Hydrogen Technology Roadmap

Marcel VAN DE VOORDE

CERN-GENEVA & MAX PLANCK STUTTGART & European Commission BRUSSELS

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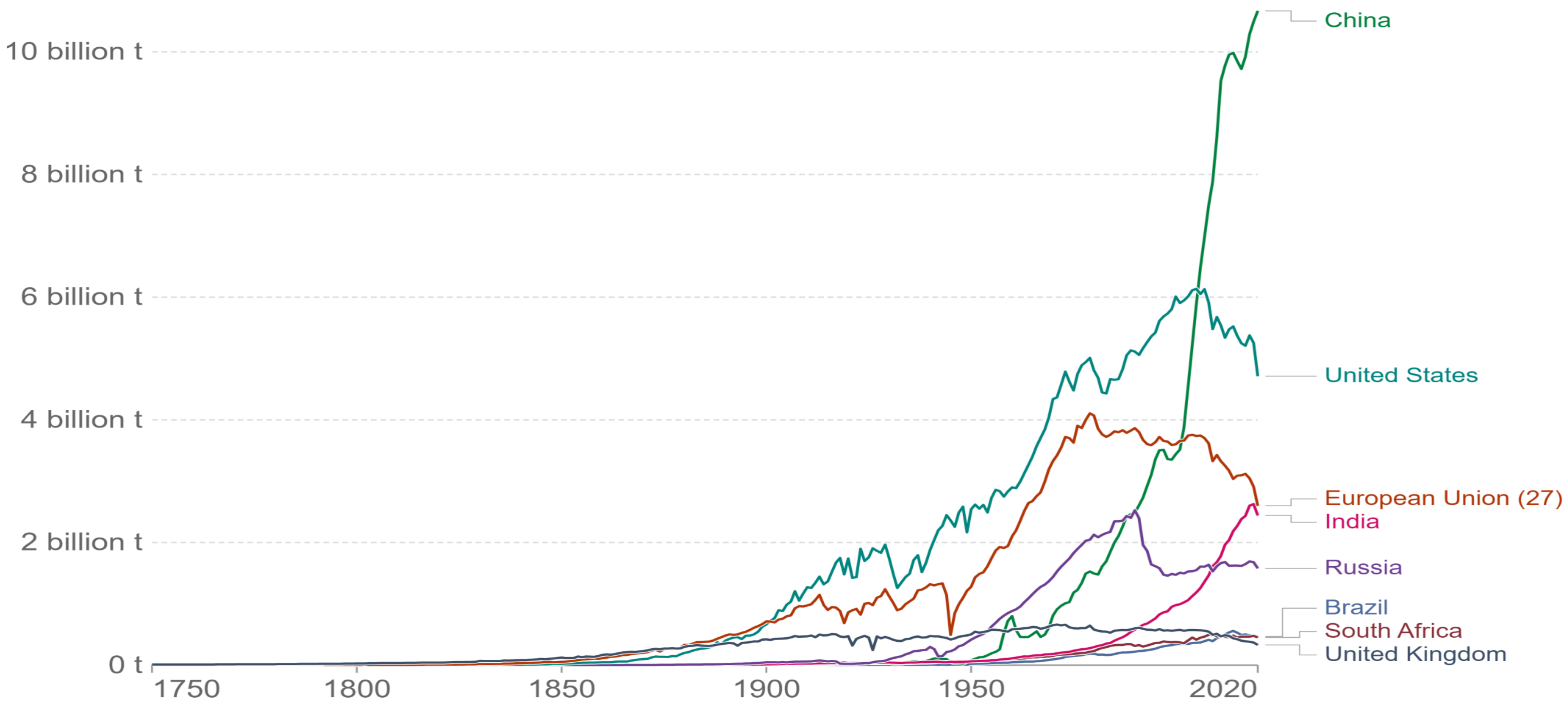
Annual CO_2 emissions

Carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.



Source: Global Carbon Project

FIGHTING THE GLOBAL WARMING

Worldwide recognised serious concerns about our changing climate

CO_2 emissions are the primary driver of global climate change

What can be done to completely remove fossil fuels from the energy system?

To this regard, hydrogen as energy carrier is the most powerful tool to power mobility, supply energy and heat, decarbonize industrial sectors

Several Government strategies have been released to reach a net zero emission goal with the essential contribution of hydrogen

Hydrogen as a key solution to help the transition to a lower carbon hydrogen-based economy.

In Hydrogen Technology - Innovations and Applications, Vol. 1-3, M Van de Voorde, De Gruyter 2021

