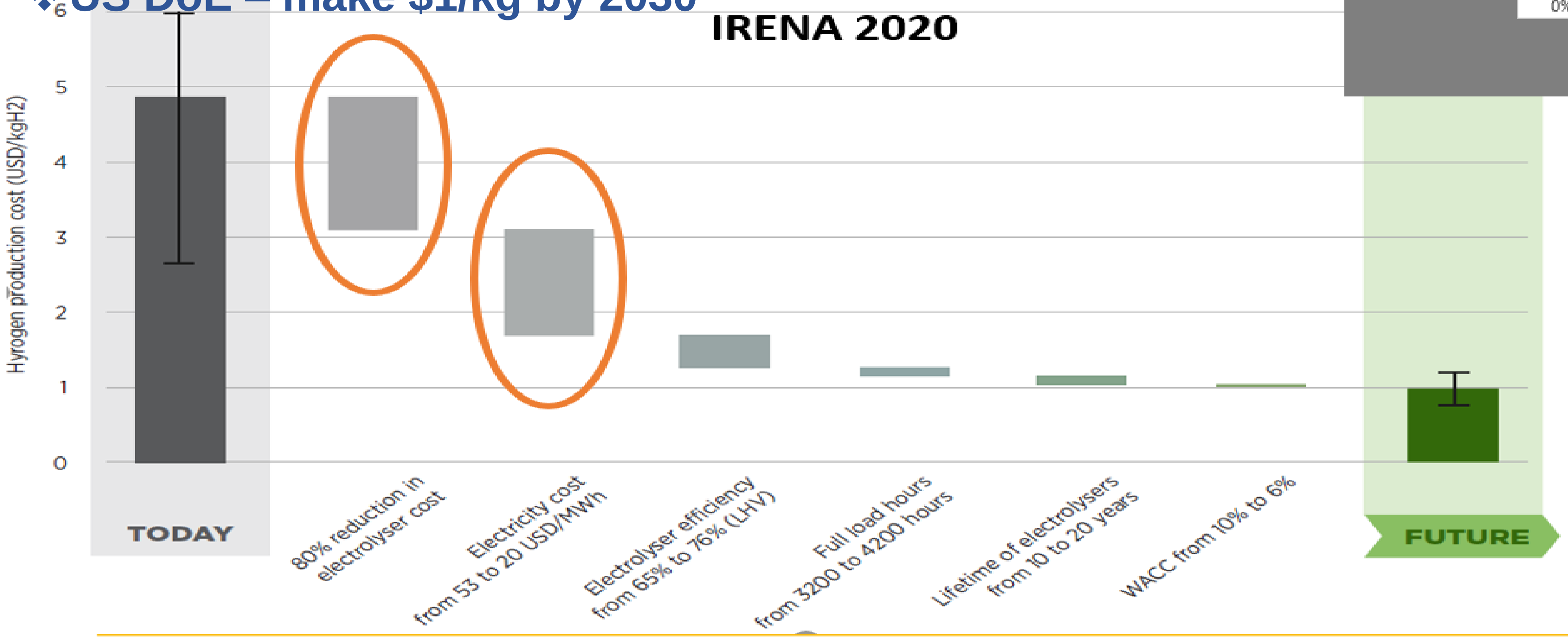
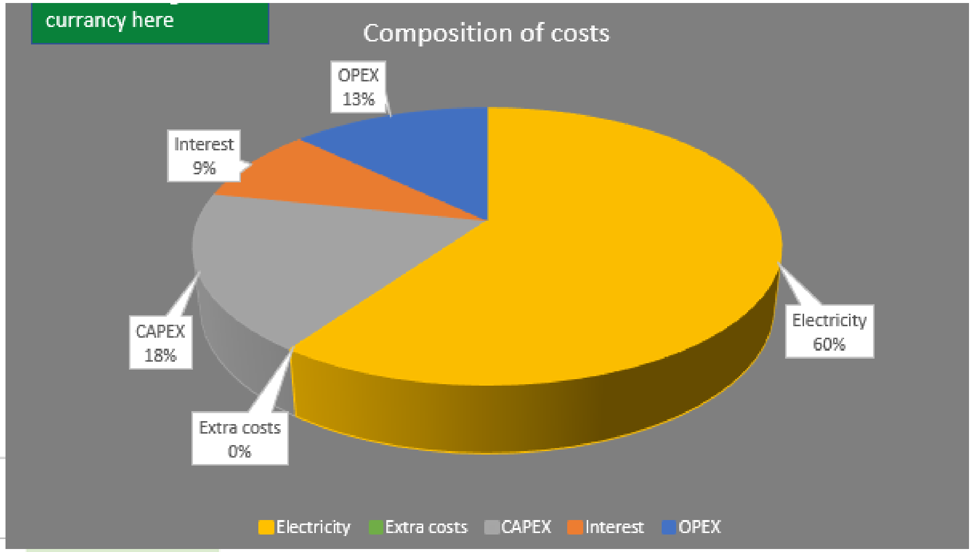
Green Hydrogen Cost

