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The Current Status of Hydrogen Development and Outlook

Presenter：Yihua Liu

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01 Overview of Hydrogen

Overview of Hydrogen

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Why Does Hydrogen matters ?

According to IEA, hydrogen is a molecule that can help the world to decarbonise. It is a light-weight, and energy-dense (by weight) molecule that can be produced and burned with zero emissions. Like traditional fuels, it can be stored and transported for use at a different time and location. It is also an irreplaceable component of important chemicals, including nitrogen fertilisers that help feed the world.

- as the secondary energy, it is the best carrier to achieve carbon neutrality and tackle climate change challenge.
- can effectively drive the transformation and upgrading of traditional industries in order to promote the economic development.
- promote the scientific and technological revolution.

“Electrify everything we can and use hydrogen where we can't” .

Overview of Hydrogen

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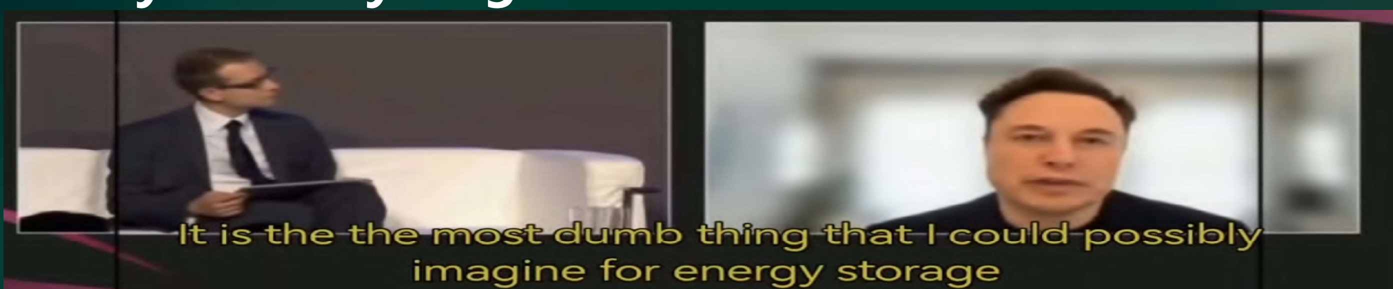
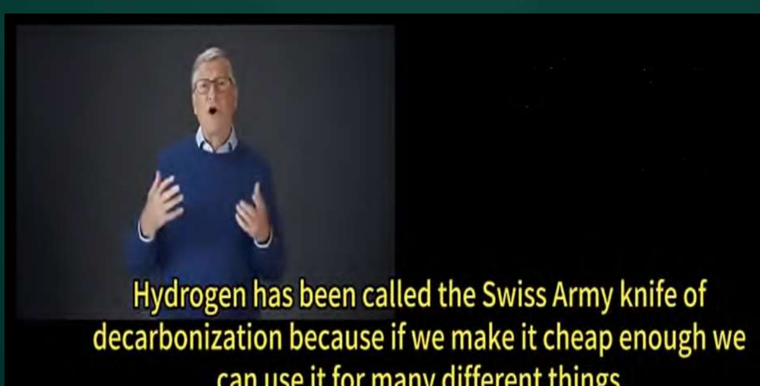
Why Does Hydrogen matters ?





Overview of Hydrogen

Hydrogen National Strategy

By the end of 2023, more than 50 countries, accounting for nearly 80% of global energy-related CO_2 emissions, had announced their hydrogen energy strategies. In 2023, 4 governments have updated their hydrogen strategies and a further 15 governments(Algeria, UAE, Brazil, India, Singapore, Kenya, Türkiye, ect.) – mostl emerging markets and developing economies (EMDEs) – have adopted new national hydrogen strategies.

Government	Description
Belgium (update)	Vision structured around four pillars: become an import/transit hub for renewable hydrogen in Europe, expand technology leadership, establish a robust domestic market and international co-operation.
Germany (update)	Target to install 10 GW of electrolysers by 2030, and increased demand in industry and transport to replace larger shares of natural gas, with over 1 800 km of pipeline infrastructure.
Japan (update)	Interim target for 12 Mt of hydrogen demand by 2040 (complementing previous targets for 3 Mt by 2030 and 20 Mt by 2050) and to meet 1% of the gas supply in existing networks with synthetic methane by 2030, increasing to 90% by 2050. Target to install 15 GW of electrolysis globally. Shift focus from FCEVs to the use of hydrogen in applications, notably in steel and petrochemical industries.
Korea (update)	Updated target to reach 2.1% of total electricity production with hydrogen and ammonia by 2030, and 7.1% by 2036. Creation of a framework for a Clean Hydrogen Certification Mechanism to be released by the end of 2023.

Overview of Hydrogen

Hydrogen National Strategy - China

The National Development and Reform Commission and the National Energy Administration of China released a plan for hydrogen energy development for the 2021-2035 period on 2022. The plan set down two tangible targets for the whole hydrogen industry for 2025, which are：

- Hydrogen fuel cell vehicles in the country would reach 50,000. The nation will develop "a bunch of" hydrogen fuel cell vehicle filling stations.
- The renewable hydrogen production capacity of the nation would be between 100,000 and 200,000 tons per year. "Green" hydrogen will be a significant part of China's incremental H_2 production.