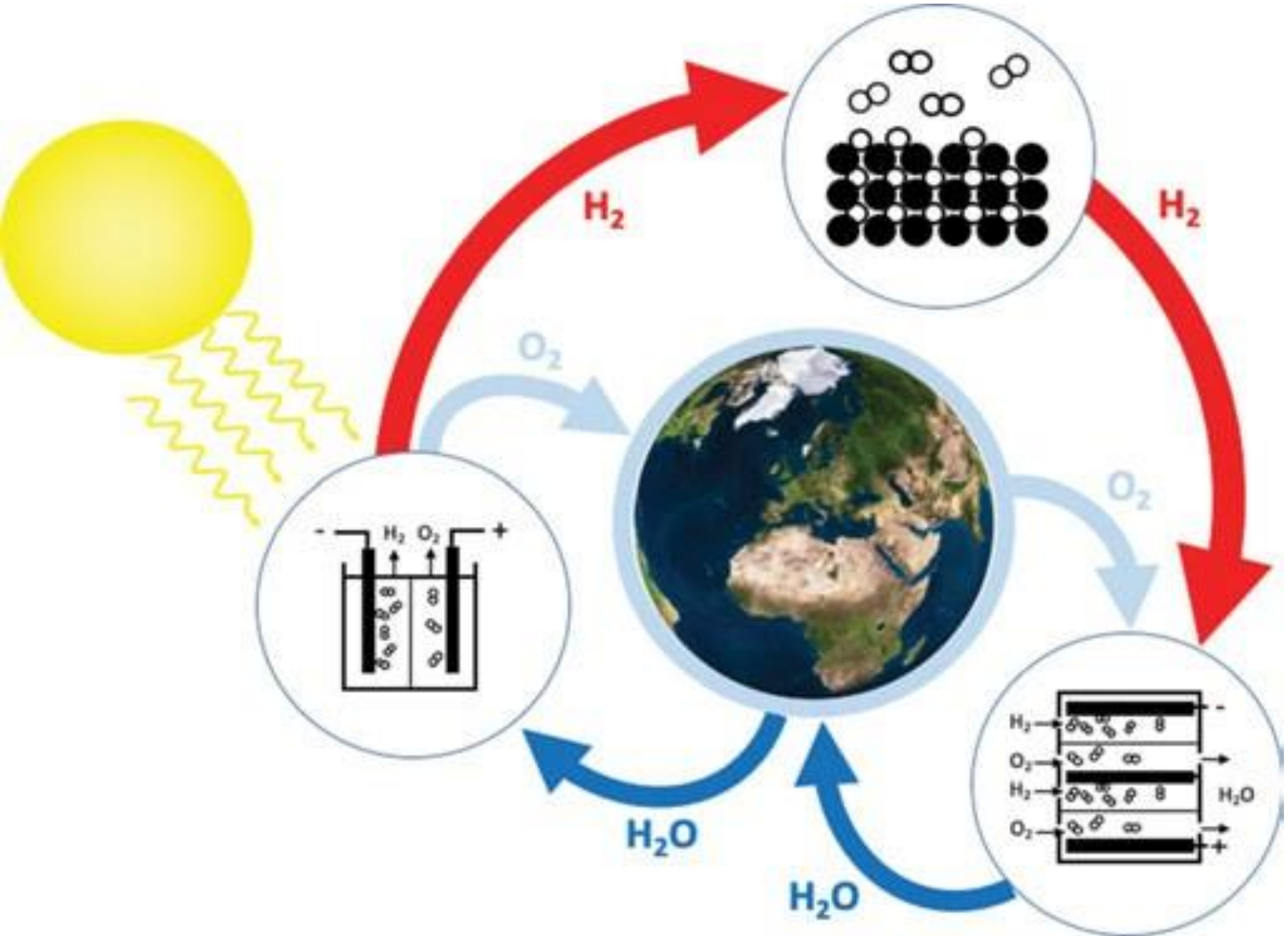
Hydrogen Technology Roadmap

1. **Hydrogen production technologies**
   The development of high efficiency electrolysis, coping with varying loads, based on solid electrolyte and polymer electrolyte membranes.
2. **Infrastructure for the transport of hydrogen**
   Upgrading existing natural gas (NG) pipelines for 10% hydrogen mixture, and plan hydrogen dedicated pipeline networks. Developing light-weight containers for compressed hydrogen.
3. **Direct use of hydrogen in transportation**
   Development of heavy-duty Fuel-cell vehicles (buses, trucks, ships, local trains) and the concomitant build-up of refuelling infrastructures.
4. **Storage of hydrogen**
   Scale-up of advanced technologies for the synthesis of liquid fuels for heavy-duty transport and aviation. Power-to-methane for storage in NG grids.
5. **Hydrogen for the decarbonisation of industrial sectors**
   Industrial scale proven use of hydrogen in the production of iron, steel, cement and glass.
6. **Feedstocks for the chemical industry**
   Power-to-chemical technologies based on hydrogen (methanol, Fischer-Tropsch, biogas)

Commonly used terminology to designate routes of hydrogen production:

1. Green hydrogen, using clean electricity from solar or wind to electrolyse water.
2. Blue hydrogen, by methane steam reforming (MSR), by-product CO2 being captured and stored (CCS).
3. Grey hydrogen, mostly by (MSR).
4. Black or brown hydrogen, from coal.
5. Pink hydrogen, through water electrolysis powered by nuclear energy.
6. Turquoise hydrogen, by methane pyrolysis to hydrogen and solid carbon.

The hydrogen cycle



Electrolysis of water with renewable (solar) energy

↓

Hydrogen storage

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Combustion of hydrogen in a fuel cell

FROM FOSSIL TO GREEN HYDROGEN

In the short-to-medium term it will be necessary to resort to low-carbon hydrogen, while supporting the growth of renewable hydrogen.

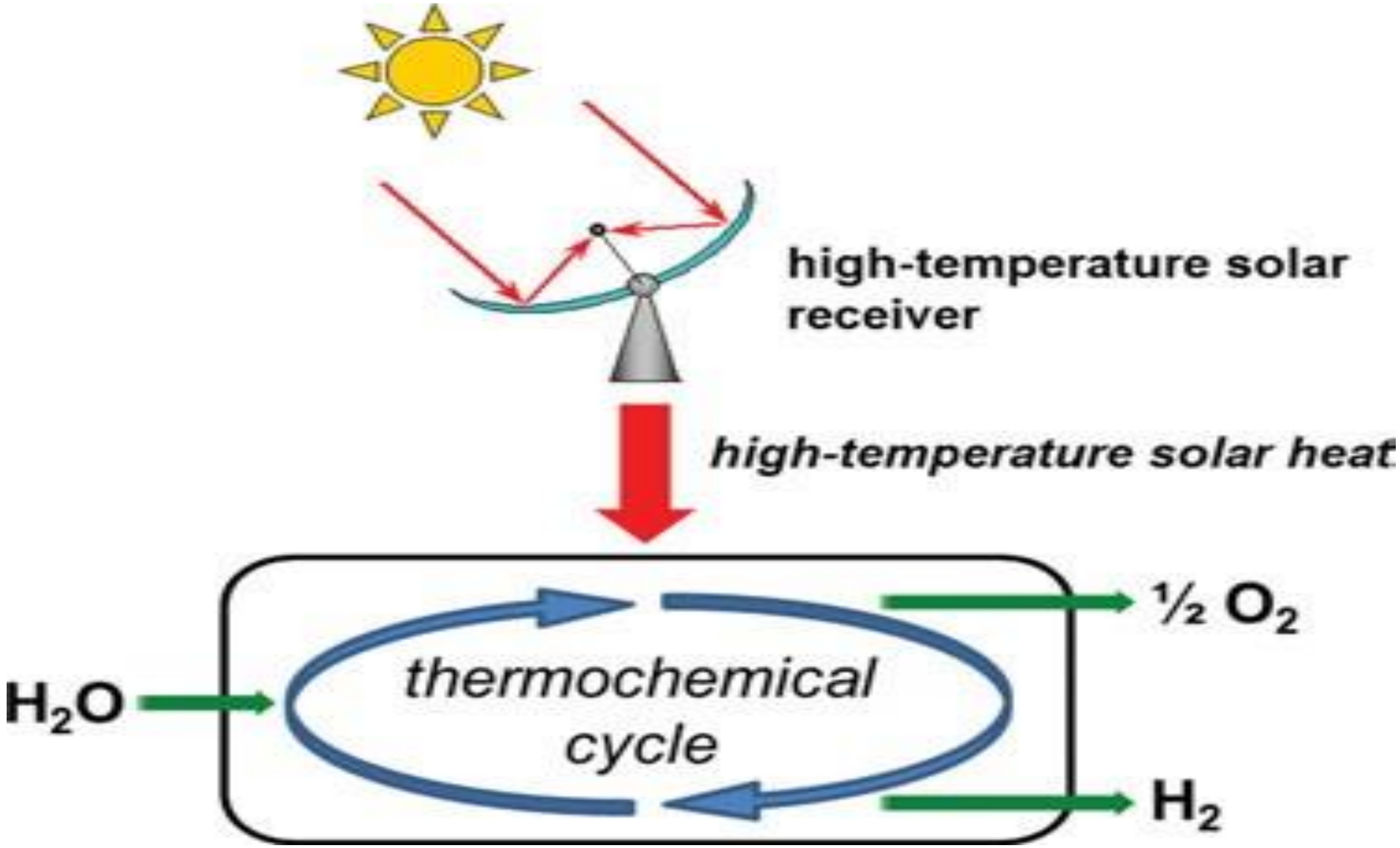
To lower the carbon footprint, CO_2 emissions during the production of hydrogen could be captured, utilised, stored (CCUS).