- ❖ Current cost of Green hydrogen € 3-8/kg
- ❖ Cost of grey hydrogen €1-2/kg
- ❖ **US DoE – make $1/kg by 2030**





Source: grinix.de
Parameters:
electricity € 50/MWh
Operating time 6000h/a
Interest -3%
Depreciation – 20y.

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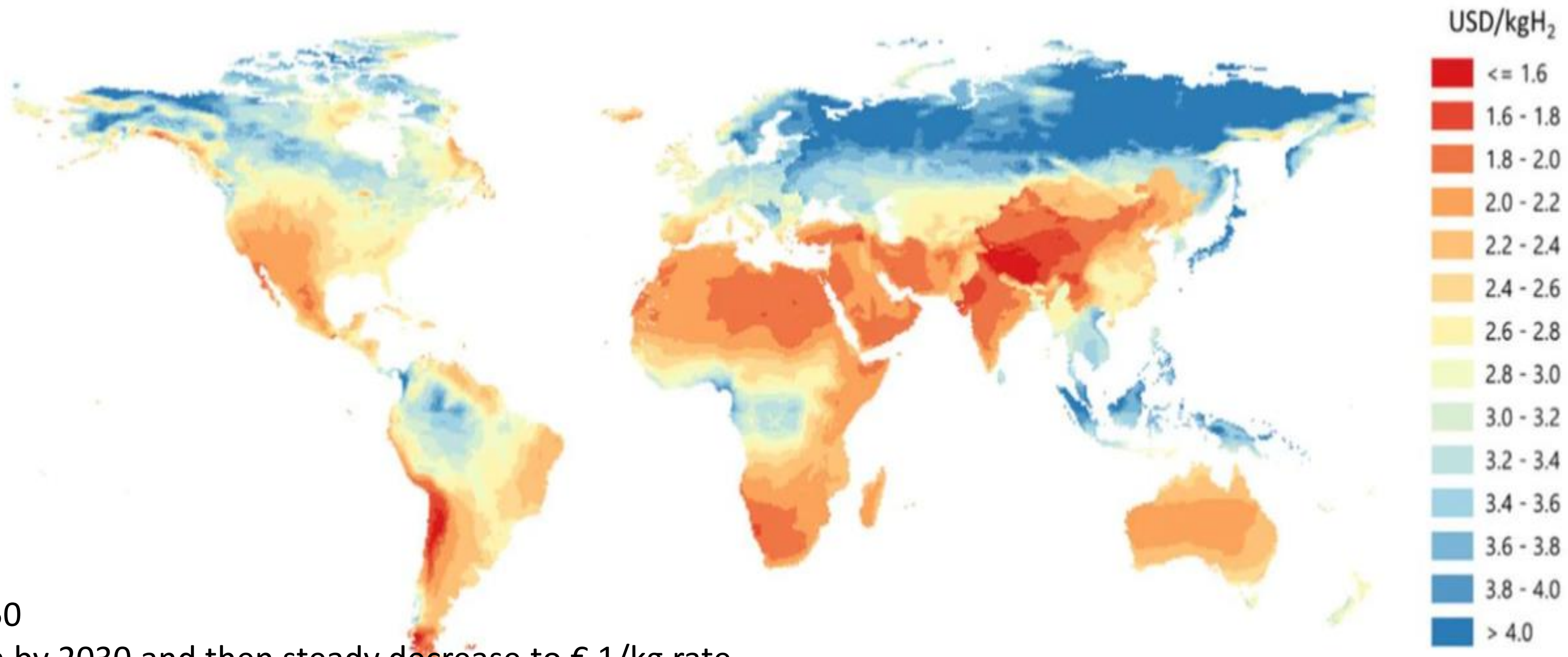
Prospective price of h_2



PWC projection 2050

- 50% cost reduction by 2030 and then steady decrease to € 1/kg rate until 2050.
- By 2050, green hydrogen production costs in some parts of the Middle East, Africa, Russia, China, the US and Australia will be in the range of €1/kilogram.