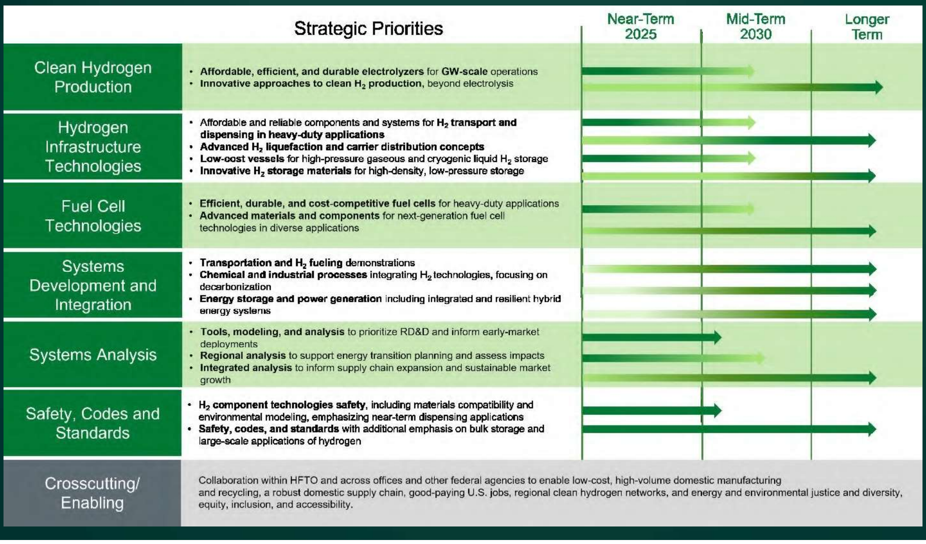
The regulators also laid down critical "principles"：

- "Consumption near Production" Principle: H_2 utilisation will be near the production locations. The gas supplies will mainly come from industrial by-product gas (recovery) and renewable hydrogen.
- "Diversified Gas Sources" Principle: Hydrogen production will embark on diversified clean technologies-fossil-fuel-based grey hydrogen production will be restricted。

Overview of Hydrogen

Hydrogen National Strategy - US (the latest update)

On the 6th of May, the US Hydrogen and Fuel Cell Technologies Office of DOE released an updated multi-year program plan（MYPPs), which identifies detailed targets and plans for fulfilling HFTO’s mission-to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy.



Clean H_2 production:

- $2/kg by 2026; $1/kg by 2031

Electrolyzer systems (low temperature):

- 2026: $250/kW, 65% efficiency, 80,000-hour durability

Electrolyzer systems (high temperature):

- 2026: $500/kW, 76% efficiency, 40,000-hour durability

H_2 dispensed for heavy-duty transportation:

- 2028: <$7/kg

Fuel cell manufacturing for heavy-duty transportation:

- 2030: 20,000 stacks/year (single manufacturing system)

Fuel cell systems for heavy-duty transportation:

- 2030: $80/kW, 25,000-hour durability

Overview of Hydrogen

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Hydrogen Investment momentum is strong:

- More than 1,000 project proposals have been announced globally as of the end of January 2023. Of the total, 795 aim to be fully or partially commissioned through 2030 and represent total investments of USD 320 billion of direct investments into hydrogen value chains through 2030 (up from USD 240 billion).

- Europe remains the global leader in hydrogen project proposals, with the highest total investments (USD 117 billion, 35% of global investments) and highest absolute growth(USD 40 billion). Latin America and North America follow Europe , each representing about 15% of announced investments. Growth in North America increased following the announcement of the IRA .
- Giga-scale project proposals account for 112 project proposals (requiring about USD 150 billion investment until 2030), Of these112 proposals, 91 are renewable and 21 are low-carbon hydrogen.
- Momentum is strong, and the industry is planning investments into clean hydrogen, yet much more needs to be done. To be on track to net zero in 2050, more than a doubling of announced investments is needed by 2030 – and these need to be matured and deployed.

Overview of Hydrogen

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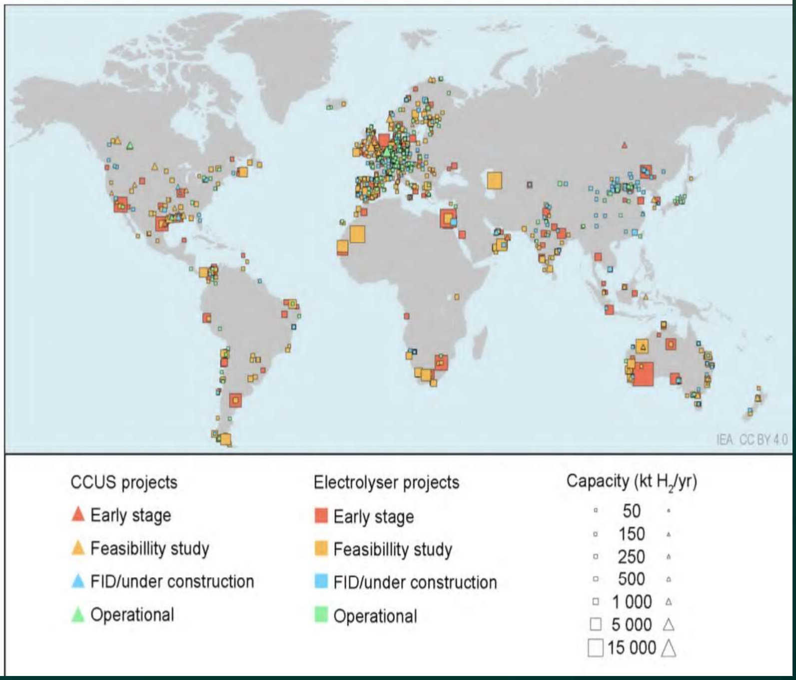
According to IEA, the number of announced projects for low-emission hydrogen production is rapidly expanding. Annual production of low-emission hydrogen could reach 38 Mt in 2030, if all announced projects are realised, although 17 Mt come from projects at early stages of development.

The potential production by 2030 from announced projects to date is 50% larger than it was at the time of last year. Although Only 4% of this potential production has at least taken a final investment decision (FID), a doubling since last year in absolute terms Of the total, 27 Mt are based on electrolysis and low-emission electricity and 10 Mt on fossil fuels with carbon capture, utilisation and storage.