The highest CCUS uptake is projected for the blue hydrogen production, iron and steel, and cement sectors

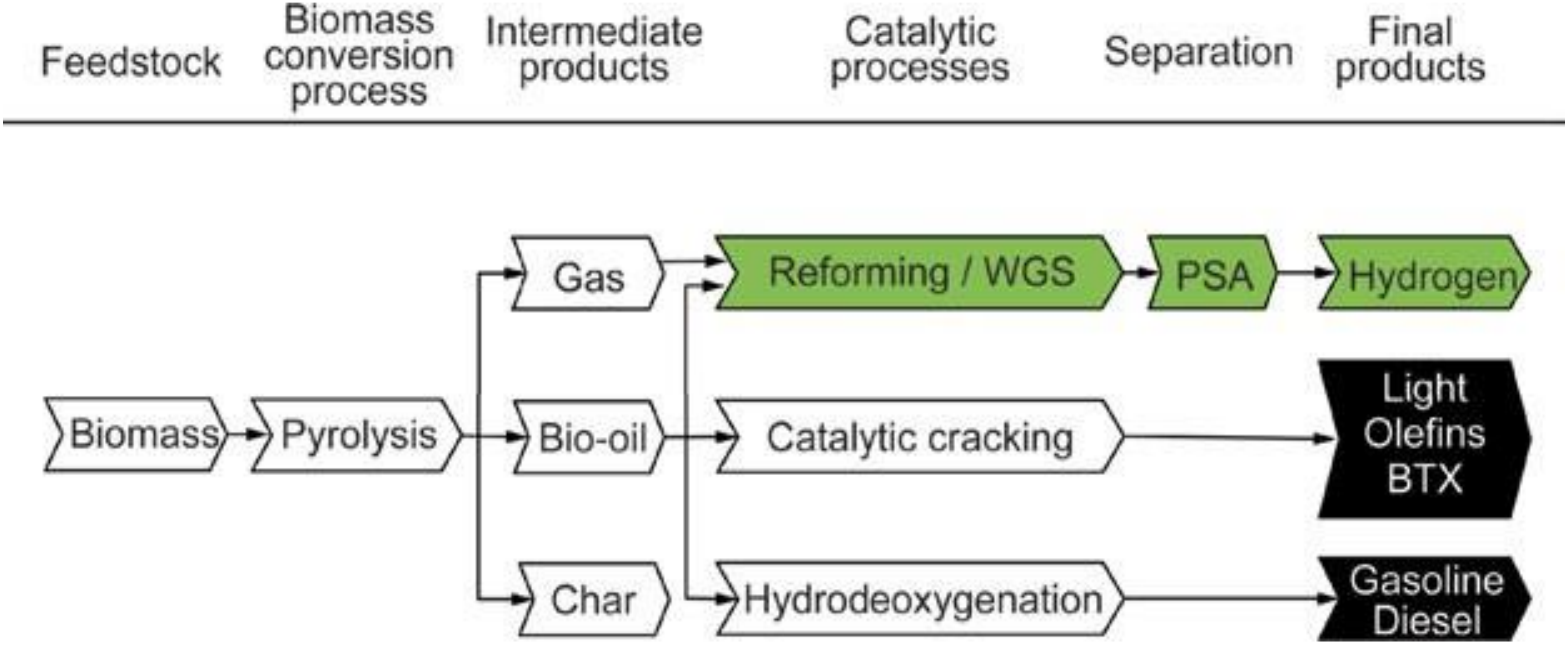
However, these technologies still require higher capture efficiency and lower cost.

Large uncertainty on the revenue streams for CCUS, given the projected carbon dioxide prices (up to 150-200 $/ton CO2) are too low to scale up CCUS, especially for low-purity point sources

