Introduction to Green Hydrogen Production

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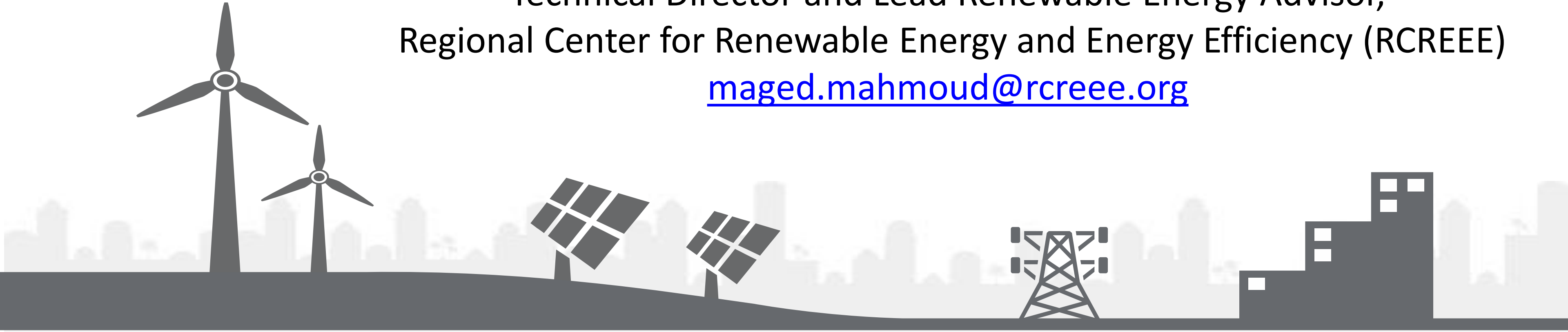


RCREEE
Regional Center for Renewable Energy and Energy Efficiency
المركز الإقليمي للطاقة المتجددة وكفاءة الطاقة

July 2022

RCREEE – Who we are

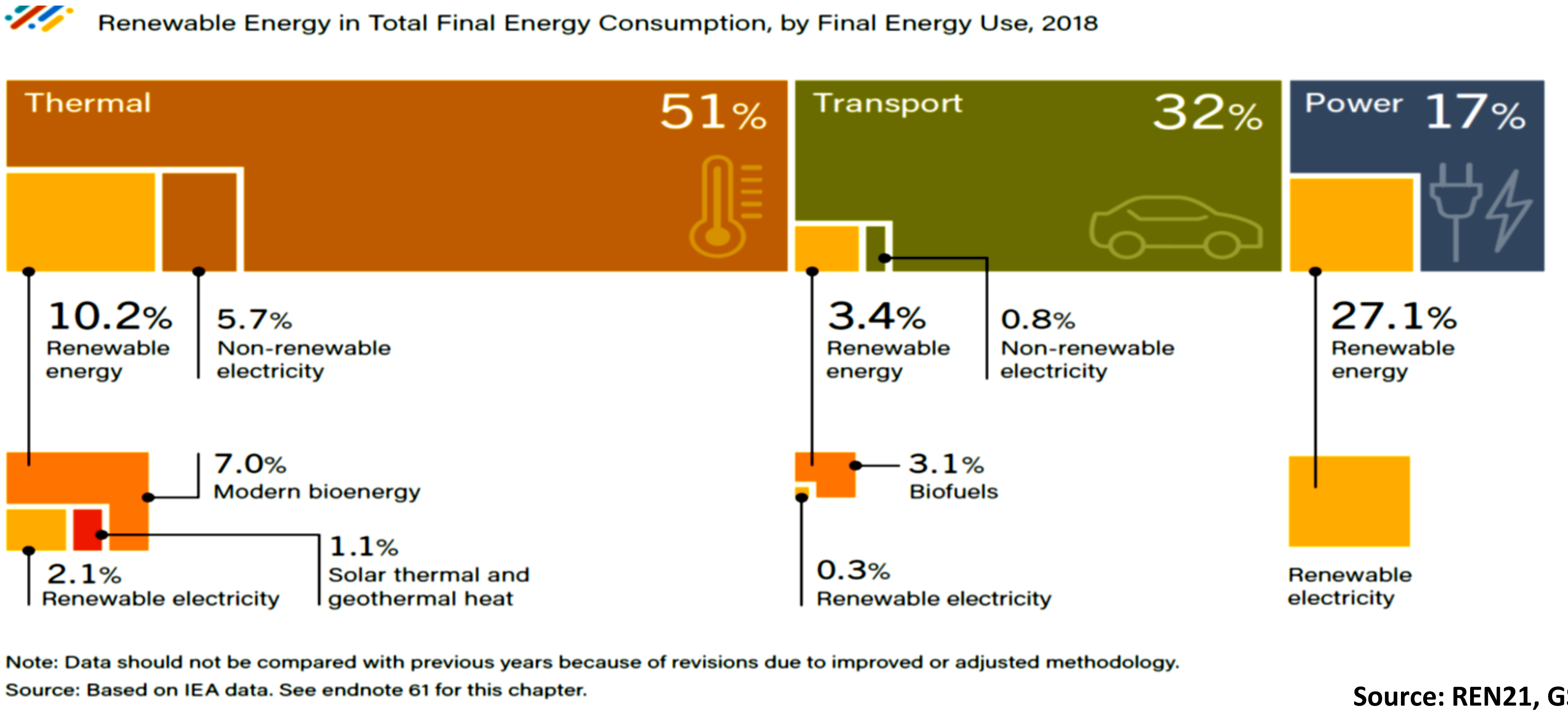
*"We, the Regional Center for Renewable Energy and Energy Efficiency, are the **strategic partner** for the **Arab countries** driving **energy transition** for the **prosperity** of all our **people**."*

- **Intergovernmental Organization with 17 Member States**
- **The technical arm of the League of Arab States**
- **A leader in clean energy policy dialogues, strategies, technologies, investments promotion, and capacity development**
- **The first regional renewable energy and energy efficiency center across the world**
- **Secretariat in Cairo, Egypt with regional antennas and a pool of short-term experts**

Work in the Pan-Arab Region… know how to navigate your way

Knowledge → Partnership → Replicability → Leadership

Global Market Realities



Source: REN21, GSR 2021

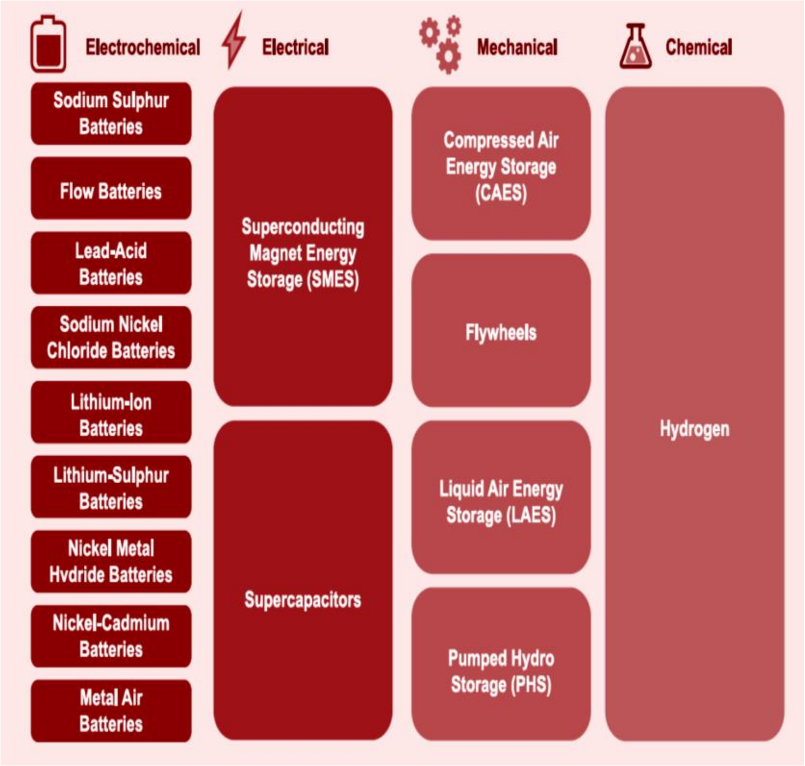
Some Key Challenges

Storage of renewable energy: One major problem with some renewable energy sources is inability to store the produced energy in a viable manner.

What about biomass? This is not a problem with biomass since the fuels produced from biomass such as ethanol and biodiesel can be stored and used anytime.

Storage of renewable electricity: Batteries are not yet a commercially viable option for *large scale applications* in today's technology due to their very limited capacity.

Hydrogen? One possible solution to this problem is production of hydrogen from renewable electricity by the electrolysis of water. Once produced, hydrogen can be stored and used anytime.

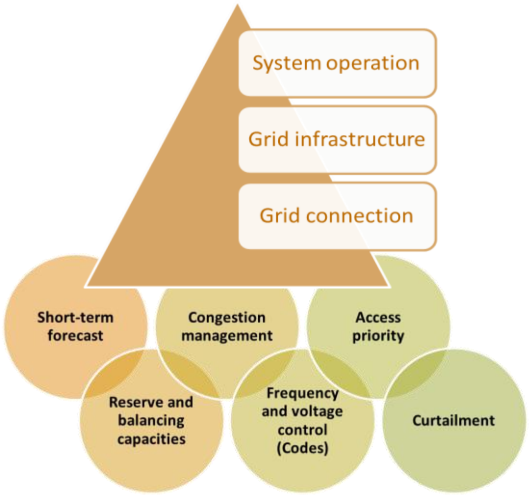


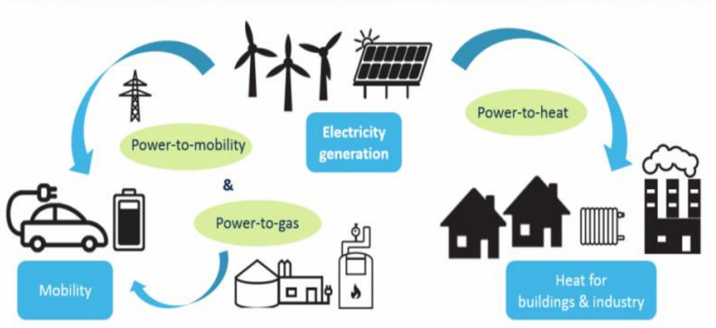
Main classification of Energy Storage Systems

Linkages

- Although many RE technologies have reached reasonable degree of maturity however adequate finance is still needed to:
  - improve its **integration** with the current power systems
  - improve its **reliability**
  - reduce the need for **balancing energy**
  - improve energy **storage techniques**
  - Transition to wider deployment of green **"power to X"** solutions.

thus support is needed for **boosting different solutions** as well as to ensure the necessary cash flow for development.

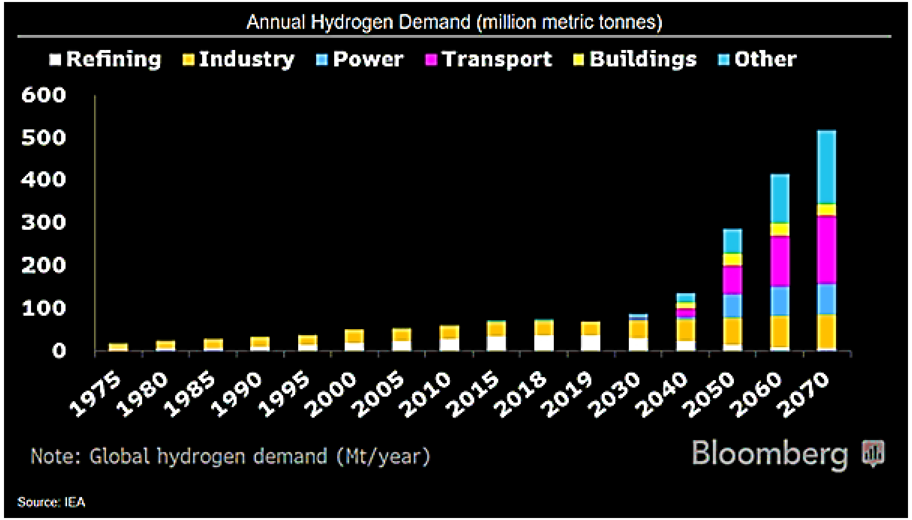




https://www.cleanenergywire.org/factsheets/sector-coupling-shaping-integrated-renewable-power-system

Introduction

- Hydrogen demand in 2020 was ~100 Mt, with:
  - more than 75 Mt used as pure hydrogen and
  - less than 25 Mt mixed with carbon-containing gases in methanol production and steel manufacturing.
- Almost all this demand was for refining and industrial uses.
- Demand for hydrogen has grown more than threefold since 1975.
- Currently, hydrogen is produced mainly from fossil fuels with 6% of global natural gas and 2% of global coal.
- Hydrogen production results in in close to 900Mt of CO_2 emissions per year.



https://netzeroweek.com/news/page/13/#/

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Introduction

Hydrogen: Hydrogen is a colorless, odorless, nonmetallic, tasteless, highly flammable diatomic gas with the molecular formula H2. It is also the lightest element with a molecular mass of 2.016 kg/kmol.

Although hydrogen is the most plentiful element in the universe, making up about three quarters of all matter, free hydrogen is scarce.

Is H2 a fuel? Hydrogen is a *fuel* with a higher heating value of 141,800 kJ/kg and a lower heating value of 120,000 kJ/kg.

Is H2 an energy source? Hydrogen is not an energy source like coal, oil, and natural gas since there are no hydrogen reserves in the earth.

How is H2 obtained? Hydrogen must be produced from other fuels such as natural gas or from water through electrolysis by consuming electricity.