Source:Analysing the future cost of green hydrogen | PwC

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Hydrogen derivatives

- Ammonia
  - feedstock for fertilizers - 20 million tonnes per year (Mtpa), and 195 ammonia terminals at over 120 ports.
  - Cofiring in coal PPt
  - Shipping fuel
  - Cracking – takes 30% of energy
- Methanol
  - Feedstock for chemical processes 15Mt/a -2021.
  - Can be used as a car fuel

$$2N_2 + 3H_2 \rightleftharpoons 2NH_3$$

Nitrogen Hydrogen Ammonia

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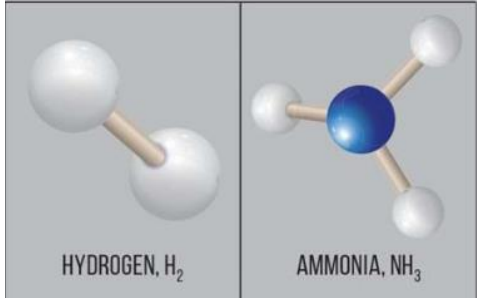
Ammonia (NH_3) a carrier for GH_2

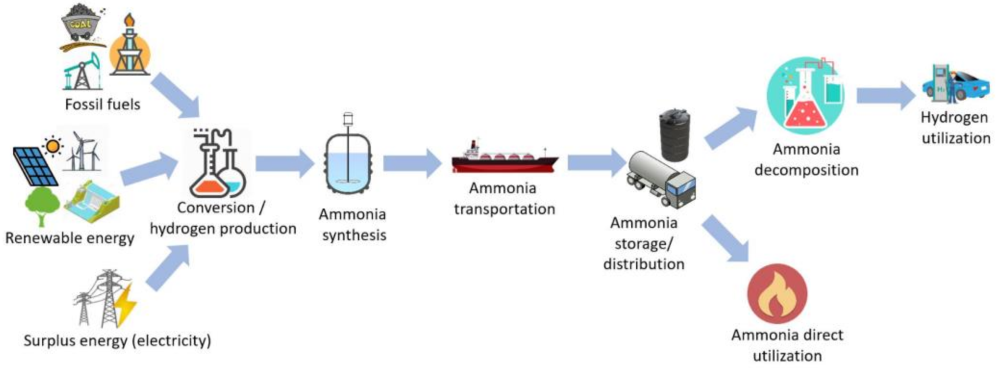


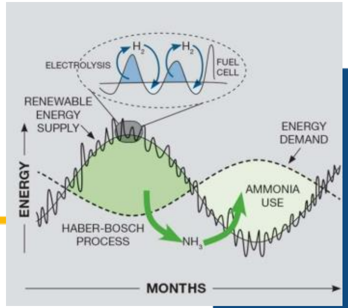
Advantages:

- **High Hydrogen Content**: - Ammonia contains a high percentage of hydrogen by weight (approximately 17.6%). means that a significant amount of hydrogen can be stored and transported in the form of liquid ammonia.
- **Easy Storage and Transportation**: - Ammonia can be stored and transported at relatively low pressures and moderate temperatures. This makes it easier and safer to handle and transport over long distances.
- **Established Infrastructure**: - There is an existing global infrastructure for ammonia production, storage, and transportation, making it a practical choice for utilizing and distributing green hydrogen at scale. This infrastructure can be repurposed for hydrogen-related applications.
- **Energy Density**: higher energy density than liquid hydrogen. More energy can be stored and transported in the same volume.
- **Carbon-Free Production: -** Ammonia can be completely carbon-free if produced with renewable electricity.
- **End-User Applications**:
  - Ammonia is widely used in agriculture applications as a feedstock for fertilizers
  - Ammonia can be converted back into hydrogen through "cracking" and used for various applications, including fuel cells for electricity generation and hydrogen fueling stations for vehicles.