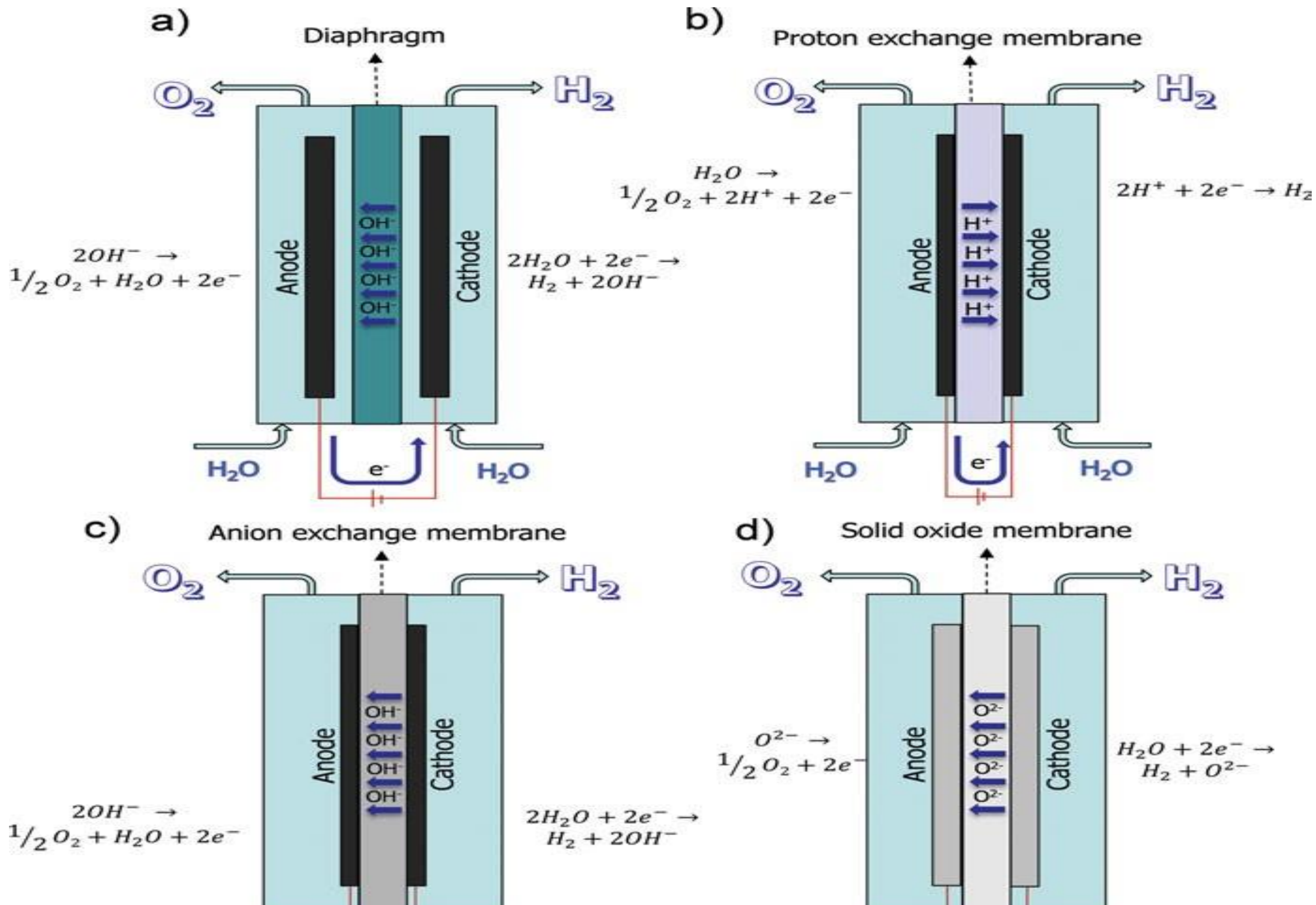
General scheme of a solar-driven thermochemical water-splitting cycle



A flowchart of H_2 production by biomass pyrolysis

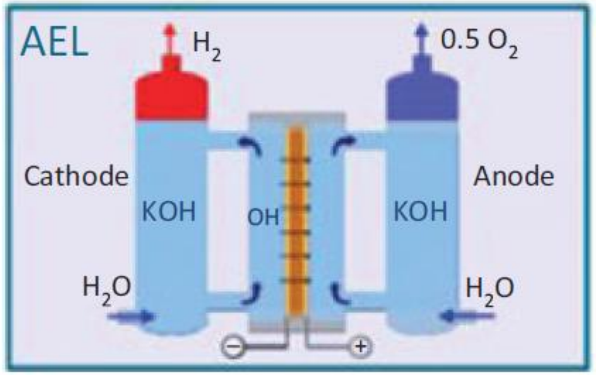


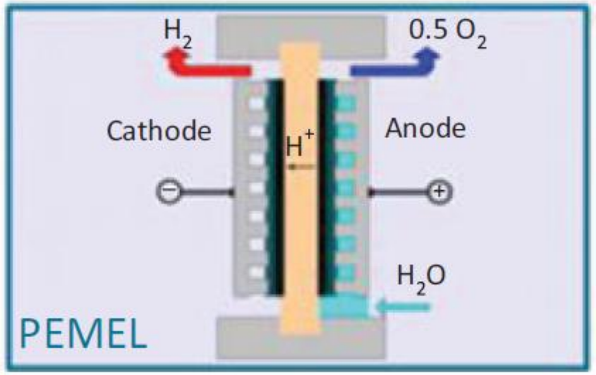
Schematic drawing of different types of electrolyzers: (a) AWE, (b) PEM electrolyzer, (c) AEM electrolyzer, and (d) SOE.