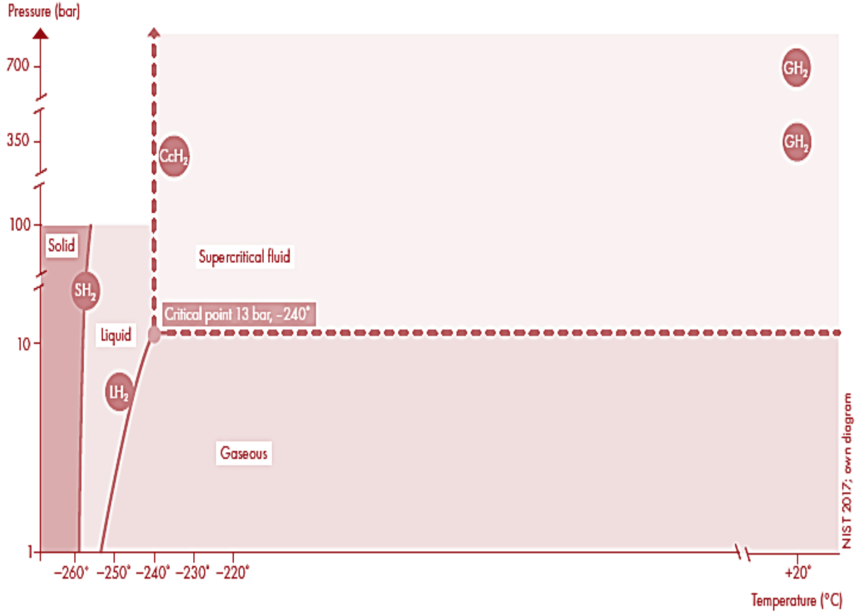
Hydrogen should be called an **energy carrier** rather than an *energy source*.

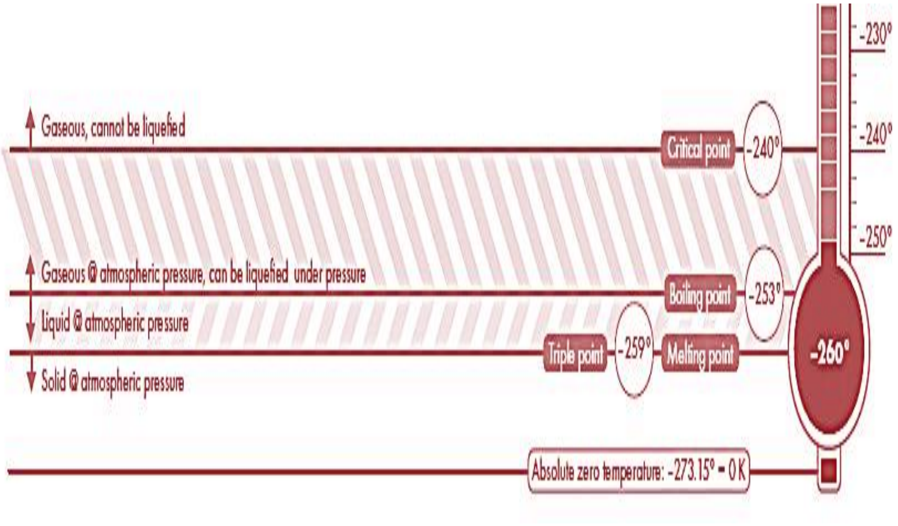
Hydrogen key properties:

- light,
- storable,
- high energy content per unit mass,
- colorless
- odorless
- highly combustible
- non-Toxic
- can be produced at industrial scale

Introduction

- Hydrogen is available in different states depending on the temperature and pressure it is subjected to.
  - At room temperature and pressure, it exists as a colorless gas.
  - When cooled to −252.87°C, its state changes to liquid hydrogen.
  - Solid hydrogen is produced when hydrogen is cooled below -259.14 degrees Celsius.





Introduction

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Introduction

- **Hydrogen's specific energy** is the **highest** among conventional fuels, but its **energy density is the lowest**, so pressurization or **liquefaction is required for hydrogen to be used as a fuel**. These fundamental characteristics of hydrogen are the primary drivers of its value as a fuel. Based on lower heating value:
  - The energy content of **1 normal cubic meter (Nm^3) of hydrogen is equivalent to 0.34 liter of gasoline,**
  - 1 liter of liquid hydrogen is equivalent to 0.27 liter of gasoline, and
  - **1 kg of hydrogen is equivalent to 2.75 kg of gasoline**.

FUEL	SPECIFIC ENERGY (MJ/kg) (1kWh = 3.6 MJ)	ENERGY DENSITY (MJ/L)
Hydrogen	142.0	0.01 (1 atm); 7.10 (1,000 bar); 10.00 (liquid)
Methanol	20.0	15.90
Ammonia	22.5	15.60
Gasoline	47.1	35.00
Diesel	42.8	40.40
Heavy fuel oil	42.4	40.70
Biodiesel	42.2	33.00
Natural gas	50.0	0.04
LNG	50.0	22.20

Source: World Bank compilation of higher heating values obtained from multiple sources.
Note: atm = atmospheres; kg = kilogram; kWh = kilowatt-hour; L = liter; LNG = liquefied natural gas; MJ = megajoule.

Introduction

- Hydrogen was used to fuel the first internal combustion engines over 200 years ago.
- Hydrogen provided lift to balloons and airships in the 18th and 19th centuries

The British R101 airship that crashed in 1930

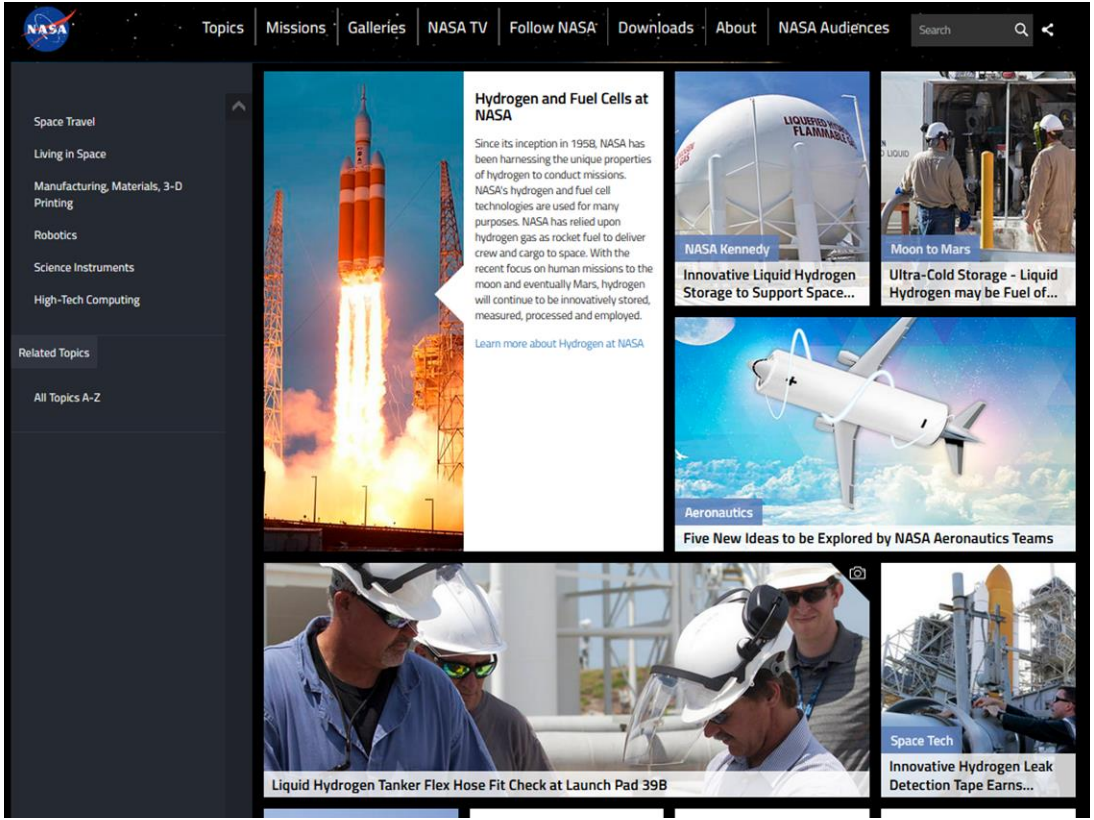
Flying Whales: a new take on the airship, 2020.
https://www.airliquide.com/stories/innovation/flying-whales-new-take-airship

Why The Airship Was A Design Disaster?
Watch and we'll discuss next week
https://www.youtube.com/watch?v=3flx3G2a-eI

Introduction

"Since its inception in 1958, NASA has been harnessing the unique properties of hydrogen to conduct missions. NASA's hydrogen and fuel cell technologies are used for many purposes. NASA has relied **<u>upon hydrogen gas as rocket fuel to deliver crew and cargo to space</u>**. With the recent focus on human missions to the moon and eventually Mars, hydrogen will continue to be <u>innovatively stored, measured, processed and employed</u>."

https://www.nasa.gov/topics/technology/hydrogen/index.html



Hydrogen Production Methods

Hydrogen can be produced by more than 17 production methods. Some of them are technically and economically matured and others are not.

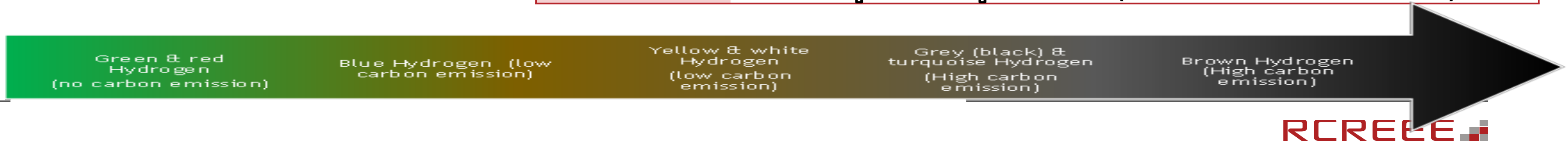
- Steam reforming converts methane (and other hydrocarbons in natural gas) into hydrogen and carbon monoxide by reaction with steam over a nickel catalyst (the most common way).
- Gasification uses heat to break down biomass or coal into a gas from which pure hydrogen can be generated
- Electrolysis uses electrical current to split water into hydrogen at the cathode and oxygen at the anode
- Steam electrolysis (a variation on conventional electrolysis) uses heat, instead of electricity, to provide some of the energy needed to split water.
- Thermal water splitting uses a very high temperature (approximately 1000°C) to split water
- Thermochemical water splitting uses chemicals and heat in multiple steps to split water into its component parts
- Photoelectrochemical systems use semi-conducting materials (like photovoltaics) to split water using only sunlight
- Photobiological systems use microorganisms to split water using sunlight
- Biological systems use microbes to break down a variety of biomass feed stocks into hydrogen

Hydrogen Production

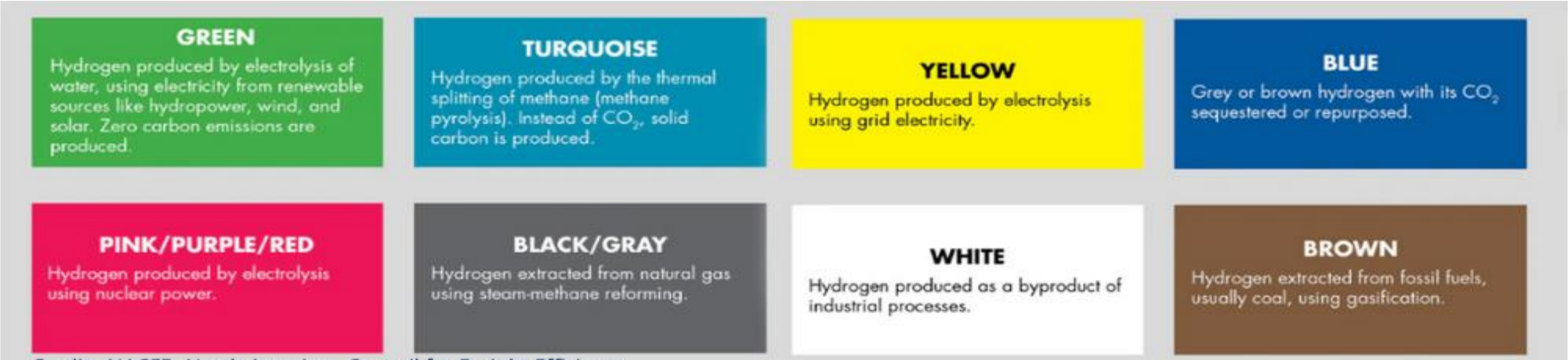
- The production sources can generally be classified in 4 groups: Natural gas, coal, biomass and water.

- Hydrogen types can be classified according to carbon emissions from hydrogen production process. Green and red (pink) hydrogen are the lowest as no carbon emitted during the production process. While gray, black, turquoise, and brown hydrogen are the highest emitting processes.

Hydrogen color	Production processes
Black/ Brown Hydrogen	Hydrogen produced from fossil fuels, typically coal, using gasification. Using brown (lignite) or black (bituminous) coal in the hydrogen-making process gasification.
Black/ Grey Hydrogen	Hydrogen is produced by steam reforming of natural gas. It is the most popular way to produce hydrogen currently and the most economical way.
Blue Hydrogen	Blue hydrogen is produced using carbon capture and storage (CCS) technology. CCS is a technology to capture CO2 emission that are generated from industrial process such as steam reforming that generate grey hydrogen. The captured CO2 does not enter the atmosphere and this process considered carbon neutral.
Green Hydrogen	Water electrolysis is to split the water into oxygen and hydrogen. This process generates no carbon emissions. If water electrolysis is powered by renewable electricity, then the hydrogen produced is green hydrogen.
Pink/Red Hydrogen	Pink hydrogen is generated through electrolysis of water by using electricity from a nuclear power plant. Red hydrogen is produced through the high-temperature catalytic splitting of water using nuclear power thermal as an energy source. Of course, there is a concern about the nuclear wastes and safety issues related to this type of power stations.
Turquoise Hydrogen	Hydrogen can be produced by thermal splitting of methane. This process is called methane pyrolysis and produce solid carbon instead of CO2. To name hydrogen produced from this process the heat for the high temperature reactor should be derived from renewable or carbon neutral energy sources (Biomass).
White Hydrogen	White hydrogen is the hydrogen produced as by product from industrial processes or naturally.
Yellow Hydrogen	It is the same as green hydrogen, water electrolysis is used. However, the electricity consumed is generated using mixed sources (renewable and non- renewable sources)

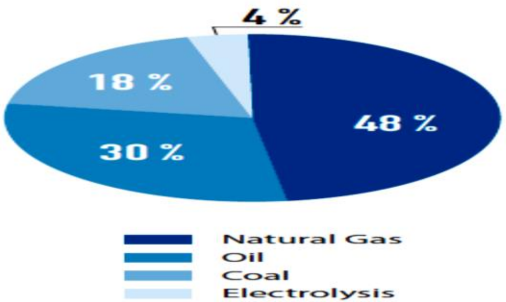


Hydrogen Production



Credit: NACFE--North American Council for Freight Efficiency

- The most common way of producing hydrogen is from natural gas, through a process called steam methane reforming (SMR), followed by oil reforming and coal gasification.
- Hydrogen production via water electrolysis is only 4% of the global production.