Challenges:,

- Need for efficient and cost-effective cracking technologies,
- Safety concerns,
- Potential for nitrogen oxide emissions.





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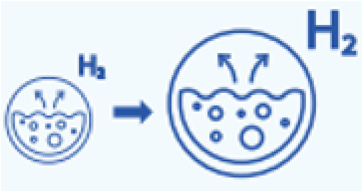
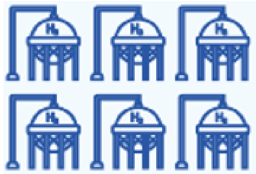
EU Green hydrogen strategy

08/07/2020





Till - 2024 → 2024 - 2030 → 2030 - 2050

Phase I

6 GW electrolyzers

1 mln t green hydrogen/a

Policy – regulated Hydrogen market

Sector – production/industry.

Investment € 180-470bln in the EU

Phase I I

40 GW Electrolizers

10 mln t green Hydrogen produced

10 mln t green Hydrogen imported

Sectors – transport, energy, residential

Policy – hydrogen trade, transporting, efficient distribution

Phase I I I

The use of renewable hydrogen will take a large scale and penetrate into hard-to-reach sectors. Aviation, marine transport, high emission industrial and commercial buildings.

Policy - harnessing all possible sectors with renewable hydrogen.

Investor certainty a crucial factor

https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1594897267722&uri=CELEX:52020DC0301

Changing Geopolitics of energy

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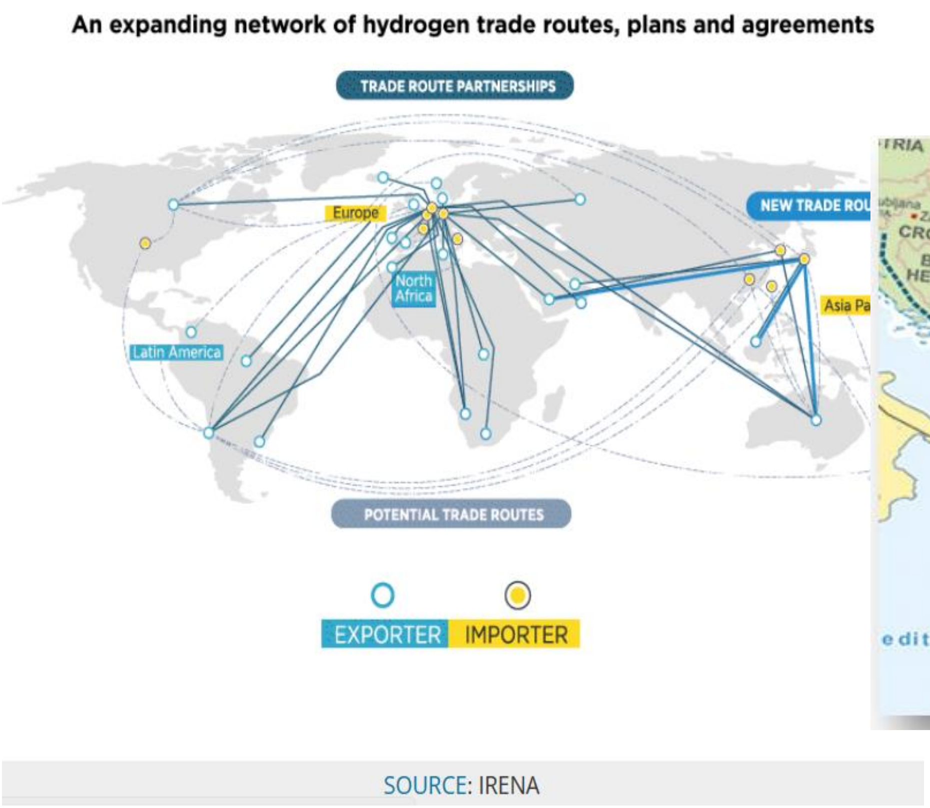

[The Green Hydrogen disruption: what nations, firms and investors are doing to reshape global energy - Energy Post]

[Central Asia decarbonizing the Southern Gas Corridor]

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Ways forward
State support measures

- Technical standards and norms
  - Technical standards – purity, storage, pipelines, transportation, use equipment etc.
- Financing mechanisms
- Regulatory framework
  - Additionality requirements
  - Certification mechanisms
- ETS and carbon pricing
- R & D & I policy and support
- Technology development
  - Electrolyzers, Fuel cells, storage
  - Hydrogen liquefaction
  - Ammonia cracking , Etc.
- Etc.