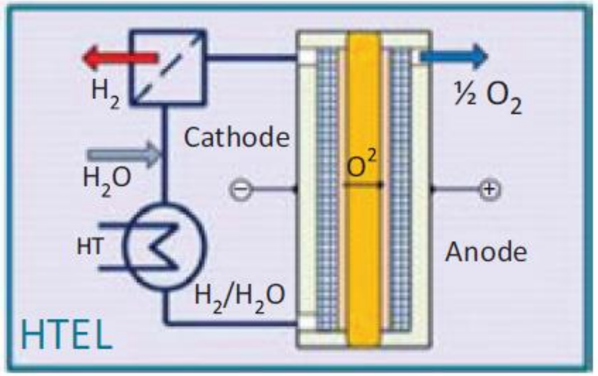


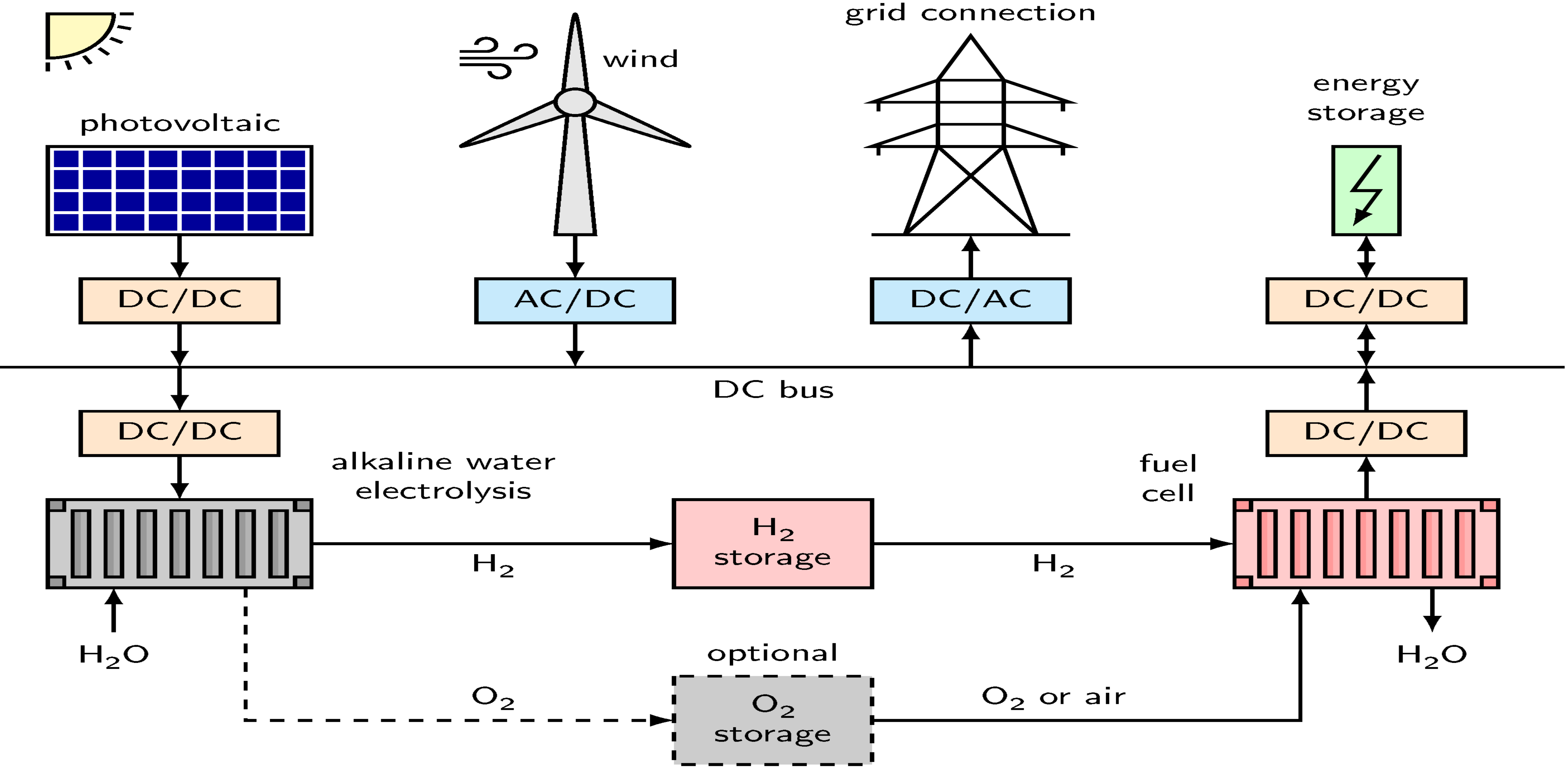
Schematic view, cathodic and anodic reactions for alkaline, membrane and high temperature electrolysis

Technology	Temp. Range	Cathodic Reaction (HER)	Charge Carrier	Anodic Reaction (OER)
Alkaline electrolysis	40 – 90 °C	$2H_2O + 2e^- \Rightarrow H_2 + 2OH^-$	OH^-	$2OH^- \Rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$
Membrane electrolysis	20 – 100 °C	$2H^+ + 2e^- \Rightarrow H_2$	H^+	$H_2O \Rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$
High temp. electrolysis	700 – 1000 °C	$H_2O + 2e^- \Rightarrow H_2 + O^{2-}$	O^{2-}	$O^{2-} \Rightarrow \frac{1}{2}O_2 + 2e^-$