Figure ES.1 Map of announced low-emission hydrogen production projects



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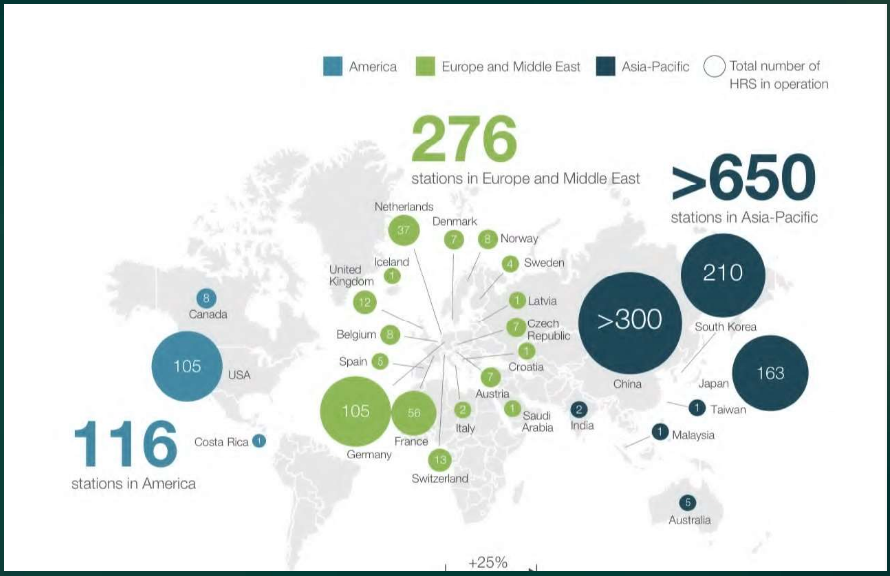
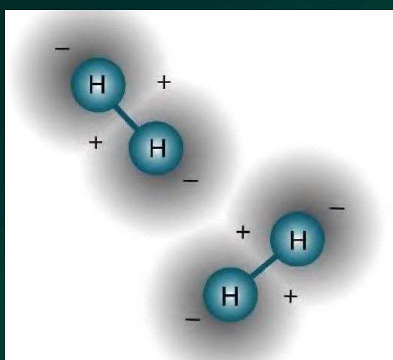
- More than 1,070 hydrogen refueling stations are now operational globally. Most of these stations are located in Asia, i.e., China, Japan, and South Korea as the largest markets (more than 650 in total), followed by Europe (about 280) and North America (about 120).
- The majority of new stations in the past year have been deployed in China and South Korea, with more than 200 stations added in China (By the end of 2023, China had deployed 407 stations, and the CAGR in 2023 was 83% from 2016 to 2023n the world) and nearly 100 in South Korea. In contrast, deployment in Europe and Japan appears to be slowing, with less than 50 new stations deployed in Europe and less than 10 in Japan.

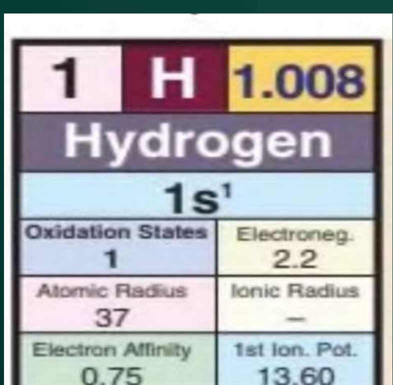


- Currently, most stations deployed are relatively small, with less than 500 kg per day and dispensing capacity is only sufficient to refuel up to 100 passenger vehicles with a 5 kg capacity tank. In the future, deployment needs to accelerate overall, and stations need to be larger to enable growth in the deployment of large commercial vehicles, such as heavy-duty trucks that could need more than 50 kg of hydrogen per refueling or ten times more than a car.

02 Characteristics of Hydrogen and Hydrogen Energy

characteristics of hydrogen and hydrogen energy





Definition

- Hydrogen is the most abundant element in the universe
- Hydrogen ranks first in the periodic table
- Hydrogen can be made from water, fossil fuels and other materials
- Hydrogen is an important industrial raw material and energy carrier and was more often used in the chemical industry
- Hydrogen is the Swiss Army knife of de-carbonization

History Background

- In the 16th century, Swiss chemists (alchemist) Paracelsus discovered hydrogen when dissolving iron in sulfuric acid
- in 1766, Henry Cavendish collected hydrogen in similar experiments and ignited it to obtain water.
- In 1783, French chemist Lavoisier first named hydrogen, meaning "water element"
- in 1800, two British scientists Nicholson and Carlisle invented electrolyser and used electric current to break down water into gas.

characteristics of hydrogen and hydrogen energy

Hydrogen Physical Property under Different Pressure Temperature 20 ℃

Pressure (Mpa)	Density (kg/cubic meter)	Compressibility Factor
20	14.772	1.125
30	20.897	1.191
35	23.705	1.225
45	28.877	1.292
70	39.7	1.459

Calorific Value of hydrogen and other energy

Energy Type	Calorific Value
Hydrogen	120.00 (MJ/kg)
Standard Coal	29.29 (MJ/kg)
Nature Gas	46.03 (MJ/kg)
Electricity	3.60(MJ/kwh)
Petroleum	41.84 (MJ/kg)

Unit conversion table for hydrogen

Weight (Kg)	Gaseous (Sm^3)	Liquid (Ltr)	Low Calorific Value(MJ)	Low Calorific Value(Kwh)
1	11.2	14.12	120	33.333
0.089	1	1.26	10.714	3
0.071	0.793	1	8.495	2.359
0.008	0.093	0.118	1	0.278
0.03	0.333	0.42	3.571	1

Comparison of Properties

Indicators	Hydrogen	Gasoline Vapor	Natural gas
Explosion Limit(%)	4.1-75	1.4-7.6	5.3-15
Burning Point Energy(MJ)	0.02	0.2	0.29
Diffusion Coefficient(m2/s)	6.11*10^(-5)	0.55*10^(-5)	1.61*10^(-5)
Energy Density(MJ/Kg)	143	44	42

characteristics of hydrogen and hydrogen energy

The classification of hydrogen:

- **By obtaining technologies and different carbon emissions produced in the process of hydrogen production, hydrogen can be divided into 8 different groups.**
- **So far, the colour which used the most by industry are:**

"Gray Hydrogen"

"Blue Hydrogen"

"Green Hydrogen"

“Pink Hydrogen”

characteristics of hydrogen and hydrogen energy

The classification of hydrogen:

1.Gray hydrogen: refers to hydrogen produced through the conversion of fossil fuels (natural gas, coal, etc.) by using steam methane reforming (SMR) and autothermal reforming (ATR). The process has relatively high carbon emissions.