Hydrogen Production: Grey Hydrogen

- Hydrogen production consumes around 205 billion m^3 of natural gas (**6% of global natural gas use**) and 107 Mt of coal (**2% of global coal use**), with coal use concentrated in China.

- Global hydrogen production emits 900 $MtCO_2$/yr corresponding to the annual CO_2 emissions of Indonesia and the United Kingdom combined. Dependence on natural gas means that hydrogen production generates significant CO_2 emissions: **9 tons of carbon dioxide per tons of hydrogen (tCO_2/tH_2) from natural gas**.

- Reforming is the most widespread method for producing hydrogen from natural gas. There are **three methods:**
  - steam reforming (using water as an oxidant and a source of hydrogen),
  - partial oxidation (using oxygen in the air as the oxidant), or
  - a combination of both called autothermal reforming (ATR).

- Steam reforming is used to extract hydrogen from natural gas and – much less frequently – from liquefied petroleum gas and naphtha.

Steam reforming reaction

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Endothermic, 206,000 kJ/kmol H_2 energy input

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2$$

Exothermic, 41,000 kJ/kmol H_2 energy output

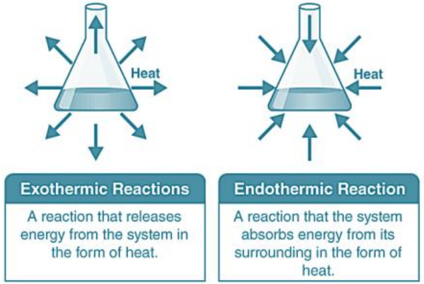
Combined reaction

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

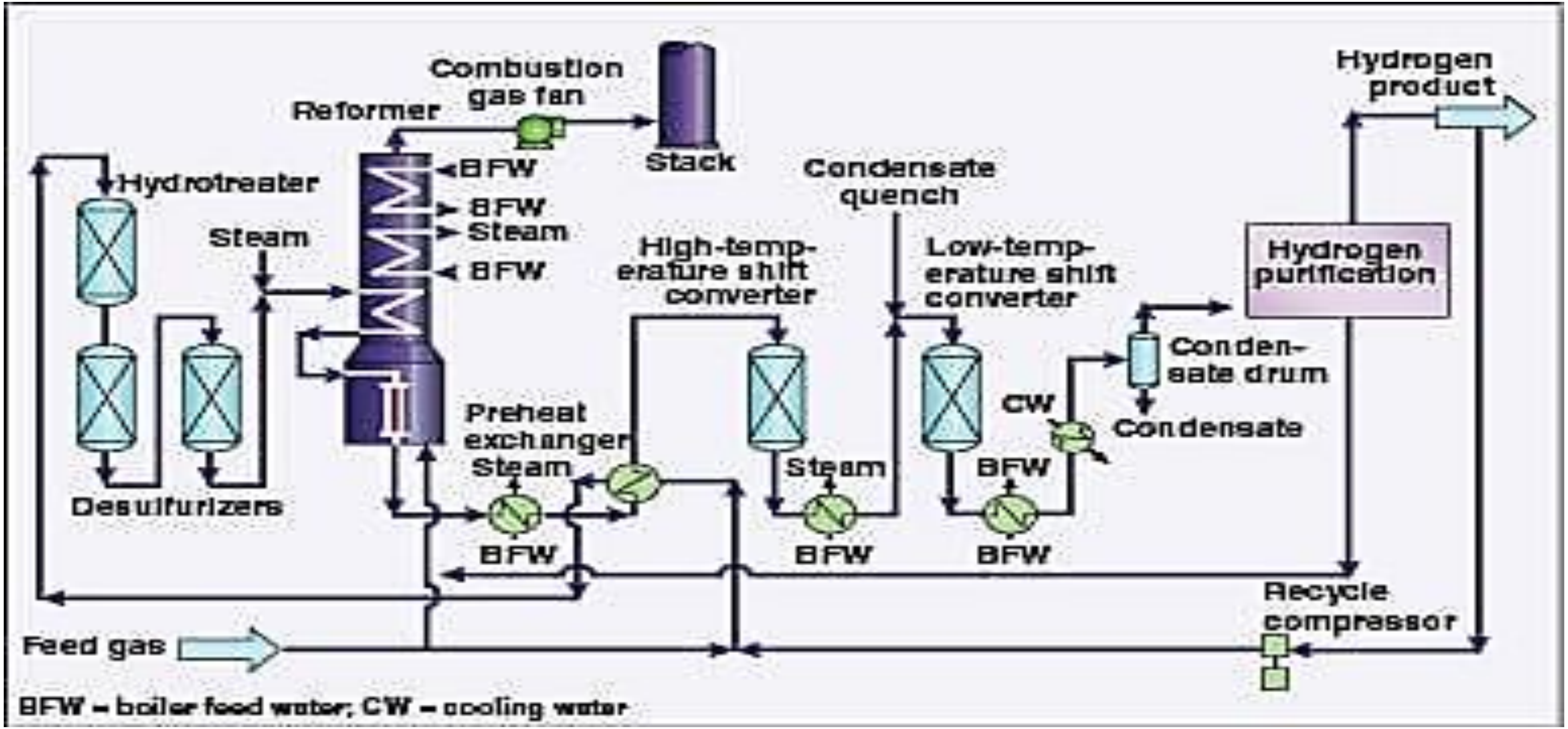
165,000 kJ/kmol H_2 energy input. This is equivalent to 81,850 kJ (or 22.73 kWh) energy input per kg of hydrogen produced.

For 1 kmol (about 16 kg) of methane used in this reaction, 4 kmol (about 8 kg) of hydrogen are produced. Hydrogen is also produced from oil, coal, and biomass.

Endothermic Reaction	**Exothermic Reaction**
A reaction that the system absorbs energy from its surrounding in the form of heat.	A reaction that releases energy from the system in the form of heat.
The energy is absorbed from the surrounding into the reaction	The energy is released from the system to its environment.
Energy in the form of heat	Energy is released as heat, electricity, light or sound.
Melting ice, evaporation, cooking, gas molecules, photosynthesis are a few examples	Rusting iron, settling, chemical bonds, explosions, nuclear fission are a few examples.



Hydrogen Production: Steam Methane Reforming (SMR)

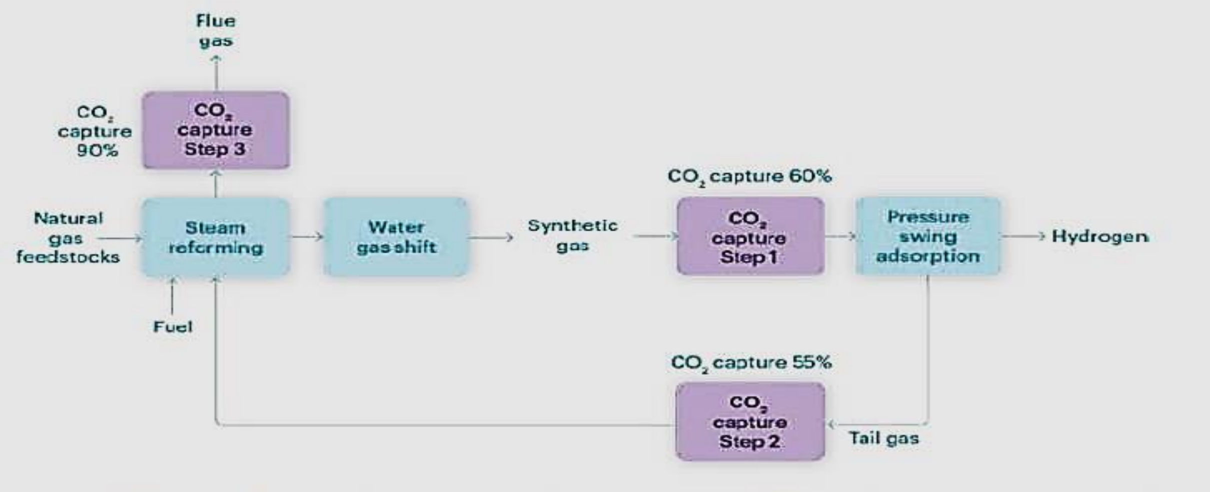


Source: https://www.chemengonline.com/hydrogen-production-by-steam-reforming/?printmode=1

Hydrogen Production: Blue Hydrogen

- Blue hydrogen is produced in the same way, but with the addition of carbon capture and storage (CCS) to prevent the CO_2 from being released. **<u>Thus, the concept of what is called Blue Hydrogen is a combination of a Grey Hydrogen plant with a facility of Carbon Capture.</u>**

- Carbon capture and utilization (CCU) and CCS are sometimes discussed collectively as carbon capture, utilization, and sequestration (CCUS). This is because CCS is a relatively expensive process yielding a product with an intrinsic low value.



Source: IEAGHG (2017a), "Reference data and supporting literature reviews for SMR based hydrogen production with CCS".

Hydrogen Production: Blue Hydrogen

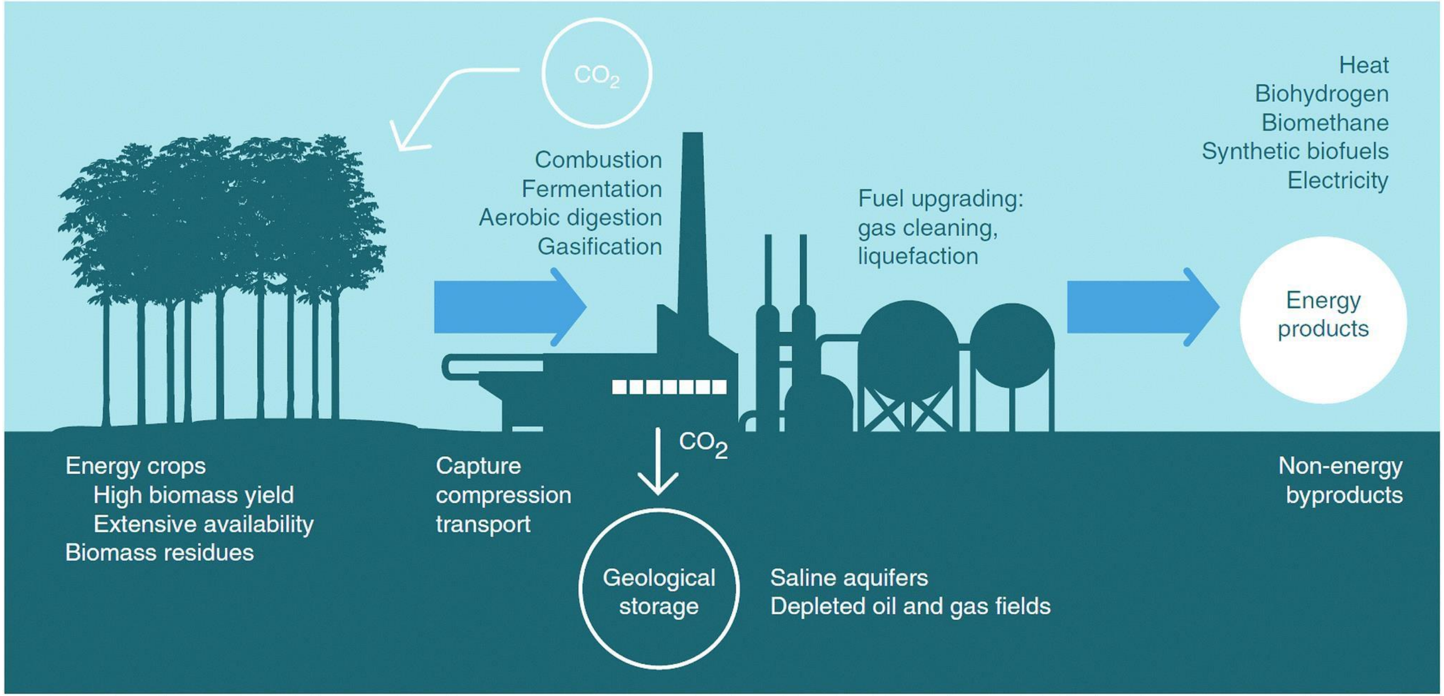
- **CCS is simply a way of reducing carbon emissions. It's a three-step process which involves:**
  - **capturing the carbon produced,**
  - **Compressing, and**
  - **transporting it to a site where it is permanently injected into rock formations within the likes of saline aquifers or depleted oil and gas reservoirs, the latter being increasingly common.**

- **CCS has been in operation since 1972. Storage sites typically need to be 1km+ under the ground.**

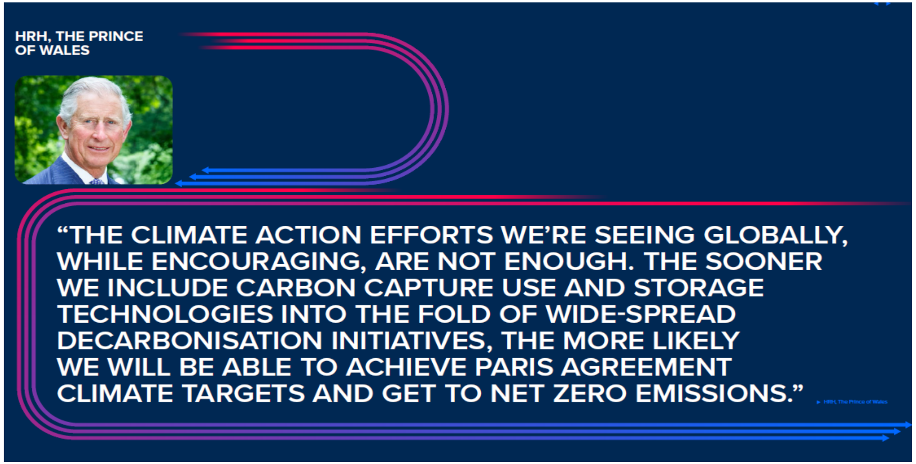
- **CCUS focusses on reusing the CO_2 from industrial processes by converting it into goods such as concrete or biofuel.**

- **CCUS is not a new idea, but the pipeline is now growing exponentially to support reaching climate targets and using policy incentives which have encouraged rapid up-scaling and wide-scale adoption.**