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Sources

- Executive summary – Global Hydrogen Review 2023 – Analysis – IEA
- Hydrogen Applications and business models - Kearney
- EU Hydrogen strategy
- Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update (windows.net)
- Demystifying Electrolyzer Production Costs - Center on Global Energy Policy at Columbia University SIPA | CGEP %

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EU4ENERGY PHASE II

THANKS

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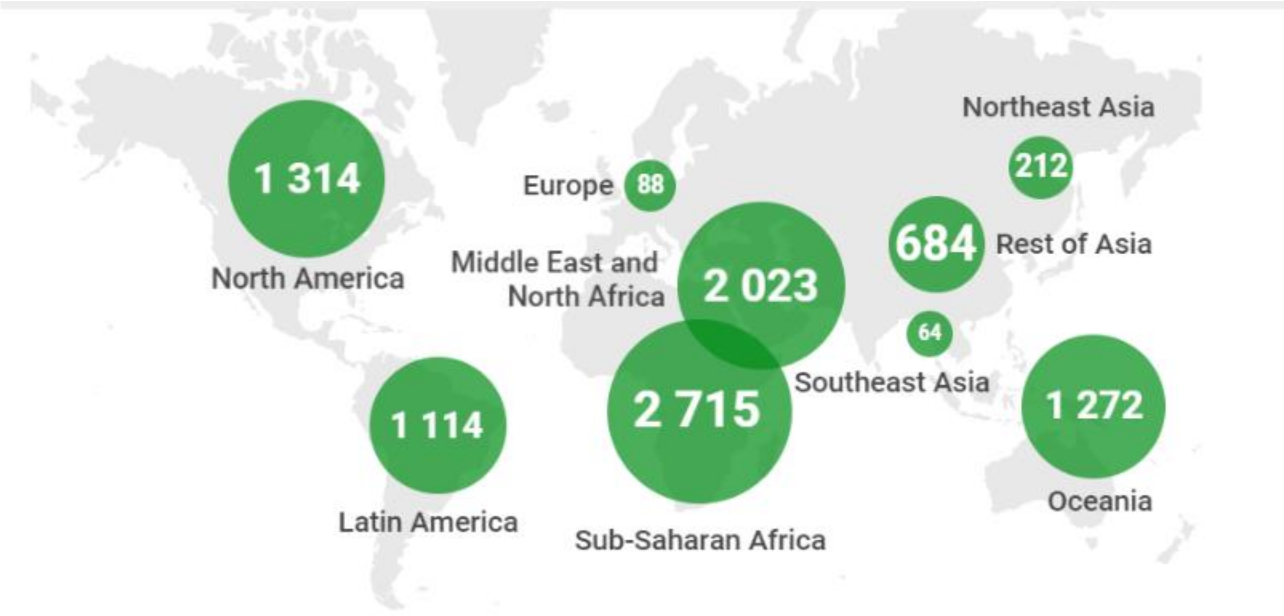
Backup slides