2.Blue hydrogen: based on the use of gray hydrogen, by using CCUS, the carbon emissions can be reduced during production process. (CCUS does not capture 100% of the CO_2, and there are also concerns regarding upstream emissions, which include both carbon dioxide and methane.)

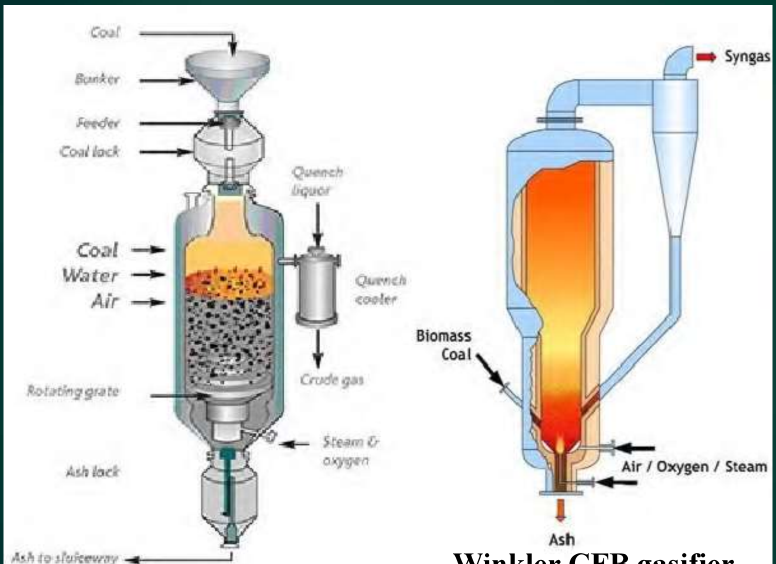
3.Green hydrogen: refers to the production of hydrogen by electrolysis of water from renewable energy and the hydrogen production process is close to zero carbon emissions.

4.Pink hydrogen: is produced by electrolyzer which is powered by nuclear power, and the hydrogen production process is also close to zero carbon emissions.

characteristics of hydrogen and hydrogen energy

The classification of hydrogen:

Gray hydrogen: coal gasification



Winkler CFB gasifier

$$C + O_2 = CO_2$$
$$CO_2 + C = 2CO$$
$$C + H_2O = CO + H_2$$

characteristics of hydrogen and hydrogen energy

The classification of hydrogen:

Gray hydrogen: nature gas steam methane reforming

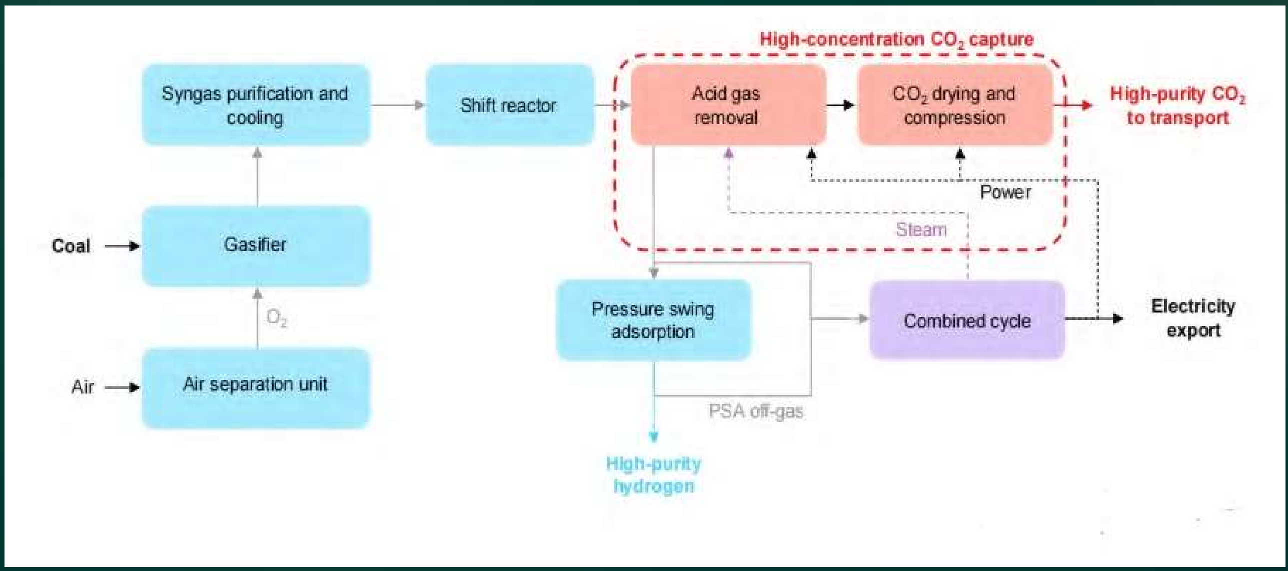
$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

characteristics of hydrogen and hydrogen energy

The classification of hydrogen:

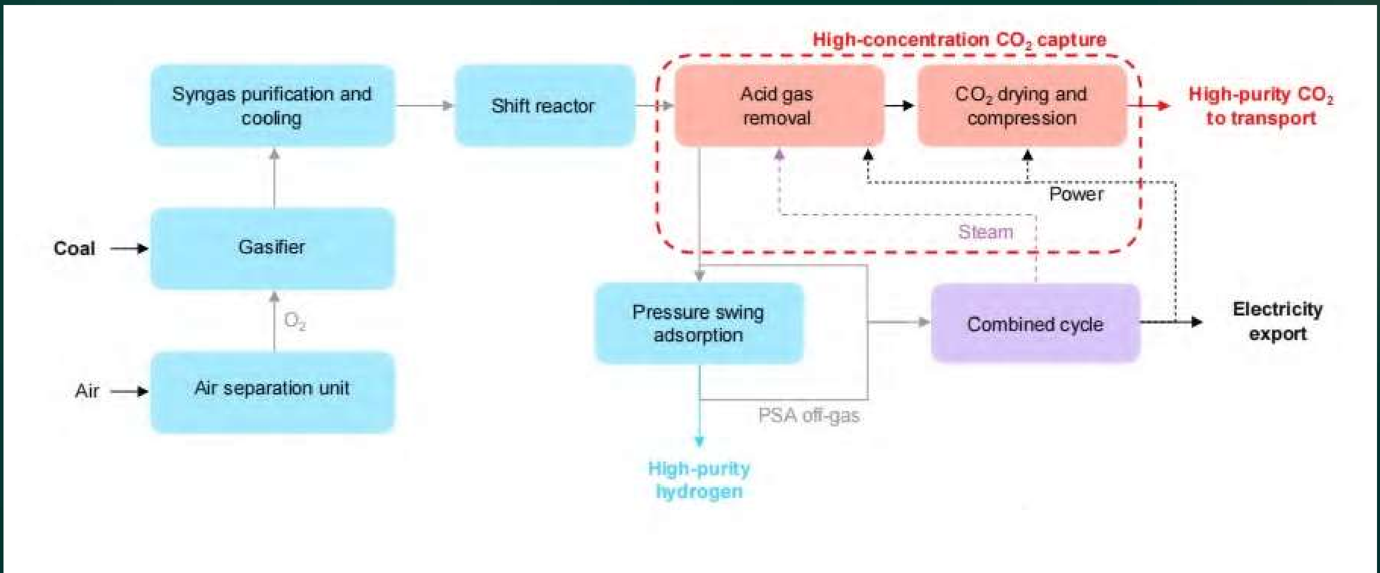
Blue hydrogen： coal gasification with CCUS



characteristics of hydrogen and hydrogen energy

The classification of hydrogen:

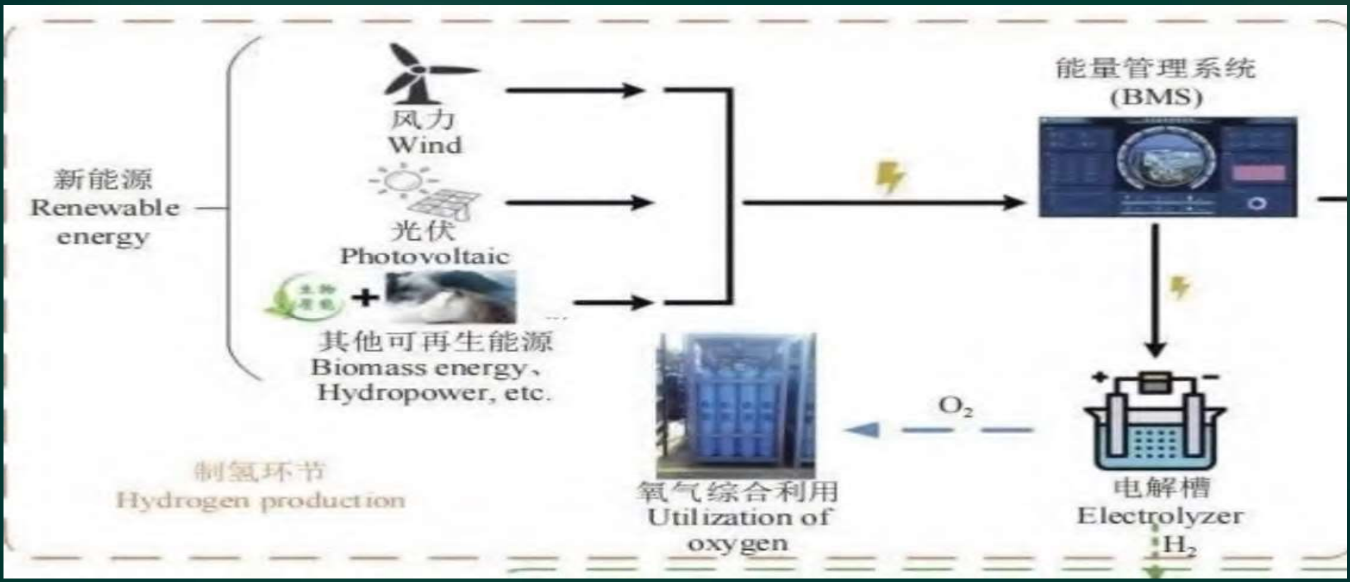
Blue hydrogen：nature gas SMR with CCUS



characteristics of hydrogen and hydrogen energy

The classification of hydrogen:

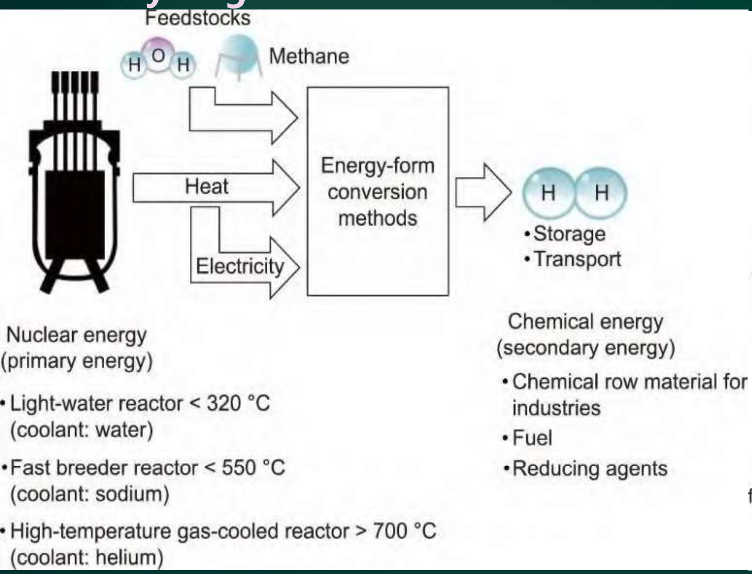
Green hydrogen:

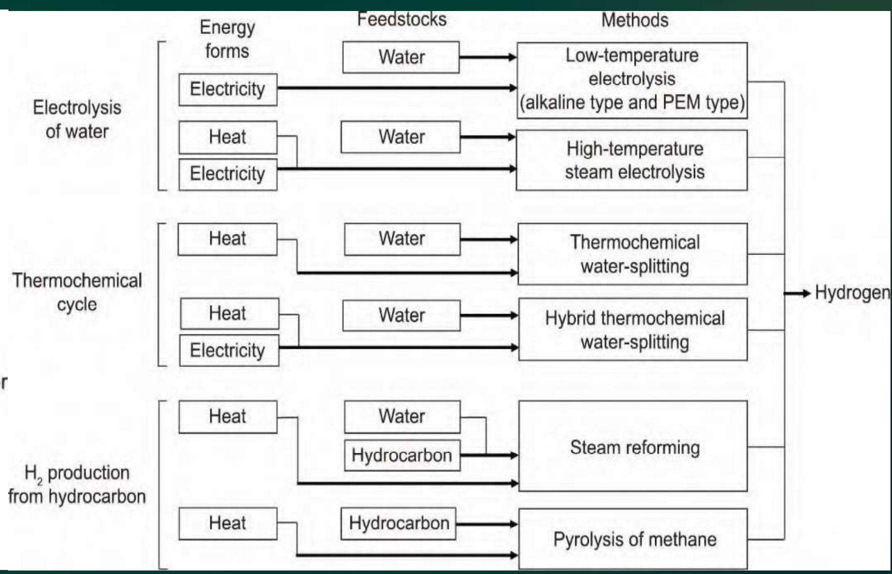


characteristics of hydrogen and hydrogen energy

The classification of hydrogen energy:

Pink hydrogen:





characteristics of hydrogen and hydrogen energy

The classification of hydrogen energy:

- **By Different Purities:** Hydrogen can be classified as ordinary hydrogen with 99.9% purity,pure hydrogen with 99.99% purity and high purity hydrogen with 99.999% purity.

- **By Different Purposes:**

➢ Industrial hydrogen: mainly used for industrial production process, such as the chemical industry, oil refining industry and metal processing industry. Industrial hydrogen is usually prepared by fossil fuel reforming or electrolysis of water.

➢ Energy hydrogen: mainly used for hydrogen fuel cells, fuel cell vehicles and other energy applications.

➢ Laboratory hydrogen: used for experiments and analysis in scientific research laboratories.

characteristics of hydrogen and hydrogen energy

The classification of hydrogen energy:

- **By state of the application:**
- **Liquid hydrogen: Hydrogen is in a liquid state at extremely low temperature (-253℃), and requires special equipment for storage and transportation. Liquid hydrogen is widely used in spacecraft fuels, laboratory research, and hydrogen energy systems.**
- **Compressed gas hydrogen(CGH_2): hydrogen is gaseous at room temperature and high pressure.**
- **Cryogenic compressed hydrogen(CCH_2): by compressing hydrogen at extremely low temperatures, the CCH_2 brings the storage density up to 80g / L which is 27% higher than liquid hydrogen and more than 75% higher than compressed gas hydrogen.**
- **Solid state hydrogen: hydrogen is stored in the form of a metal hydride solid. It has the characteristics of high density, low pressure, no leakage and safety.**

characteristics of hydrogen and hydrogen energy

Why Green Hydrogen is important ?

Gray hydrogen and Blue hydrogen have relatively high carbon emmision. For instance,the Coal Gasification Technique produce 20kg CO_2 when 1 kg Hydrogen obtained,whereas the Nature Gas SMR produce 10kg CO_2. Among all the available technologies, Green Hydrogen is Carbon free.

Comparison of Carbon Intensity

Obtaining technologies	Carbon Intensity(KgCO2/KgH2)
Coal Gasification	22-35
Nature Gas SMR	10-16
Oil SMR	12
Coal Gasification + CCUS	3-5
Nature Gas SMR + CCUS	1.5-2.4
Renewable Energy Electrolysis	<0.5

characteristics of hydrogen and hydrogen energy

Why **Green Hydrogen** is important ?

According to World Bank:

- **Green Hydrogen** provides a sustainable way to store and transport renewable energy sources. This helps to overcome one of the major challenges of renewable energy —— continuity.
- **Green Hydrogen** can help reduce emissions in poorly electrified industries, such as heavy industry and long-distance transportation. This makes green hydrogen an important tool to reduce global greenhouse gas emissions and combat climate change.
- **Green Hydrogen** helps ensure energy security because it provides a way to store and transport energy and diversifying energy sources. This is especially important in the context of the world trying to "transition away" from fossil fuels to renewable energy.