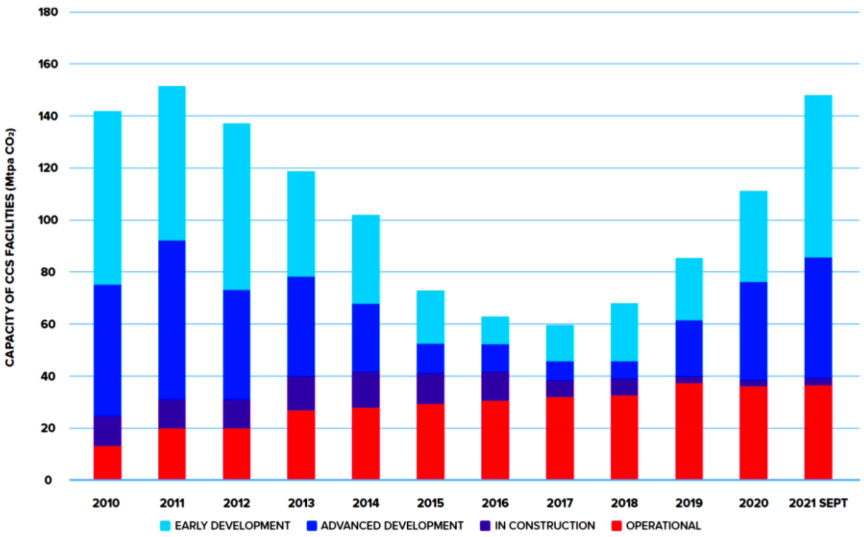
Hydrogen Production: Blue Hydrogen



Hydrogen Production: Blue Hydrogen



- **There are 27 CCS facilities operational worldwide. Many of them are enhanced oil recovery projects.**



Facilities that have not announced their capacity are not included in this chart

FIGURE 7 PIPELINE OF COMMERCIAL CCS FACILITIES FROM 2010 TO SEPTEMBER 2021 BY CAPTURE CAPACITY

	OPERATIONAL	IN CONSTRUCTION	ADVANCED DEVELOPMENT	EARLY DEVELOPMENT	OPERATION SUSPENDED	TOTAL
Number of facilities	27	4	58	44	2	135
Capture capacity (Mtpa)	36.6	3.1	46.7	60.9	2.1	149.3

https://www.globalccsinstitute.com/resources/global-status-report/

Hydrogen Production: Water Electrolysis

- Water electrolysis is an electrochemical process that splits water into hydrogen and oxygen. Demineralized water is split by an electrical current into oxygen and hydrogen in an electrolyzer. In contrast to the conventional method of steam reforming, e.g. from natural gas ('gray' or 'blue'), this type of production is CO_2-free.

- Currently, the hydrogen produced by this means is mostly used in markets where high-purity hydrogen is necessary (for example, electronics and polysilicon).

- Electrolysis requires water as well as electricity. Around 9 liters of water are needed to produce 1 kgH_2, producing 8 kilograms (kg) of oxygen as a by-product.

- There are several types of electrolyzers, the most common are:
  - Alkaline Electrolyzers, and
  - Proton Exchange Membrane (PEM) Electrolyzers.

Hydrogen Production: Water Electrolysis

We are primarily interested in water electrolysis since it allows the use of electricity generated from renewable energies (Green Hydrogen). The efficiency of a typical electrolyzer is *about 80 percent*.

$$H_2O \rightarrow H_2 + \tfrac{1}{2}O_2$$ Water electrolysis reaction

Water electrolysis: This reaction produces 1 kmol hydrogen (about 2 kg) and 0.5 kmol of oxygen (about 16 kg) when 1 kmol *(about 18 kg) of water is used*.

Minimum work for water electrolysis: The minimum work required for this endothermic reaction is given by the Gibbs function of water at 25°C, which is

- equal to 237,180 kJ per kmol of liquid water entering the reaction.

- or to 117,650 kJ (or 32.68 kWh) per kg of hydrogen produced by the reaction.

Note that this is very close to the lower heating value of hydrogen (120,000 kJ/kg).

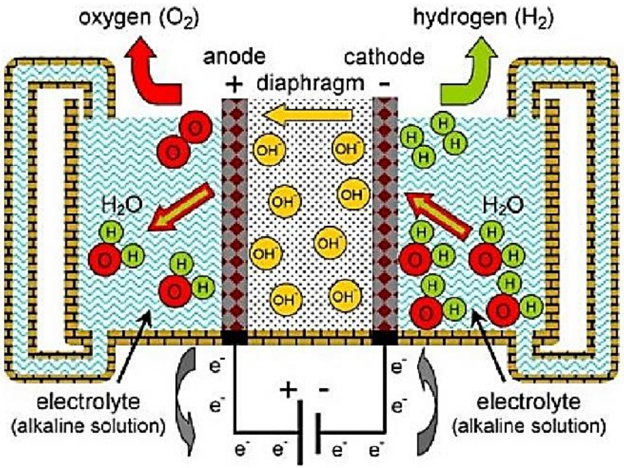
An actual electrolyzer involves irreversibilities and the *actual electricity consumption* will be greater than the minimum value.

Green Hydrogen: Alkaline Electrolysis

- Alkaline electrolysis is a mature and commercial technology. It has been used since the 1920s, in particular for hydrogen production in the fertilizer and chlorine industries.

- The operating range of alkaline electrolyzers goes from a minimum load of 10% to full design capacity.
- Several alkaline electrolyzers with a capacity of up to 165 megawatts electrical (MWe) were built in the last century in countries with large hydropower resources).
- Alkaline electrolysis is characterized by relatively low capital costs compared to other electrolyzers' technologies due to the avoidance of precious materials.

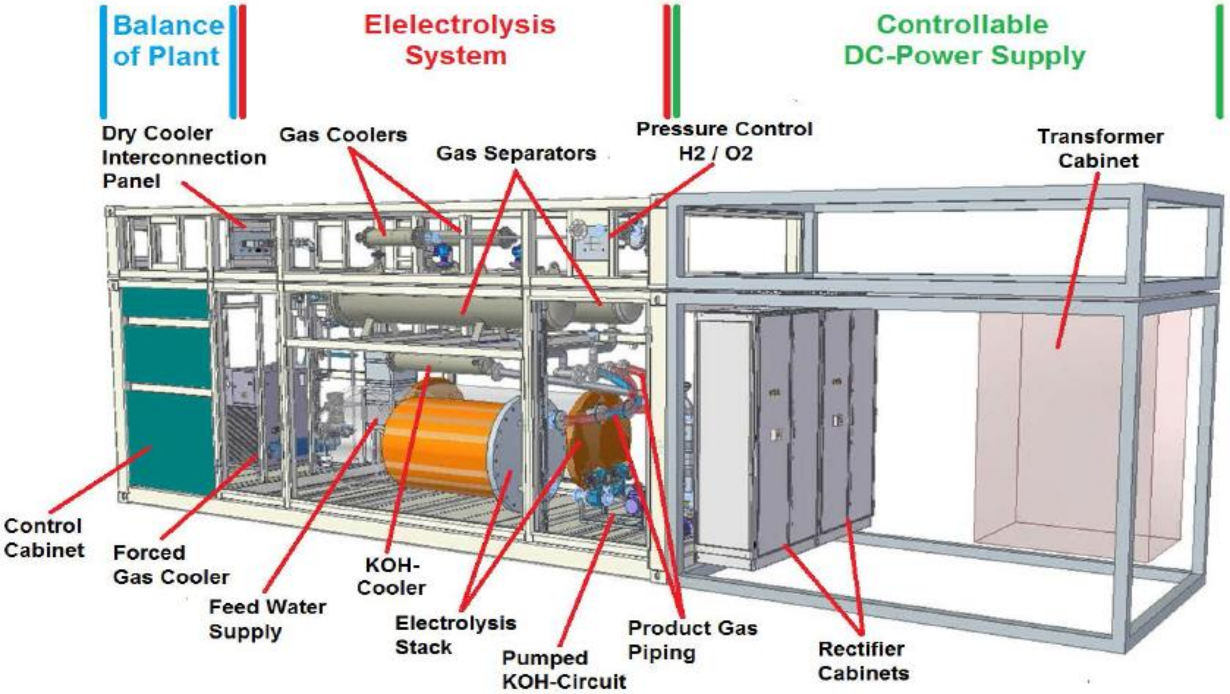
- The drawbacks are the need to recover and recycle of the potassium hydroxide electrolyte solution and the need to use additional compressor if high pressure hydrogen is needed. Also, they have limited flexibility for variable electricity input as in the case with wind and solar power.



Pressurized Alkaline Analyzer Concept [ZSW, 2021]

Aswan Electrolyser (KIMA)
165MW - 37000 m^3H_2/h

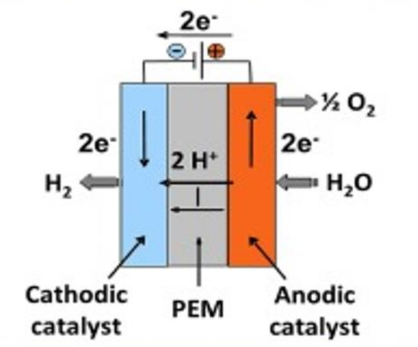
Green Hydrogen: Alkaline Electrolysis

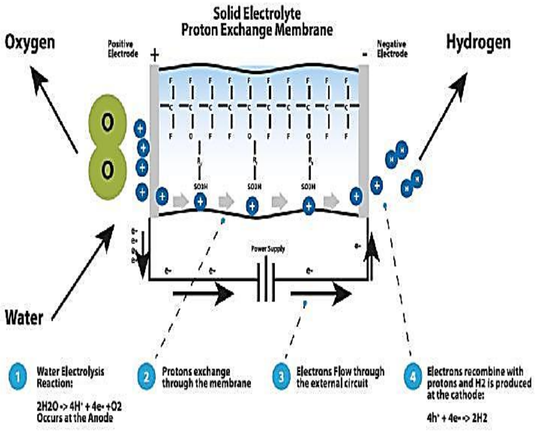


Pressurized Alkaline Analyzer System [ZSW, 2021]

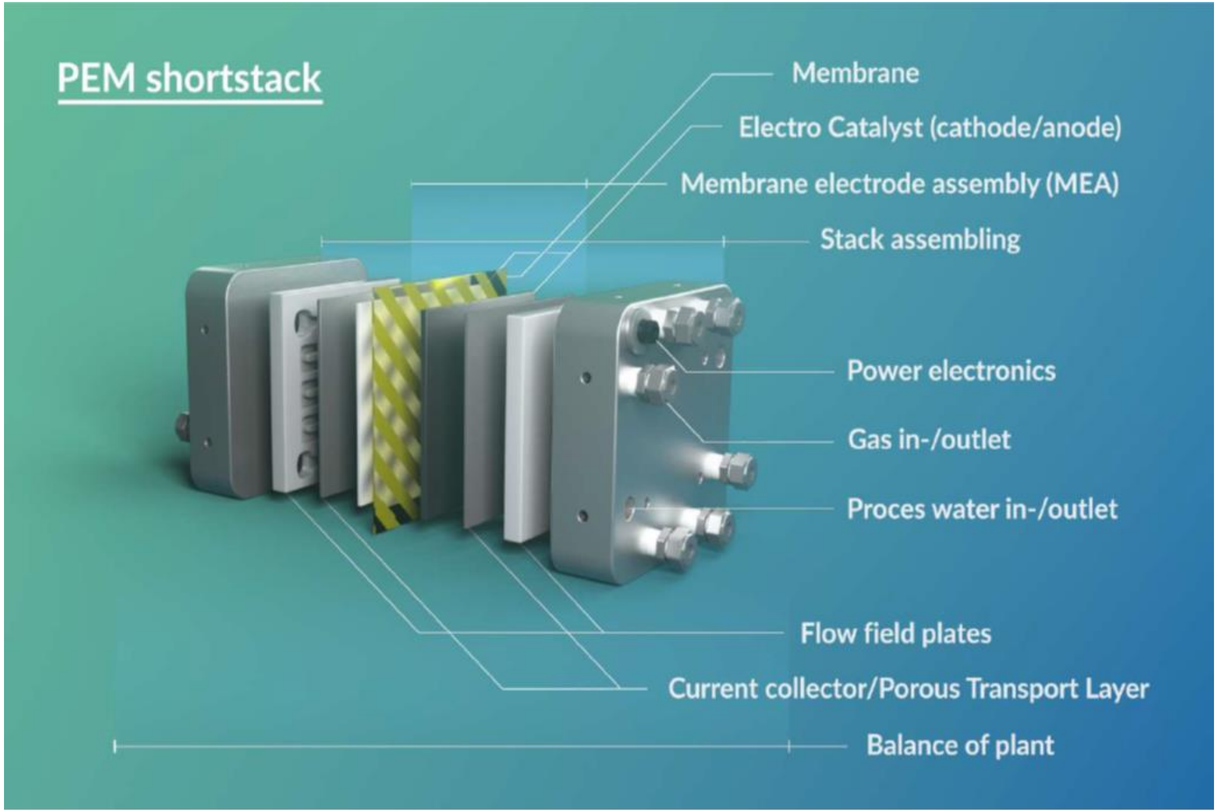
Green Hydrogen: Proton Exchange Membrane (PEM) Electrolyzers

- PEM electrolyzer systems were first introduced in the 1960s by to overcome some of the operational drawbacks of alkaline electrolyzers.
- PEM Electrolyzers use pure water as an electrolyte solution, and accordingly avoid the recovery and recycling of the potassium hydroxide electrolyte solution of the alkaline electrolyzers.
- PEM Electrolyzers are relatively small, making them potentially more attractive than alkaline electrolyzer in dense urban areas.
- They can produce highly compressed hydrogen for decentralized production and storage at refueling stations (30–60 bar without an additional compressor and up to 100–200 bar in some systems, compared to 1–30 bar for alkaline electrolyzer) and offer flexible operation, including the capability to provide frequency reserve and other grid services.
- Their operating range can go from zero load to 160% of design capacity (so it is possible to overload the electrolyzer for some time, if the plant and power electronics have been designed accordingly).
- The drawbacks are that they need expensive electrode catalysts (platinum, iridium) and membrane materials, and their lifetime is currently shorter than that of alkaline electrolyzer. Their overall costs are currently higher than those of alkaline electrolyzer, and they are less widely deployed.