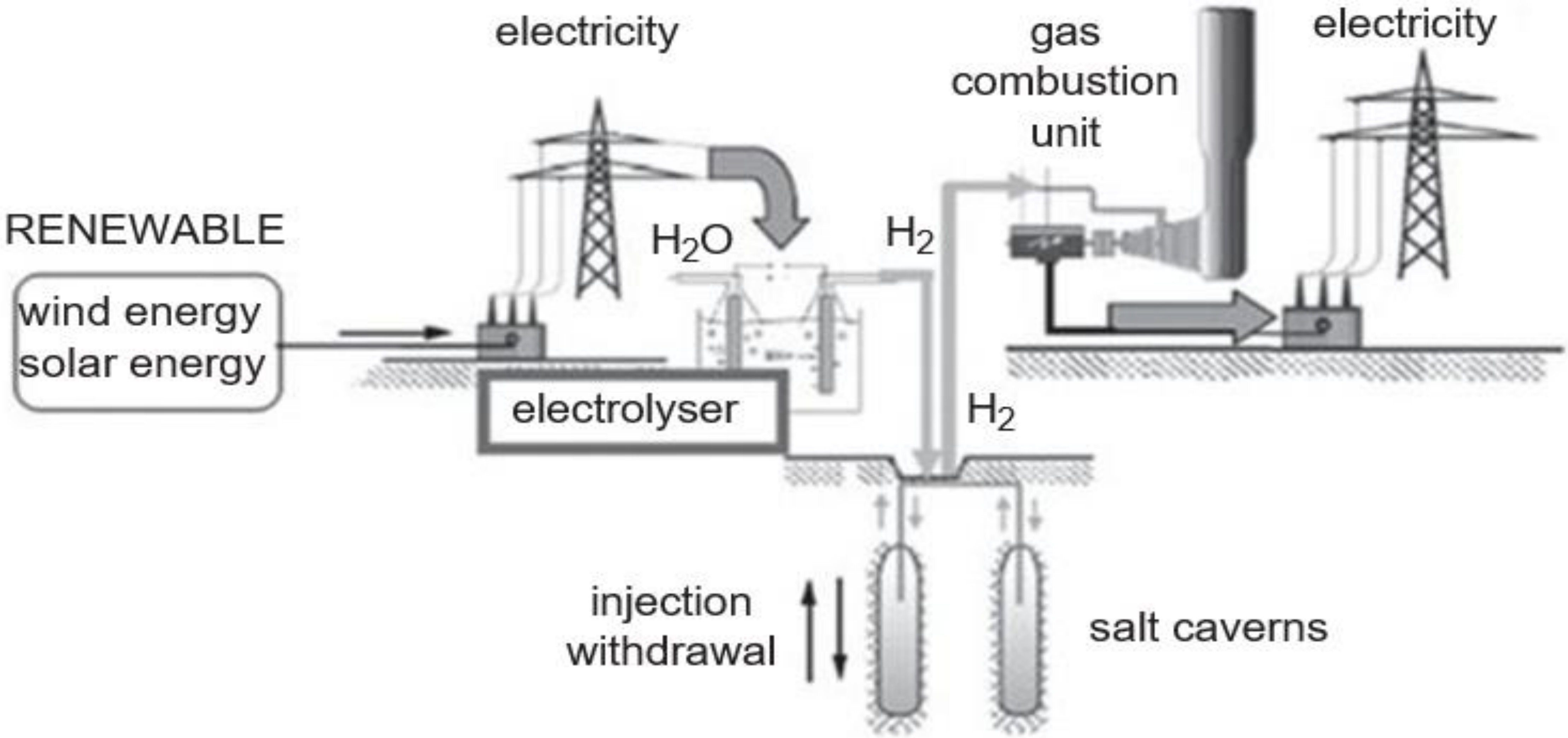




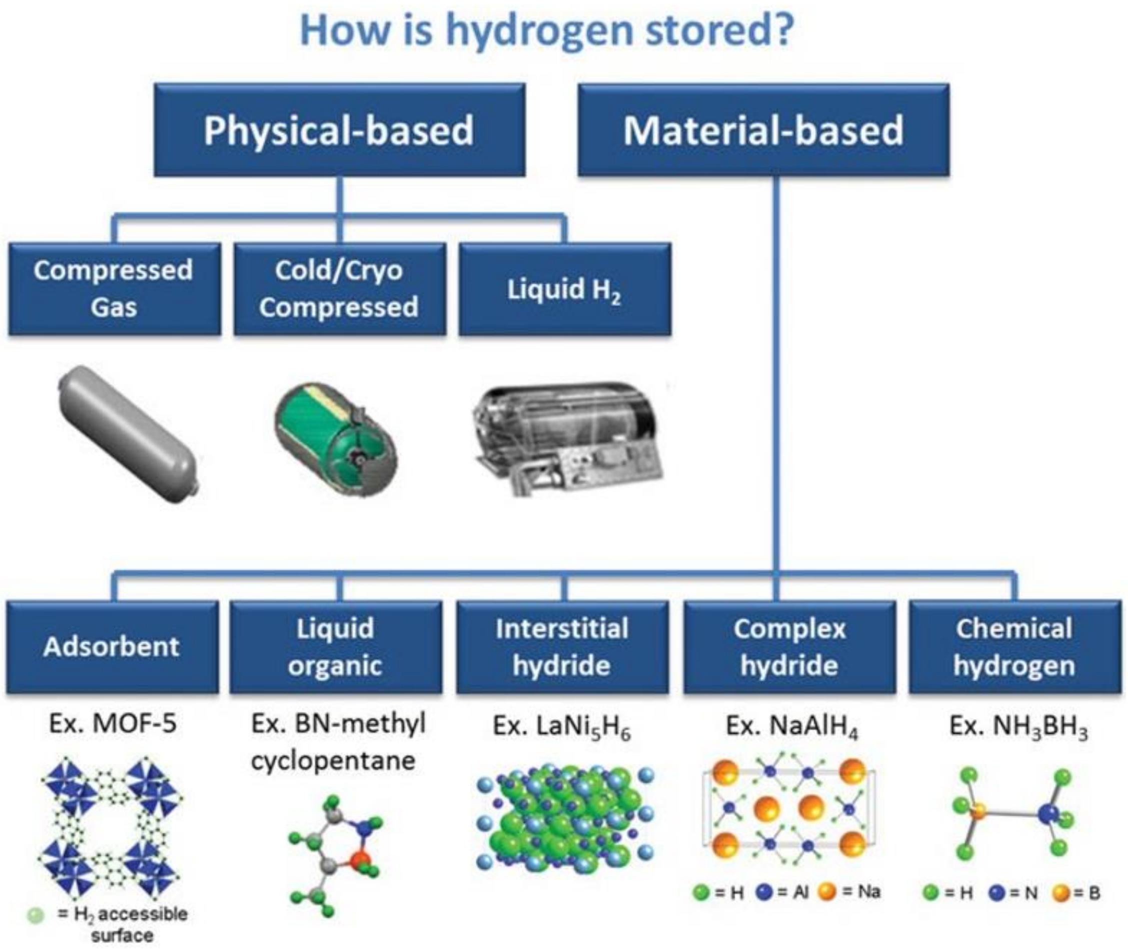


Brauns J, Turek T. Alkaline Water Electrolysis Powered by Renewable Energy: A Review. *Processes*. 2020; 8(2):248.

Salt cavern facility for hydrogen production and gas storage



Different ways to store hydrogen



HYDROGEN STORAGE

The intrinsic limitation of renewable energies is their discontinuity

The necessity of a storage system is essential issue.

Storing hydrogen in large quantities will be one of the most significant challenges for a future hydrogen economy.

Many solutions were suggested, from underground/undersea, to salt caverns, to chemicals such as methanol, to materials.

Electrolytic hydrogen is a solution in fuel combustion, fuel cell

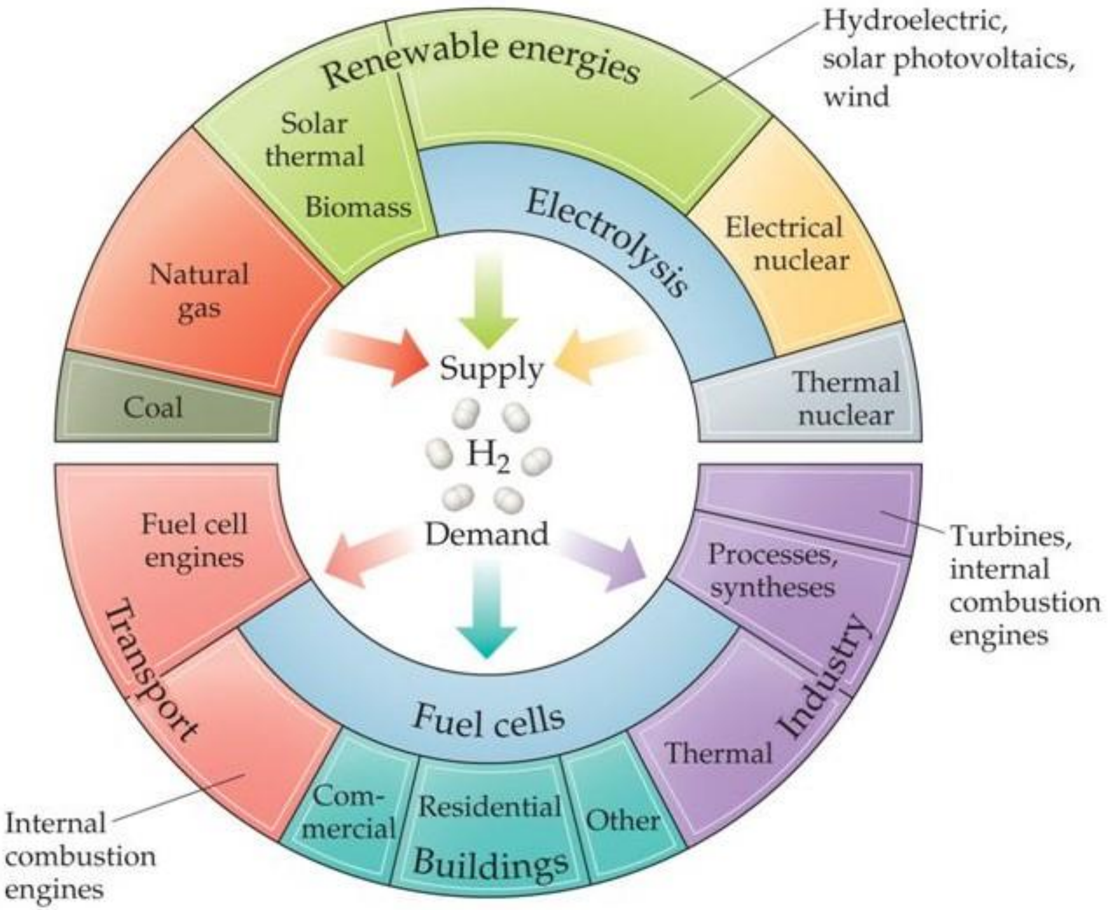
Reacting with CO_2, it is converted to methanol, then MTG, or linear liquid hydrocarbons (kerosene)