03 Green Hydrogen

Green Hydrogen Approval Standards

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Major Green Standards in the world（EU, Japan，US，IRNEA and China)

- EU Renewable Hydrogen：three scenarios that can be classified as "renewable hydrogen"

  1.hydrogen directly connected to renewable energy production facilities

  2. hydrogen in areas with more than 90% of renewable energy

  3. the use of renewable power supply in areas where low carbon dioxide emissions are limited.

EU also defines a method to quantify renewable hydrogen. The fuel threshold for renewable hydrogen must reach 28.2 g of CO2 equivalent / mejoule (3.4 kg of CO 2 equivalent / kg of hydrogen) to be considered renewable. The method takes into account the greenhouse gas emissions from the entire life cycle of the fuel, and specifies how the greenhouse gas emissions should be calculated in the case of the co-production of renewable hydrogen or its derivatives in fossil fuel production facilities。

- Japan Low Carbon Hydrogen：Japan's Ministry of Economy, Trade and Industry (METI) issued a revised version of the Basic Strategy for Hydrogen Energy。The strategy sets a "low carbon hydrogen" carbon intensity target, meaning that the carbon emission intensity from raw material production to hydrogen production is less than 3.4 kg carbon dioxide / kg hydrogen, and specifies that the carbon emissions from overseas hydrogen production should cover the whole life cycle such as long-distance transportation.

Green Hydrogen Approval Standards

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Major Green Standards in the world（EU, Japan，US，IRNEA and China）

- **US Clean Hydrogen：The U. S. Department of Energy has issued the "Clean Hydrogen" production Standards Guide, which requires "clean hydrogen" production technologies including but not limited to: using fossil fuels with carbon capture, utilization and storage technology (CCUS), hydrogen carrier fuel (including ethanol and methanol), renewable energy, nuclear energy, etc. The equivalent of carbon dioxide produced when 1kg hydrogen produced is not higher than 2 kg, and the equivalent of carbon dioxide in the whole life cycle is not higher than 4 kg .**

- **IRNEA Green Hydrogen：IRENA has released the "Green Hydrogen" Policy Development Guidelines which defines "green hydrogen", or hydrogen energy produced from renewable energy sources. The guideline mentions that the most mature green hydrogen Productiontechnologies are hydroelectrolysis technologies based on renewable electricity, and also mentions other hydrogen production solutions from renewable energy sources, including biomass gasification and cracking, thermochemical water decomposition, photocatalysis, biomass supercritical water gasification, etc. IRNEA has no clear regulations on the production of carbon dioxide equivalent per unit of green hydrogen.**

- **China Green Hydrogen：China Hydrogen Association defines electricity used in the "green hydrogen" production process must be from renewable energy, such as solar energy, wind energy, water, etc.**

Green Hydrogen Industrial Chain

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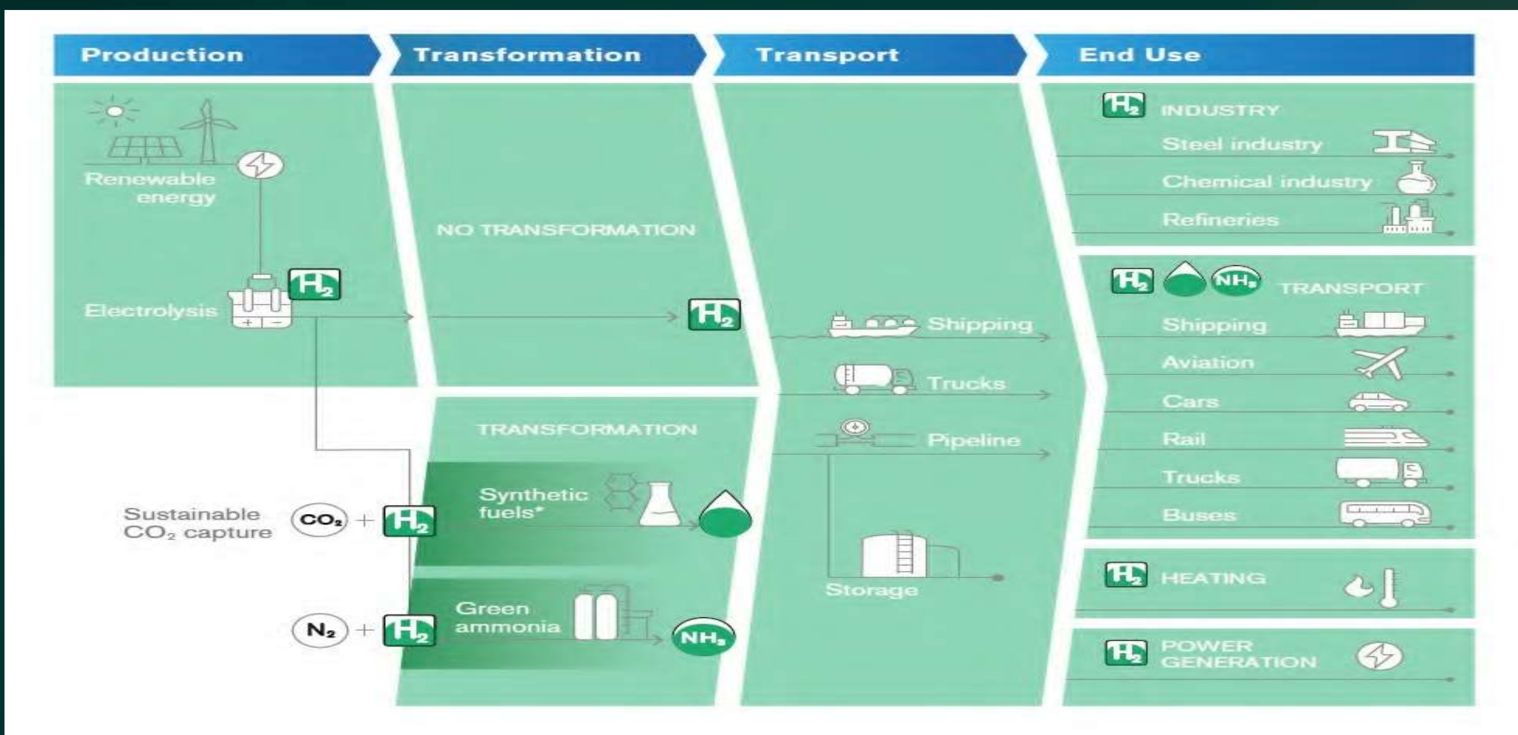