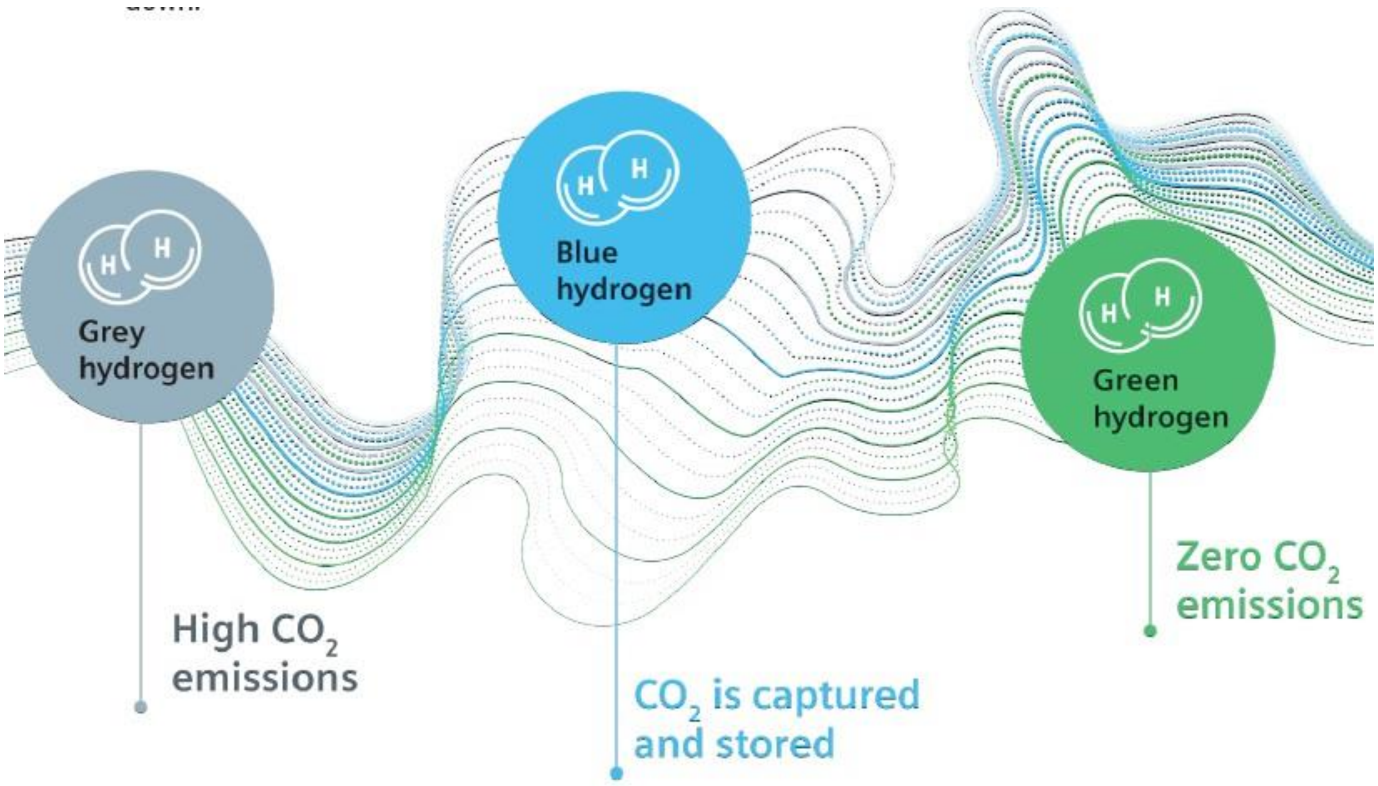
Green Hydrogen: Proton Exchange Membrane (PEM) Electrolyzers



Hydrogen Production: Water Electrolysis

	Alkaline electrolyser			PEM electrolyser		
	Today	2030	Long term	Today	2030	Long-term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74
Operating pressure (bar)	1–30			30–80		
Operating temperature (°C)	60–80			50–80		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000
Load range (%, relative to nominal load)	10–110			0–160		
Plant footprint (m^2/kW_e)	0.095			0.048		

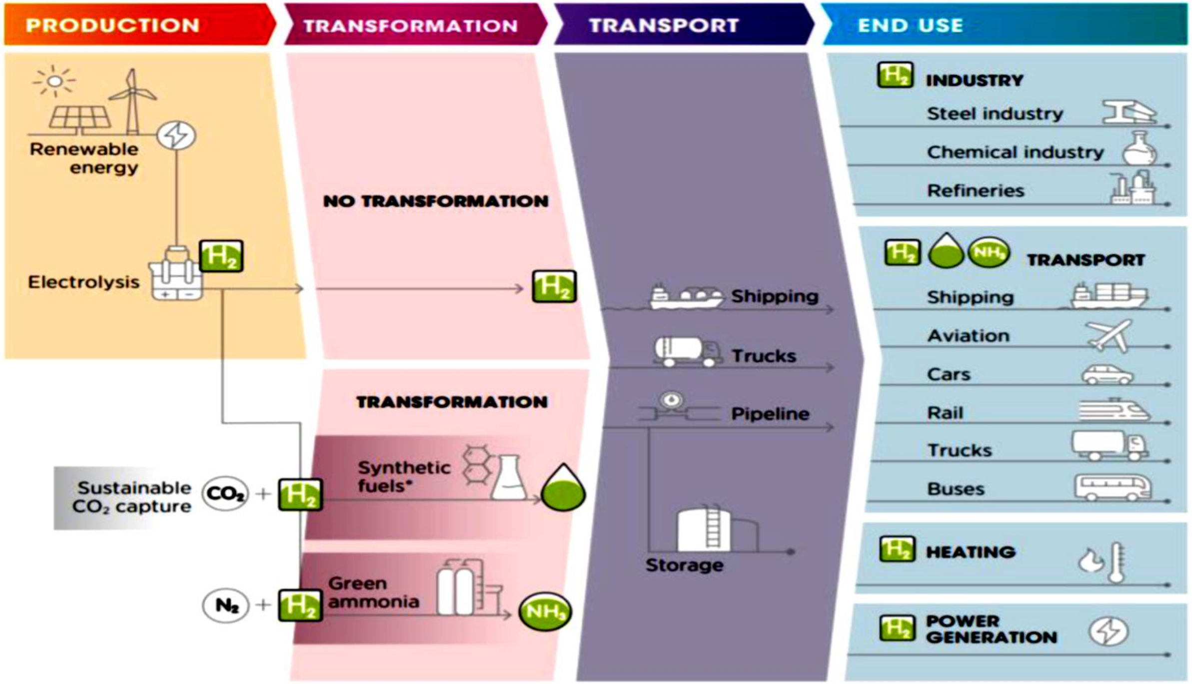
Hydrogen Production: Water Electrolysis



Green Hydrogen

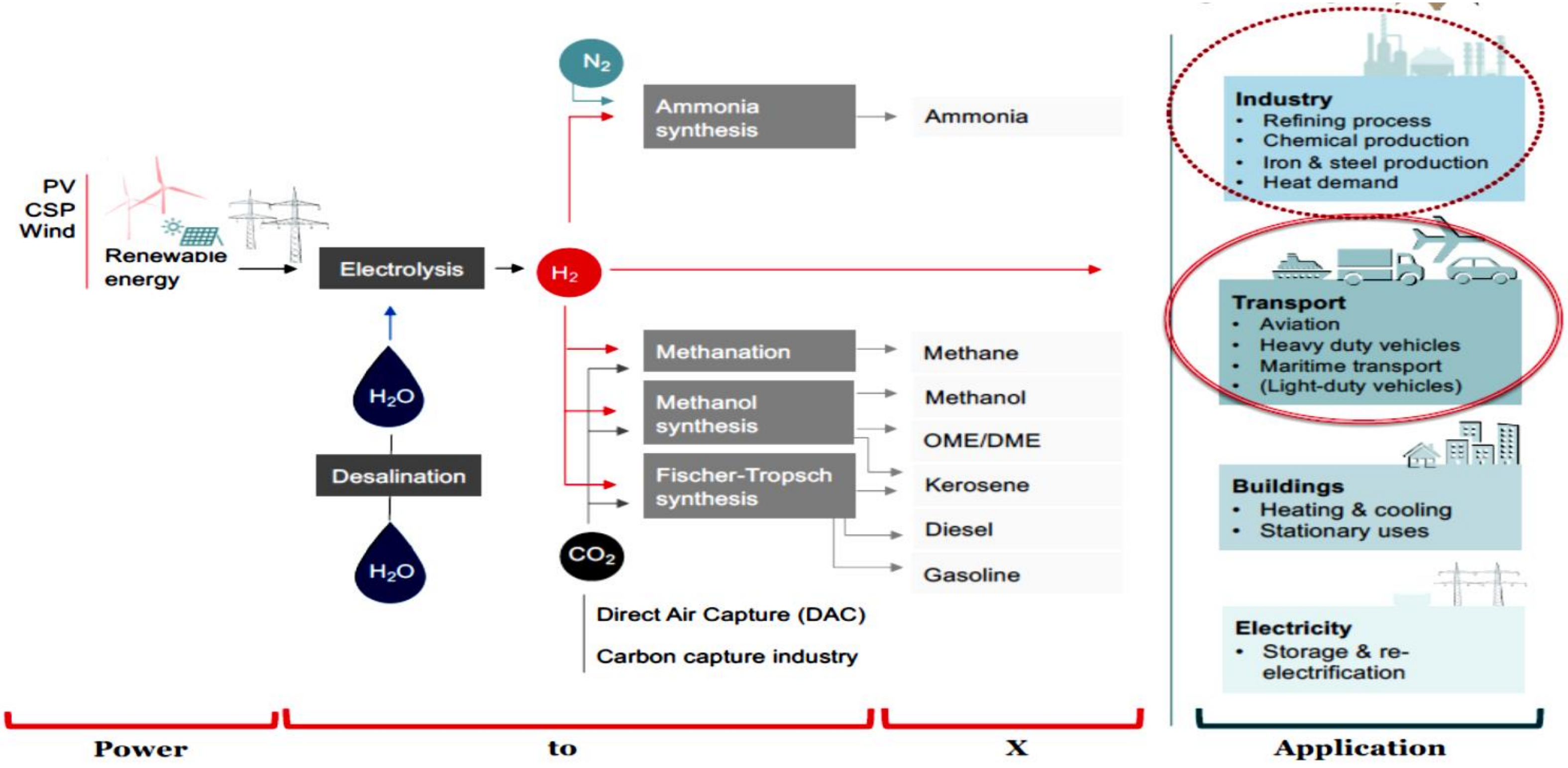
Green hydrogen can decarbonize activities in hard to abate sectors such as heavy industry and transport. As it can replace hydrocarbons in (for instance) aviation, shipping, rail and heavy road transport, as well as those in the chemical, iron, steel, and cement industries.

- Green hydrogen permanent availability is a major advantage given the seasonal and daily variations in the availability of some renewables, such as wind and solar energy, as well as seasonal variations in energy demand.



Source: IRENA

Green Hydrogen: Possible Power to X (P2X) Pathways



Viebahn P. et al, The MENA-Fuels Project Presentation", 2020, https://www.wupperinst.org/en/p/wi/p/s/pd/789/

***Hydrogen Applications:* Refining and Chemical Industries**

For decades, hydrogen has been used primarily by the **refining and chemical industries**. End applications include:

- **Petroleum Refining Industry:**

Hydrogen is commonly used in:

- ✓ Petroleum refining, hydrogen addition to heavy oils, hydrocracking to create petroleum products, including gasoline and diesel.
- ✓ Removing contaminants like Sulphur,
- ✓ Upgrading of Bitumen from Oil Sands
- ✓ Producing methanol (CH3OH)
- ✓ Production of synthetic fuels

- **Agricultural/Chemical Industry:**

Hydrogen is a fundamental raw material needed to produce ammonia (NH3), also known as azane, an important part of fertilizers used in agricultural industries around the world. Ammonia can also be used as an affordable, environmentally-friendly refrigerant (R-717).

Hydrogen Applications: Other Applications

Hydrogen also has a long history of use in several other industries. These include:

- **Food:**
  Hydrogen is used to turn unsaturated fats into to saturated oils and fats, including hydrogenated vegetable oils like margarine and butter spreads.

- **Metalworking:**
  Hydrogen is used in multiple applications including metal alloying and iron flash-making.

- **Welding:**
  Atomic hydrogen welding (AHW) is a type of arc welding which utilizes a hydrogen environment.

Hydrogen Applications: Other Application

- **Flat Glass Production:**
  A mixture of hydrogen and nitrogen is used to prevent oxidation and therefore defects during manufacturing.

- **Electronics Manufacturing**:
  As an efficient reducing and etching agent, hydrogen is used to create semiconductors, LEDs, displays, photovoltaic segments, and other electronics.

- **Medical:**
  Hydrogen is used to create hydrogen peroxide (H_2O_2). Recently, hydrogen gas has also been studied as a therapeutic gas for a number of different diseases.

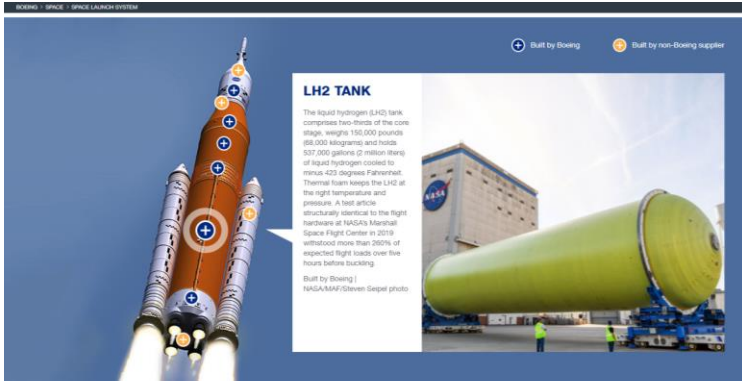
A tank car designed for transporting hydrogen peroxide by rail

Hydrogen Applications: Application as an Alternative Fuel

Hydrogen is used as an alternative combustible fuel. Notable growth areas include:

- **Space Exploration:**
  Liquid hydrogen (LH_2) fuel has played an important role in space exploration since NASA's Apollo program, when it was first used in in the secondary stage of the Saturn rockets. Today its use is expanding to include government and commercial organizations like United Launch Alliance, Boeing, and Blue Origin.