Technical potential for producing green hydrogen under USD 1.5/kg by 2050, in EJ

SOURCE: IRENA

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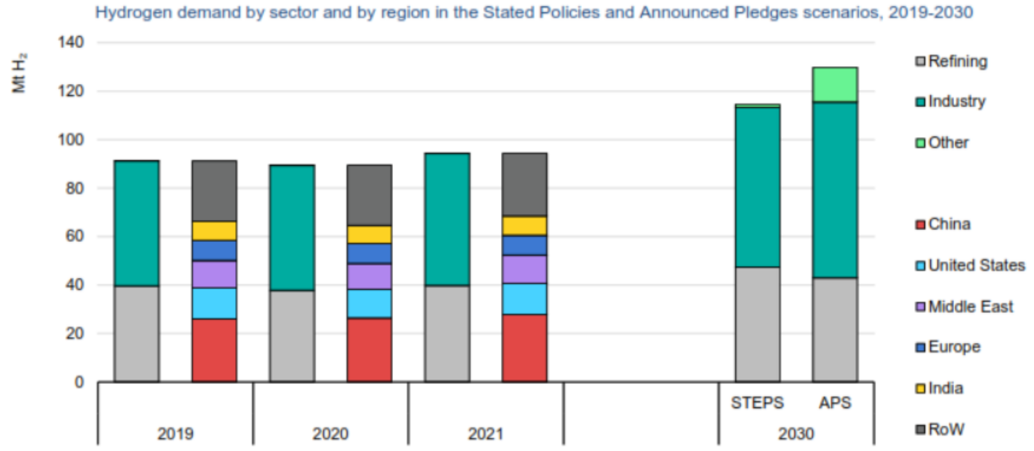
Hydrogen Demand

Global hydrogen demand increased 5% in 2021, reflecting recovery of economic activity in traditional applications from the pandemic-related curtailments



Notes: Mt H_2 = million tonnes of hydrogen; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. *Other* includes transport, buildings, power generation sectors and production of hydrogen-derived fuels and hydrogen blending.

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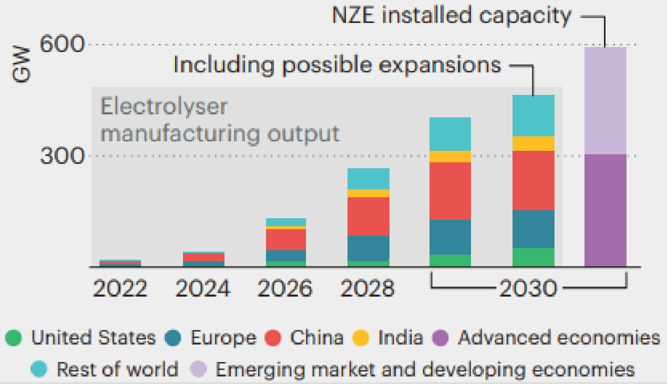
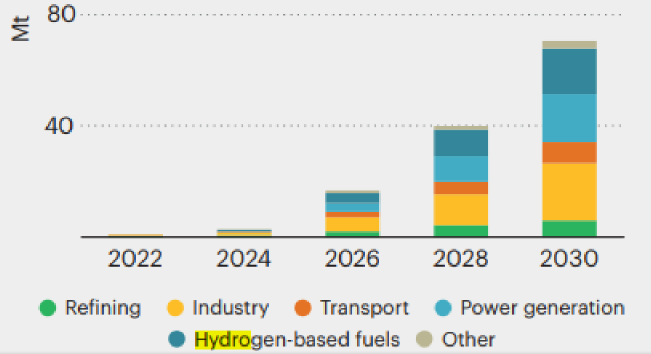
Milestones	2022	2030	2035	2050
Total hydrogen demand	95	150	215	430
Refining (Mt H_2)	42	35	26	10
Industry (Mt H_2)	53	71	92	139
Transport (Mt H_2-eq, including hydrogen-based fuels)	0	16	40	193
Power generation (Mt H_2-eq, inlcluding hydrogen-based fuels)	0	22	48	74
Other (Mt H_2)	0	6	10	14
Share of total electricity generation	**0%**	**1%**	**1%**	**1%**
Low-emissions hydrogen production (Mt H_2)	**1**	**70**	**150**	**420**
From low-emissions electricity	0	51	116	327
From fossil fuels with CCUS	1	18	34	89
Cumulative installed electrolysis capacity (GW electric input)	**1**	**590**	**1 340**	**3 300**
Cumulative CO_2 storage for hydrogen production (Mt CO_2)	**11**	**215**	**410**	**1 050**
Hydrogen pipelines (km)	**5 000**	**19 000**	**44 000**	**209 000**
Underground hydrogen storage capacity (TWh)	**0.5**	**70**	**240**	**1 200**

Announced cumulative electrolyser manufacturing capacity output, if fully realised, would be 80% of the NZE level in 2030



Demand for low-emissions hydrogen grows quickly in the NZE, particularly in heavy industry, transport and the production of hydrogen-based fuels



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