Easily transported (tracks, pipelines, ships), in particular from regions with large renewable energies resources to energy-hungries far away areas.

Hydrogen can also be transported as mixture gas in existing natural gas or future dedicated pipelines.

By the “Power to gas” process methane is produced from green hydrogen and different sources of CO_2 (atmospheric air, industrial and power plant emissions, but also raw biogas from waste).

The Hydrogen Economy



https://www.charleyrattan.com/business-opportunities-for-the-hydrogen-economy/

Hydrogen mobility markets – ready to scale

HYDROGEN FOR MOBILITY

Cars, trucks, buses, motorcycles contribute about 75% of global CO_2 emissions from the transportation sector.

Hydrogen feeds Fuel Cells, which produce electricity to power the motor of fuel-cell electric vehicles.

FC is based on the reverse reaction of water splitting, and is fed by hydrogen stored at 350 or 700 bar in special cylinders.

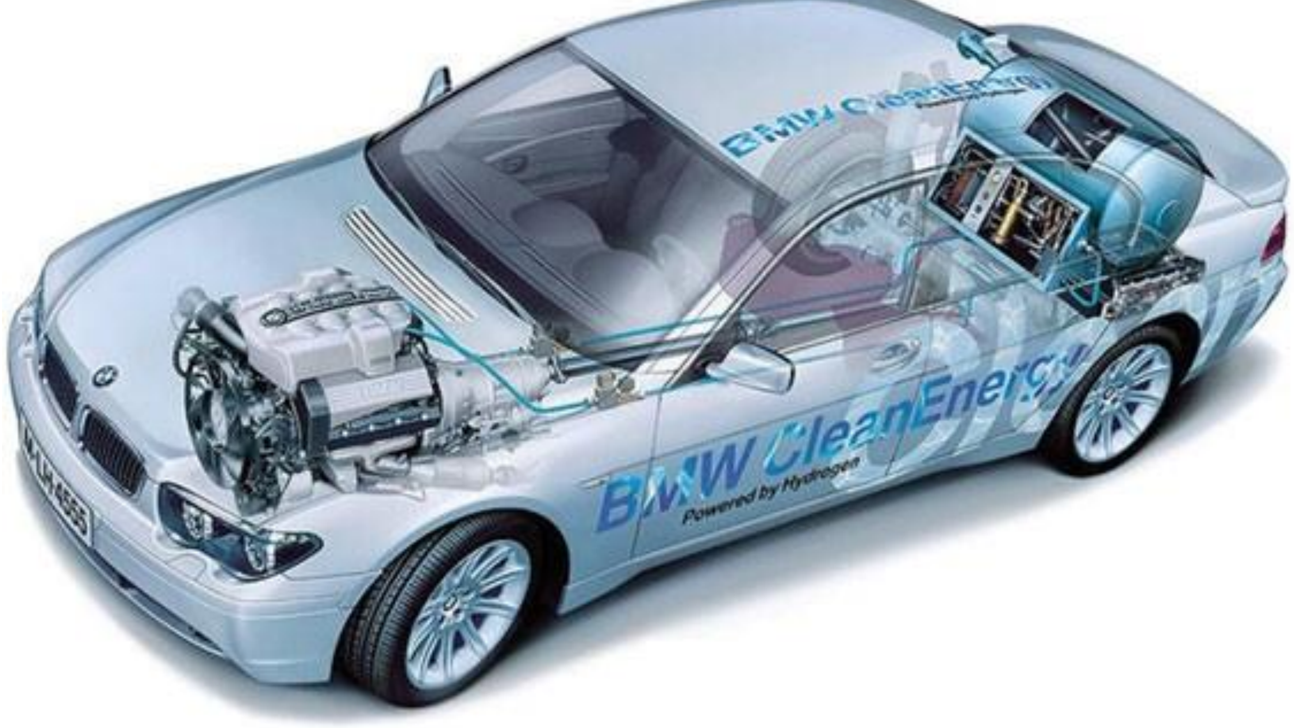
Around 60% engine efficiency in theory, and FC emits only water.

First Fuel Cell cars sold to public on 2015.