- **Aviation:**
  Several experimental programs have utilized hydrogen fuel cells in projects like the Pathfinder and Helios unmanned long duration aircraft. Recently, Airbus unveiled concepts for hydrogen-fueled "ZEROe" aircraft that utilize liquid hydrogen to power modified gas turbine engines.



Boeing: Space Launch System

Airbus reveals new zero-emission concept aircraft | Airbus

Hydrogen Applications: Application as an Alternative Fuel

- **Global Logistics:**
  Dozens of companies with large warehouse and distribution needs are turning to hydrogen fuel cells to power trucks, forklifts, and more. Companies like Nikola Motors, Hyundai, Toyota, Kenworth Truck Co, and UPS have big aspirations for hydrogen powered trucks, vans, and semis.

- **Personal Transportation:**
  Nine of the major auto manufacturers are developing hydrogen fuel cell vehicles (FCVs) designed for personal use.

- **Public Transportation:**
  Hydrogen fuel cells are also being considered for other public transportation applications including trains and buses. Several major cities including Chicago, Vancouver, London, and Beijing have experimented with hydrogen powered buses. Hydrogen-powered trains have now appeared in Germany, and in the next five years, other models are expected to come to Great Britain, France, Italy, Japan, South Korea, and the United States.

H_2 Fuel Cell buses and cars for Belfast

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Hydrogen Applications: Application in Electric Utility

- **Power Generation:**
  Hydrogen is already used for cooling power plant generators, but it also provides a promising means of electrical grid stabilization. Electrical energy can be turned into hydrogen through electrolysis, then stored and used in an end-use application like transportation.

- **Backup Power Generation:**
  At a local level, stationary fuel cells are used as part of uninterruptible power supply (UPS) systems, where continuous uptime is critical. Both hospitals and data centers are increasingly looking to hydrogen to meet their uninterruptible power supply needs.

Fuel Cells in Transportation Sector

Hydrogen fuel cell electric vehicles (HFCEVs) may not have received the public attention of battery electric vehicles (BEVs), but the technology is not just for personal use.

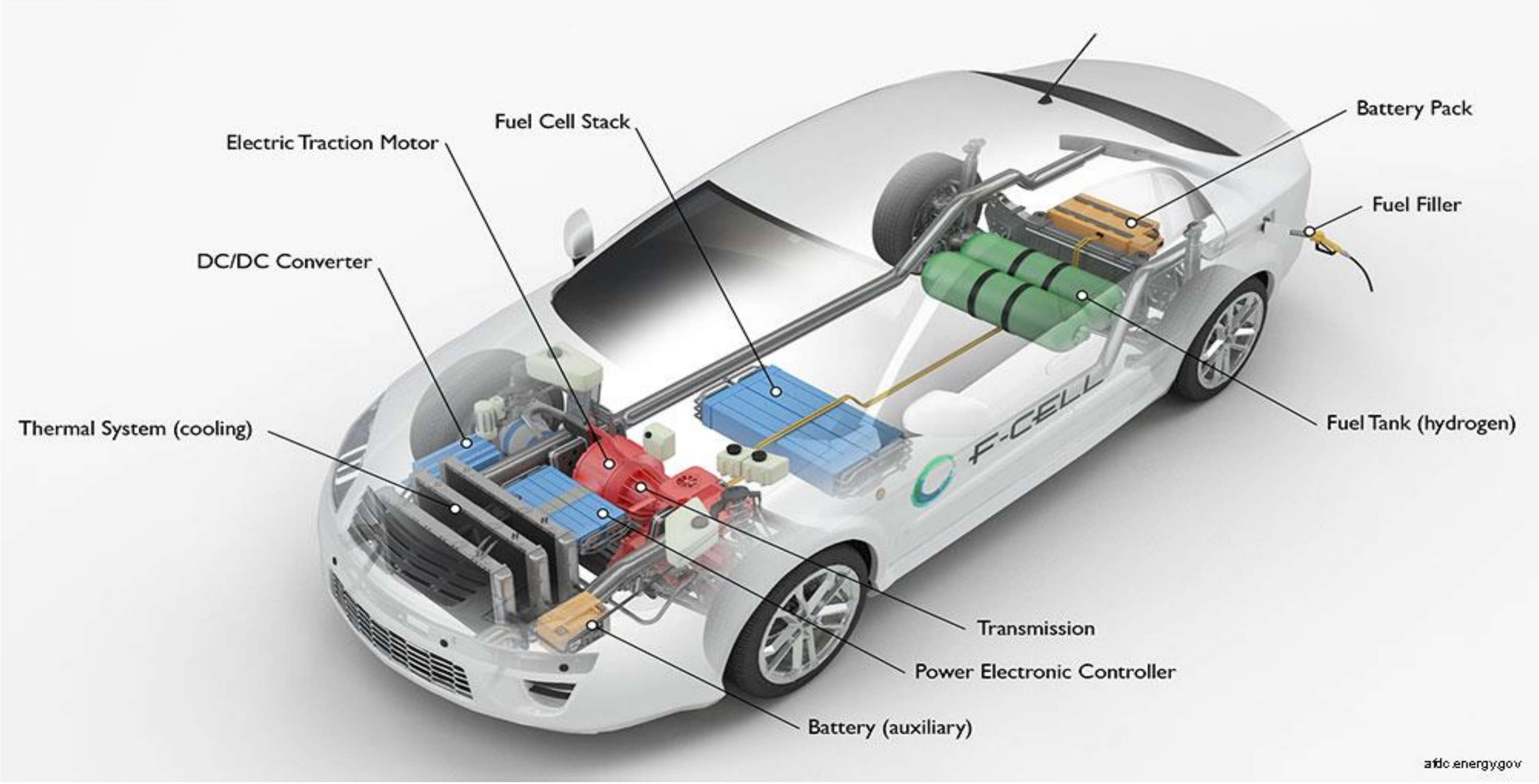
In fact, current storage and logistic challenges of BEVs mean that **hydrogen is often better suited for larger scale commercial applications such as heavy-duty trucking**.

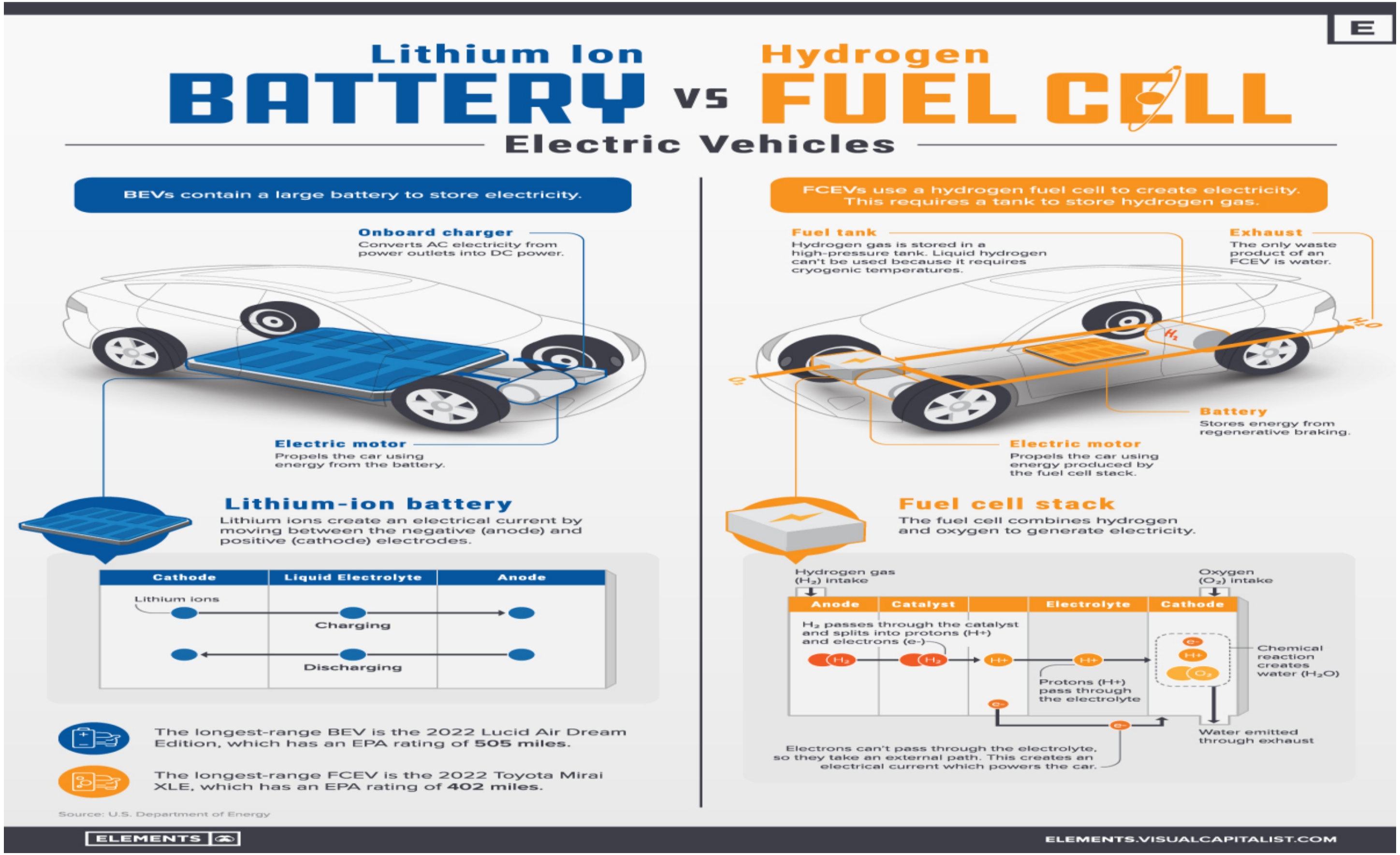
Hydrogen fuel is readily available and efficiently produced as a petroleum byproduct or through electrolysis using energy generated by renewable sources.

As a liquid or pressurized gas, it’s relatively easy to transport and quick to refuel, bypassing the long charge times required by today’s batteries.

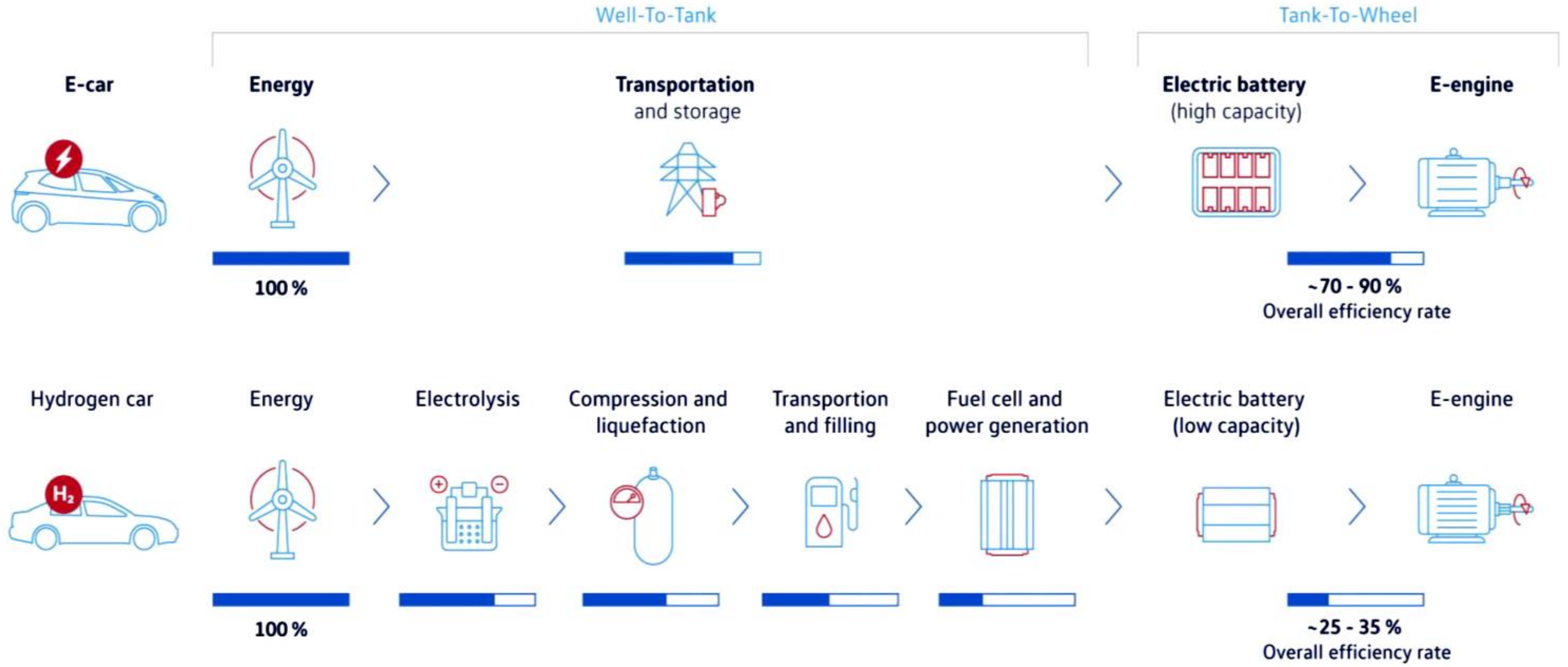
The Toyota Mirai is one type of hydrogen FCEVs hat has already been in production for a number of years. It can be seen on the road and used by customers in California. Image courtesy of USA Today.

Hydrogen Fuel Cell Vehicle





Source: Visualized: Battery Vs. Hydrogen Fuel Cell (visualcapitalist.com)



Source Volkswagen

Fuel Cells in Transportation Sector: A wide market

Warehouse Logistics

Dozens of companies with large warehouse and distribution needs are turning to hydrogen fuel cells to power clean trucks, forklifts, pallet jacks, and more.

Global Distribution

Fuel cells boast both the range and power required for long-haul trucking and local distribution. Companies like Nikola, Hyundai, Toyota, Kenworth, and UPS are already building hydrogen powered semi-trucks and vans.

Buses

Hydrogen power is being considered for other public transportation applications, including hydrogen fuel cell buses. Several major cities including Chicago, Vancouver, London, and Beijing have experimented with hydrogen powered buses.

A reach truck powered by Plug Power; Amazon is a big Plug Power customer.
Image courtesy Plug Power

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Fuel Cells in Transportation Sector: A wide market

Trains

Hydrogen fuel cell trains have now appeared in Germany, and in the next five years, other models are expected to come to Great Britain, France, Italy, Japan, South Korea, and the United States.

Personal Vehicles

Nine of the major auto manufacturers are developing hydrogen fuel cell electric vehicles (HFCEVs) for personal use. Notable models include the Toyota Mirai, Honda Clarity, Hyundai Nexo, and BMW I Hydrogen Next.

Planes

Several experimental projects like the Pathfinder and Helios prototypes have explored application of hydrogen fuel cells in aerospace. These long-range unmanned vehicles utilized a hybrid system with hydrogen fuel cells which were replenished by electrical power from solar arrays, allowing for theoretically indefinite day and night continuous flight.

The world's two first hydrogen-powered trains have begun service in Germany.
First Hydrogen-Powered Trains Rolling in Germany (popularmechanics.com)

Helios Prototype Solar-Powered Aircraft | NASA

Fuel Cell Aircraft Example

- HY4 - World's first 4-seat hydrogen fuel cell powered aircraft
  - Developed by DLR, H2Fly, Pipistrel, the University of Ulm, and Hydrogenics
    - Maiden flight 29/09/2016 from Stuttgart Airport

HY4 Aircraft characteristics (based on Pipistrel Taurus G4)	
Size	Length 7.4 m, Wingspan 21.36 m
Engine Power	80 kW (peak), 26 kW at cruise
Speed	200 km/h (peak), 140 km/h cruise
Range	750 km to 1,500 km (depending on the speed, load and altitude)
Mass	MTOW 1500 kg Empty weight without power system ~630 kg Weight of power system including tanks 400 kg
PEM Fuel cell	3 x 15 kW stacks
Hydrogen storage	2 x 300-400 bar composite cylinders (1 per fuselage)
Li-ion battery pack	21 kWh, 45 kW peak power Provides peak power for take off and climb + 15 minutes emergency power

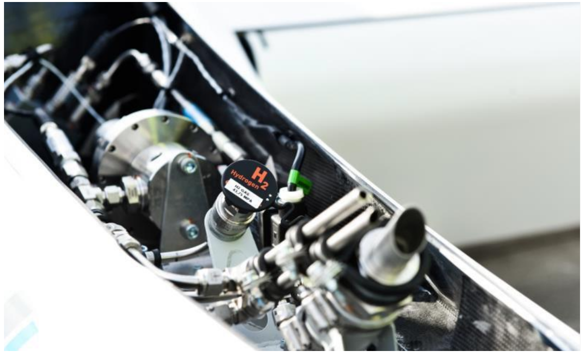


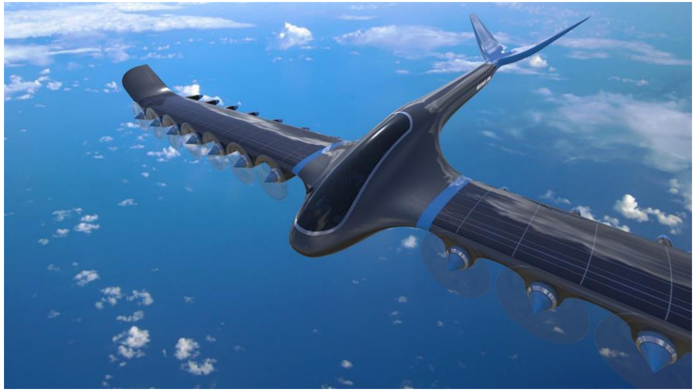
Image Credits: DLR (CC-BY 3.0)

Source: QinetiQ Hasla, RAeS Light Aircraft Design Conference, 2019
https://www.aerosociety.com/media/12868/raes-fuel-cell-presentation-v31.pdf

Fuel Cell Aircraft Development

- ZeroAvia - HyFlyer project - announced September 2019
  - £2.7M Funding from UK Government ATI programme, supported by the Department for Business, Energy & Industrial Strategy, the Aerospace Technology Institute and Innovate UK
  - Project to deliver 250-300 NM range for a Piper M-class six-seater in 2022
  - Cranfield Aerospace Solutions (CAeS) provide aircraft integration expertise
  - Fuel cell to be developed by Intelligent Energy
  - Compressed hydrogen storage

- H3 Dynamics - Element One – announced September 2018
  - Distributed propulsion and energy storage system concept
  - Nacelle contains 5 kW fuel cell, compressed H_2 storage and battery
  - Provides redundancy/safety benefits
  - Targeting regional transport for 4 passengers
  - Ground infrastructure at airport could include H_2 production via renewables
  - First prototype planned for demonstration by 2025



Powered by HES

Image of Element one used with permission of H3 Dynamics

Source: QinetiQ Hasla, RAeS Light Aircraft Design Conference, 2019
https://www.aerosociety.com/media/12868/raes-fuel-cell-presentation-v31.pdf

Fuel Cells in Transportation Sector: A Wide Market

9. Unmanned Arial Vehicles (UAVs)

From package delivery to search and rescue operations, many new applications of UAVs (i.e. drones) are significantly limited by the power and range provided by traditional batteries. Both military and private industry plan to overcome these challenges with hydrogen fuel cells that boast up to three times the range of battery-based systems. Fuel cells also have a higher energy to mass ratio and can be refueled in a few minutes.

10. Boats and Submarines

Hydrogen fuel cells have found their way into a number of marine applications. Some boats like the Energy Observer even use onboard solar panels and wind turbines to generate their own hydrogen for a fuel cell system. For military stealth submarines like the German Type 212, hydrogen fuel cells offer an alternative to nuclear power with long range, silent cruising, and low exhaust heat.

Doosan's hydrogen fuel cell technology is used as a basis for scalable solutions for long-range, autonomous BVLOS (beyond visual line of sight) UAS unmanned aerial systems) flights.

Hydrogen Fuel Cell Technology for BVLOS UAS Flights | Unmanned Systems Technology

Energy Observer is a vessel powered only by energy that it generates itself, be it the onboard solar panels, wind turbines or a hydrogen fuel cell. It's a floating laboratory, showing how the future of transportation could be. Halfway through its six-year journey around the world, the vessel stopped in London so we could learn what's happened since its voyage started.

Image courtesy Toyota – Source: The Energy Observer is a boat that makes its fuel out of seawater | Engadget

- The U212/214 submarines are capable of long-distance submerged passage to the area of operation.

- The U212 propulsion system combines a conventional system consisting of a diesel generator with a lead-acid battery and **an air-independent propulsion (AIP) system used for silent slow cruising with a fuel cell equipped with oxygen and hydrogen storage. The system consists of nine polymer electrolyte membrane (PEM) fuel cells, providing between 30kW and 50kW each**.

- For higher speeds, a connection is made to the high-performance lead-acid battery. An MTU 16V-396 diesel engine powers the generator from Piller GmbH for charging the battery installed on the lower of the two decks at the forward section of the submarine.

- The diesel generator plant is mounted on a swinging deck platform with double elastic mounts for noise and vibration isolation. The propeller motor is directly coupled to the seven-bladed screwback propeller.

- Performance of **the U214 AIP system was increased with two Siemens PEM fuel cells, which produce 120kW per module and give the submarine an underwater endurance of two weeks**. A hull shape, which was further optimised for hydrodynamic and stealth characteristics, and a low-noise propeller combine to decrease the submarine’s acoustic signature.

Source: [U212 / U214 Submarines - Naval Technology (naval-technology.com)]

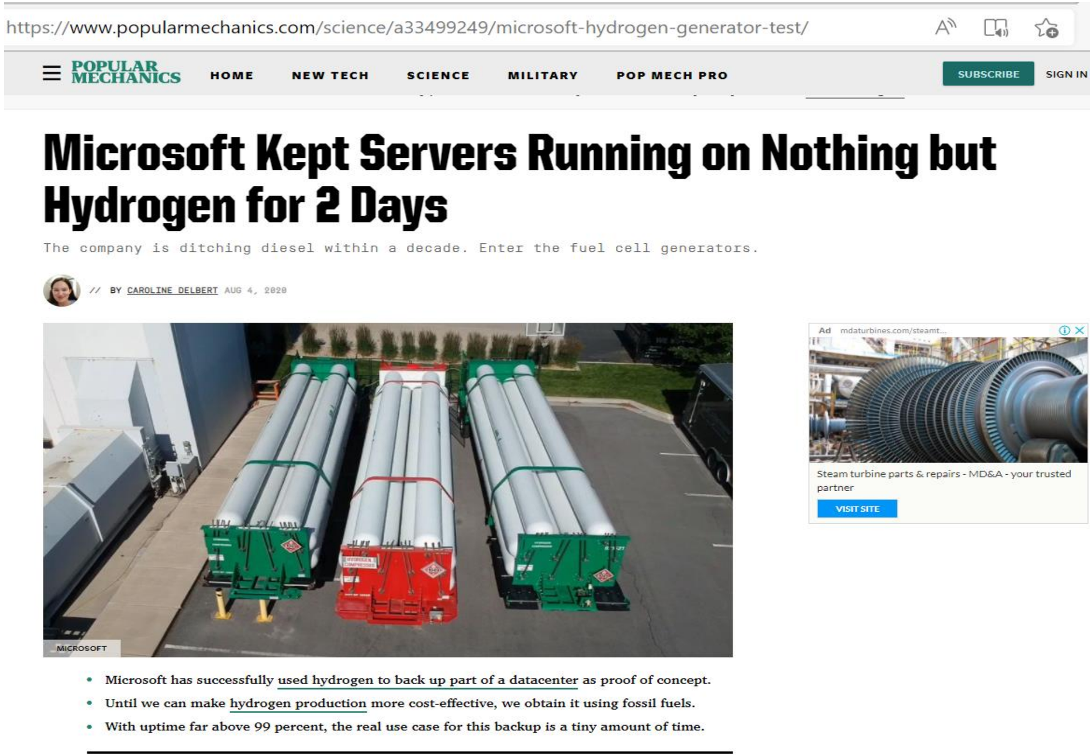
Fuel Cells in Power Generation: A wide market

Backup Power Generation

At a local level, stationary fuel cells are used as part of uninterruptible power supply (UPS) systems, where continuous uptime is critical. Both hospitals and data centers are increasingly looking to hydrogen to meet their uninterruptible power supply needs. Recently, Microsoft made headlines with a successful test of its new hydrogen backup generators, running one data center’s servers on nothing but hydrogen for two days.

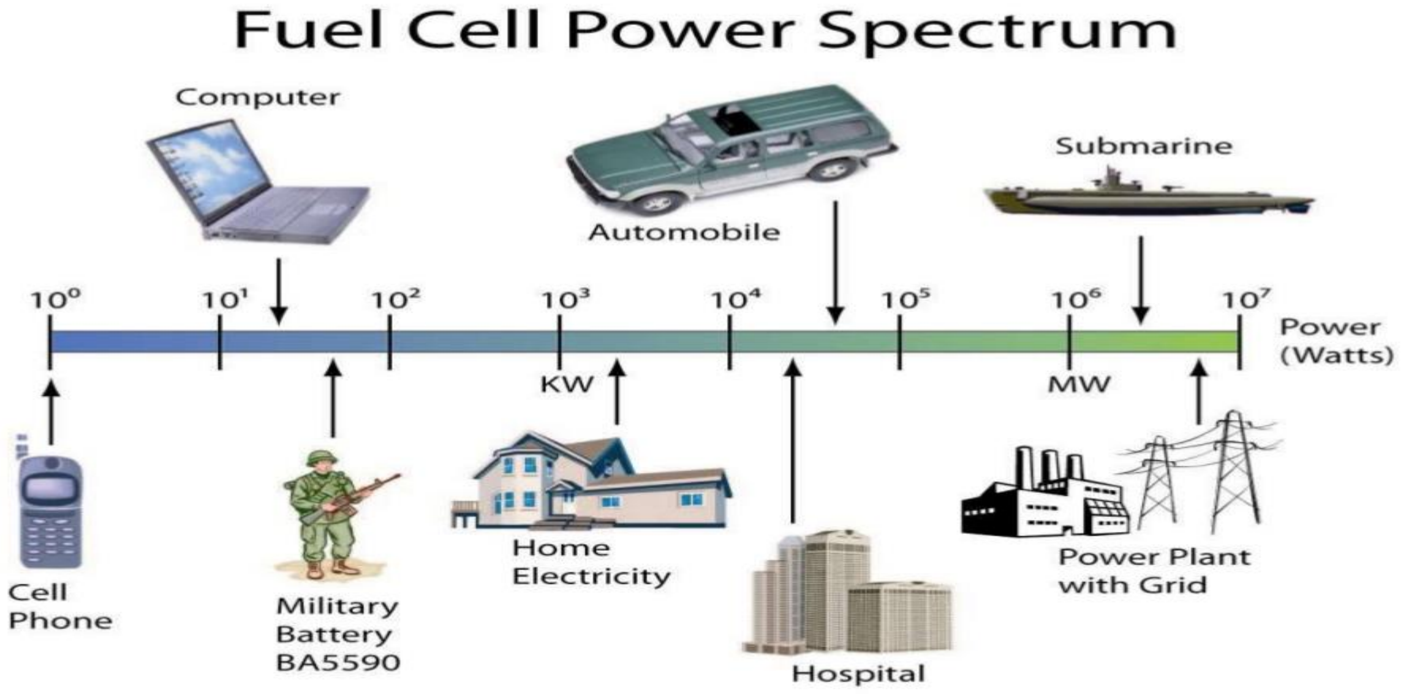
Mobile Power Generation

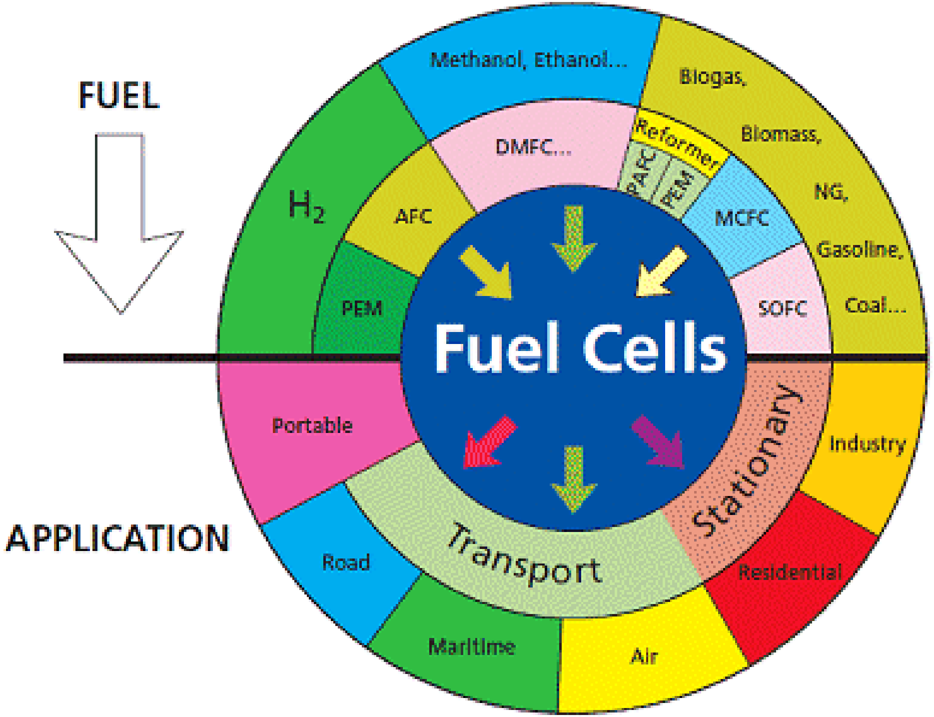
Hydrogen offers versatile options for mobile power generation. In fact, some of the earliest hydrogen fuel cells were developed by NASA to provide electricity for rockets and shuttles in space.