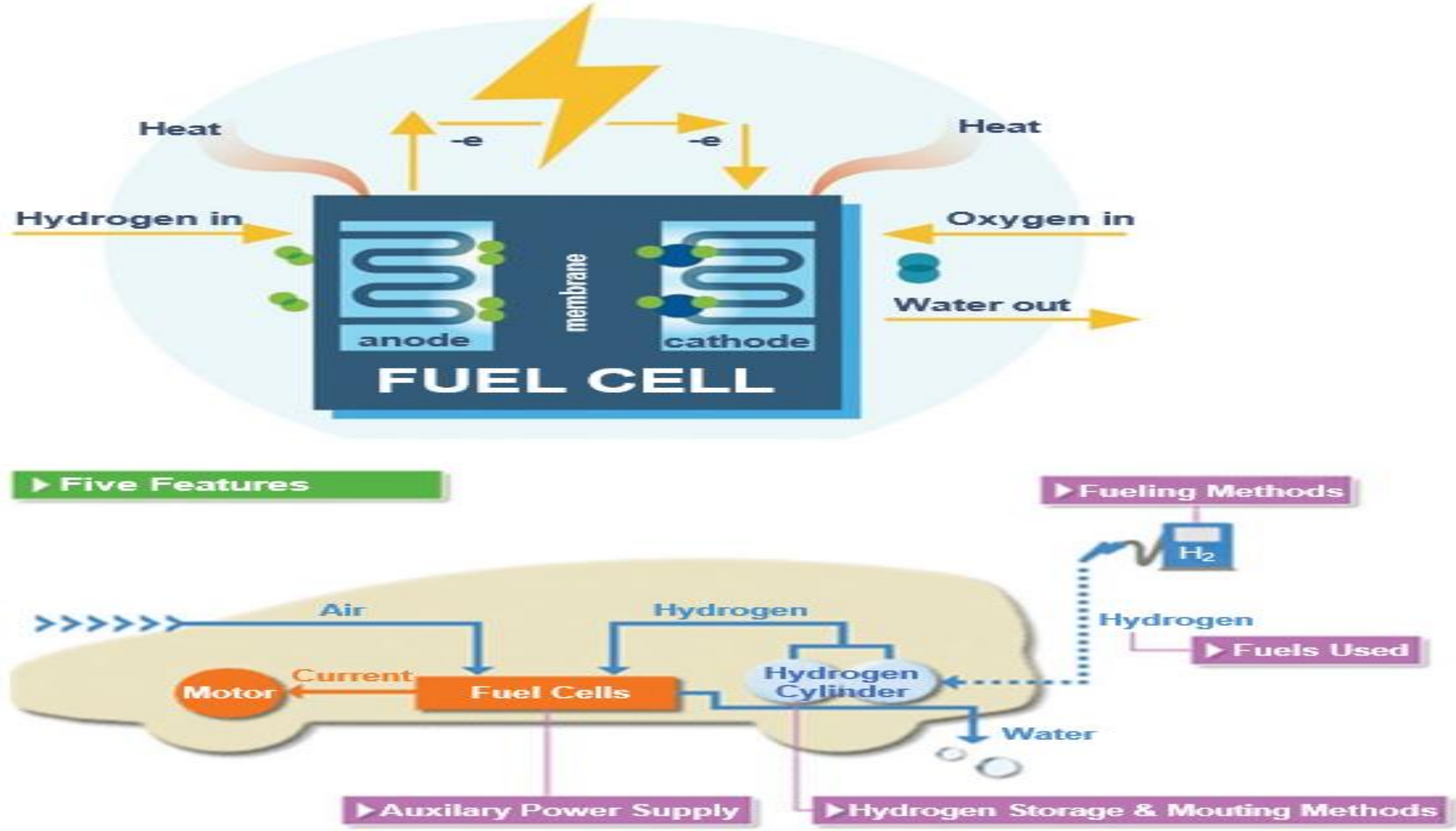
Growing trend of electric mobility. Battery electric vehicles complementary solution. Preferred for lighter vehicles (high efficiency of charge/discharge cycles, but long charging time, high weight, battery metals recovery).

FCs preferred for heavy vehicles with longer driving distances per day, and the need for fast refuelling.

Hydrogen-powered combustion engine vehicle BMW Hydrogen 7



Schematic diagram of fuel cell and fuel cell system for vehicle



HYDROGEN FOR MOBILITY

The adoption of FCEVs from 2015 up today has been very slow: 30,000 FCEVs against 11 million EV stock at the end of 2020
The 2030 objective is 10 ± 5 million FCEV stock, depending on the different scenarios

Challenges for FC. Higher power density, extended lifetime (> 40,000 hrs), versatility, and lower final cost. Novel materials as hydrogen conversion catalysts.

Critical issue. The FC mobility needs refueling station infrastructures (HRS), whose cost depends of the size and especially of the capacity utilization.

The growth of HRS was even slower than FCEVs. Only 540 HRS were installed around the world by the end of 2020: Asia (278), Europe 190, North America 68.

Current performance. 200-400 kg H_2/day and about 50 % utilization, but higher size and utilization are expected to strongly reduce the dispensed H_2 cost.
1 kg of hydrogen is consumed per 100 km journey, 500 - 750 km autonomy, 5 minutes to refuel.

Left: Kawasaki heavy industry concept design for liquid hydrogen carriers

Right: Cryogenic trailer for transporting liquid hydrogen

CEP early hydrogen station at Berlin

FROM FOSSIL TO GREEN HYDROGEN

2020 demand of H2: 90Mt, 95% from gas, coal, oil

$CH_4 + 2H_2O \rightarrow 4\ H_2 + CO_2$ .... Methane steam reforming

Very low cost of around 0.5-1.5 euro/kg

Co-product about 10 ton of CO_2 per ton of H_2

Water electrolysis with renewable energy as clean alternative

$2H_2O \rightarrow 2H_2 + O_2$ .... Water splitting

The CO_2 intensity of water electrolysis depends on the CO_2 intensity of the electricity used for the reaction. Therefore :

Water, sun, wind, electrochemical reactor for the production of green hydrogen

Water electrolysis: EC strategy to reach carbon neutral economy on 2050.

More than 60% of global electrolysis manufacturing capacity is in Europe.

Great strategic business opportunity for EU companies, supporting the Europe's role in the international market for hydrogen.

HYDROGEN AS ENERGY CARRIER

The most energy-dense fuel by mass (142 MJ/kg)

As a fuel it produces only water.

Can store renewable and low-carbon sources energy and be converted to other forms of energy

Many production routes and applications.

Viable source of energy for cars, buses, trains, ships, aircrafts.

The lowest energy density per unit volume (only 11 MJ/m3)

For energy storage it must be compressed or liquefied

Pipeline transport needs to move larger volumes

Hydrogen gas requires safe handling, due to its reactivity

Hydrogen gas is rare on Earth, it must therefore be produced.

CONCLUSIONS

A peak of energy-related CO_2 emissions is projected on 2023, followed by an accelerating declines. But, Ukraine effect ???

Global emissions remain far from a 1.5ºC pathway

Mature economies would likely need to strongly accelerate their annual emissions decline

Announcements of new clean hydrogen production projects tripled year on year in 2021

H2 demand is projected to accelerate after 2035 across all sectors

CONCLUSIONS

Beyond the reference to technology, this is only part of an integrated approach to develop a Hydrogen Economy.

It requires a primary contribution from -

- political choices by developing strategies and roadmaps on the role of hydrogen
- financial investments and incentives for manufacturing scale-up , infrastructures and supply chain
- appropriate certification, standardisation and safety regulation regimes to develop a global hydrogen market
- international cooperation and research programs for technology advancement
- education, by designing specific academic programmes; education
- convincing the society, especially for security and safety fear.

A tremendous but undeniable and not postponable effort for the future of humanity.