Microsoft Tests Hydrogen Generators - Microsoft Fuel Cells (popularmechanics.com)

Applications

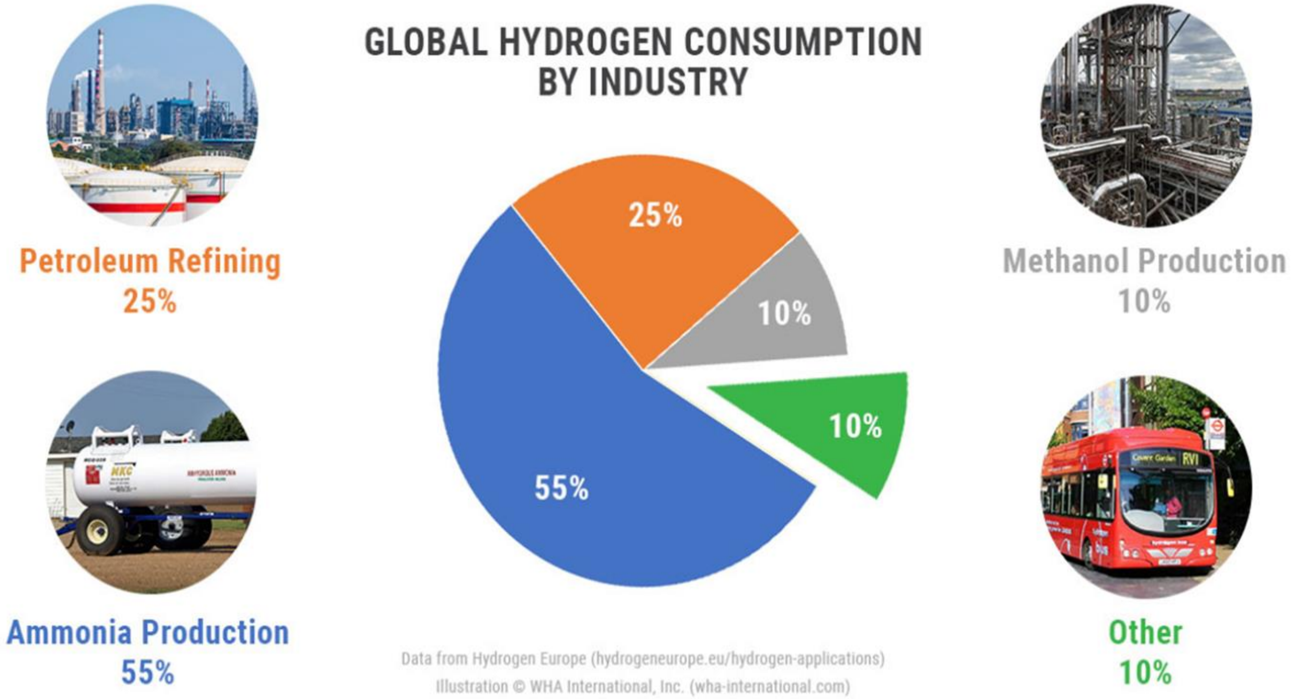




Abbreviations	
AFC	Alkaline Fuel Cell
DMFC	Direct Methanol Fuel Cell
HT PEMFC	High Temperature Proton Exchange Membrane Fuel Cell
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell

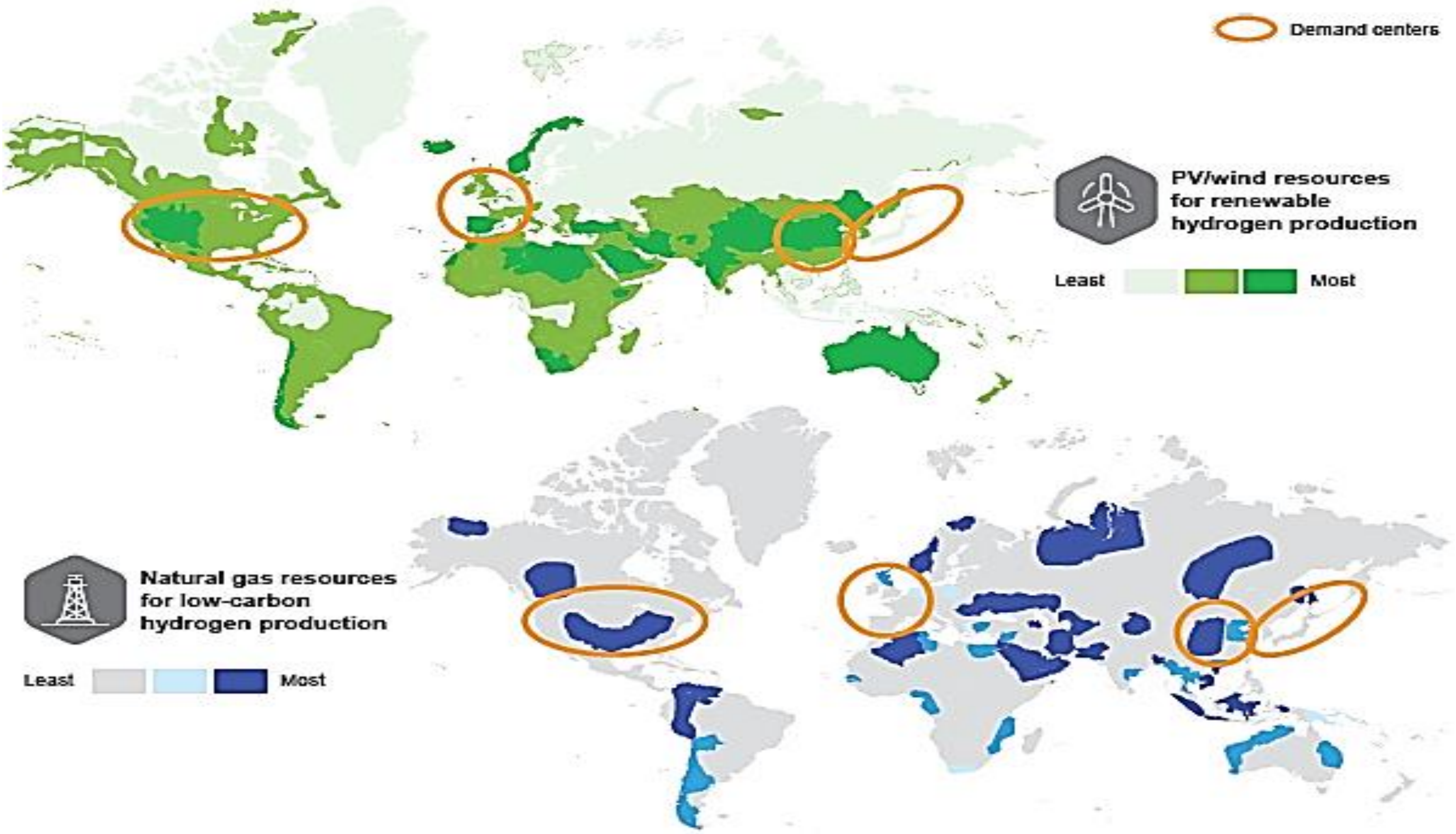
https://www.chemistryviews.org/details/ezine/4817371/Fuel_Cell_Capacity_and_Cost_Trends.html

Hydrogen Applications



About 55% of the hydrogen around the world goes to ammonia production; 25% is used in refining and about 10% is used to produce methanol. Other applications only account for only about 10%.

https://wha-international.com/hydrogen-in-industry/



Global distribution of production potential and demand for green and blue hydrogen [Hydrogen Council, 2021]

Green Hydrogen Production is <u>Old</u> in the Arab Region!!

- **Since 1960 Green Hydrogen** was produced **in Egypt** by the Egyptian Chemical Industries Company (KIMA) in Aswan, where electricity produced from the **Aswan hydro power plant** to produce **hydrogen in electrolyzers** (37000 m^3/h) which is then used with Nitrogen to produce **Ammonia** (400 Ton/day).

- The **factory was rehabilitated in 2019 to rely on natural gas instead of electrolyzers** and increasing its production capacity by several folds!!

Would Green Hydrogen Promise a Success Story for the Arab- MENA Region? similar to RE or Better? ➔ Most Probably! (1/2)

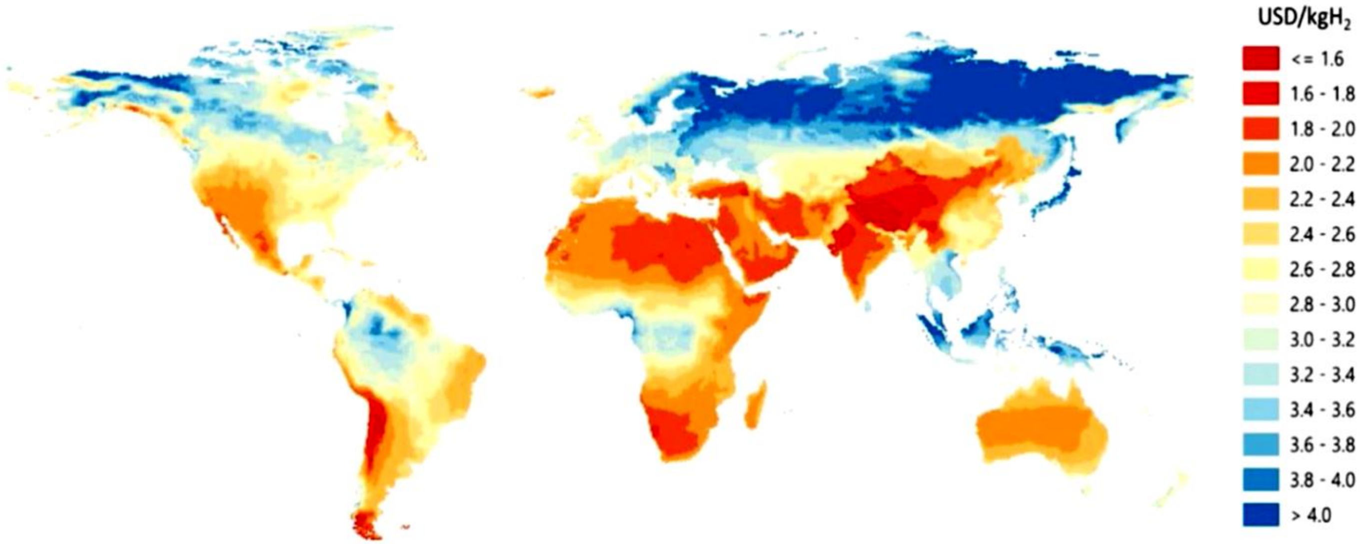
- Excellent solar and wind potential
- Available low cost land for RE projects and H_2 facilities
- Relatively low cost of capital/PPPs/concessional finance
- Existing industrial capacity
- National, regional and global growing markets: Hydrogen exists mostly in refineries, steel factories and petrochemical facilities. It could be used in ammonia, methanol, steel, food and glass production, and possibly cement and aluminum. Also, for applications in electricity generation, transport and others.
- New jobs and mainstreaming climate actions
- Pipeline-transported hydrogen is feasible in some countries, especially North Africa, given the existing NG infrastructure nationally and with Europe, whether in pure form, or blended into natural gas.
- A number of suitably-located salt deposits exit in the region in which caverns could provide low-cost buffer storage of hydrogen.

Geographical proximity to neighboring expanding "green" markets is a key factor.

E.g. The EU hydrogen strategy was published in July 2020, setting a target of 40 GW of electrolyzers installed within its borders by 2030 and another 40 GW of capacity imported from other producers, mainly North Africa and Ukraine.

Would Green Hydrogen Promise a Success Story for the Arab- MENA Region, similar to RE or Better? ➔ Most Probably (2/2)

- Green hydrogen costs are projected to fall from US$ 3.5-7.5/kg in 2020 to US$ 1.6-2.2/kg by 2030 (still hypothetical!).



Hydrogen costs from renewable energy (solar PV and onshore wind systems) in the long-term
Source: IEA, "The Future of Hydrogen", June (2019)

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Facing Challenges (1/2)

- **Arab countries are considered amongst the most exposed and least resilient to an EU carbon pricing scheme.**

- **The EU's potential carbon border tax could cut the profits from exports of oil, steel, and wood pulp by 10-65%, impacting both EU and non-EU producers of goods.**

- **This could encourage increased production of H_2-derived materials to reduce the carbon footprint of energy-intensive materials exported to Europe.**

- **Water electrolyzers currently have an efficiency of 60-81% and require around 9 liters of water to produce 1 kgH_2.**

- **The cost of water is less than 2% in the overall business case.**

- **Freshwater access may become an issue in water-scarce or water-stressed areas, meaning desalinated seawater will likely be required in the Gulf.**

- **Current electrolyzers require desalinated water, though new generations are under development that could work with salt water.**

- **Liquid hydrogen transport is costly, while liquid organic hydrogen carrier's gravimetric density is relatively low and the supply chain is complicated.**

- **Thus, the *ammonia value chain appears the most practical and cost-effective approach to transporting MENA hydrogen over long distances*, and this is the approach being pursued by KSA and Morocco.**

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Thank You

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