Green Hydrogen Production Technologies

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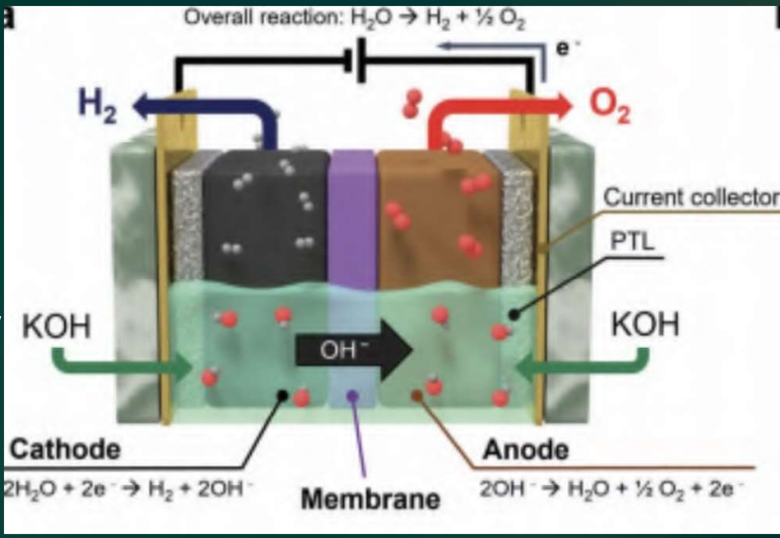
Green hydrogen Production technology includes water electrolysis of wind power, hydropower, solar energy and other renewable energy like solar photohydrolysis and biomass, among which water electrolysis by renewable energy is the most widely used and the most mature technology。 At a basic level, electrolysis splits water (H_2O) into hydrogen (H_2) and oxygen (O_2) by applying an electric current. As simple as it sounds, researchers and developers have optimized this process and currently there are four main technologies; Alkaline(ALK/AWE), Proton Exchange Membrane (PEM), Solid Oxide Electrolysis (SOE) and Anion Exchange Membrane (AEM).

Technology	Temp. Range	Electrolyte	Catalysts	Advantages	Challenges
Proton Exchange Membrane	~50°–80°C	polymer membrane-H^+-conducting	PGM-based (e.g., Pt, Ir)	• Commercial technology • High current density at high efficiency • Differential pressure operation • Dynamic operation capability	• Use of critical materials (e.g., Ti, Ir, Pt, PFAS) • Temperature-limited efficiency
Liquid Alkaline	~70°–90°C	aqueous solution - OH^-- conducting	PGM-free (e.g., Ni based)	• Commercial technology • Low-cost materials • Proven long lifetime • Established supply chain and manufacturing processes	• Corrosive electrolyte • Dynamic operation limitations • Low performance • Differential pressure operations difficult • Temperature-limited efficiency
Oxide-Ion-Conducting Solid Oxide	~700°–850°C	ceramic membrane-O^{2-}-conducting	PGM-free	• Early-commercial technology • High electrical efficiency • Thermal energy integration, e.g., with nuclear or solar	• Need for high-temperature materials • Effective thermal integration • Cold-start and intermittent operations • Lifetime
Alkaline Exchange Membrane	~60°–80°C	polymer membrane-OH^--conducting	PGM-free (e.g., Ni-based)	• Pilot demonstrations • Low-cost materials • Dynamic operation capability • Differential pressure operation	• Durability and performance of current membranes • Trace PGM catalysts still needed • Efficiency losses using pure water feed

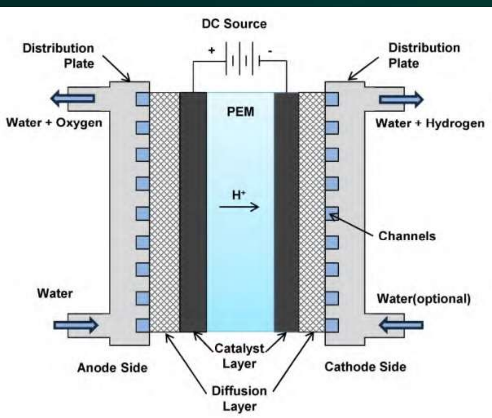
Green Hydrogen Production Technologies - ALK

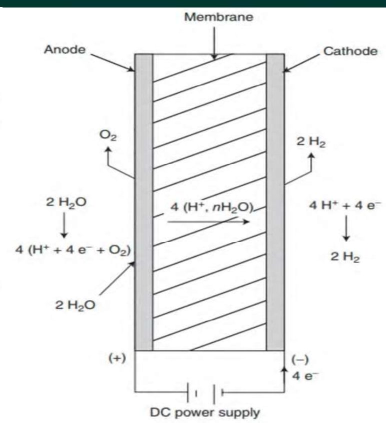
- Alkaline refers to the process of electrolysis of water to produce hydrogen in the alkaline electrolyte environment.The electrolyte is generally 30% mass concentration KOH solution or 26% mass concentration NaOH solution. Compared with other preparation technologies, alkaline can be made by non-precious metal catalyst (e. g. Ni, Co, Mn), and the electrolytic cell has a long service life of 15 years, so it has the cost advantage andcompetitiveness. However, the electrolyte is strong alkali, corrosive and asbestos membrane is not environmental friendly.

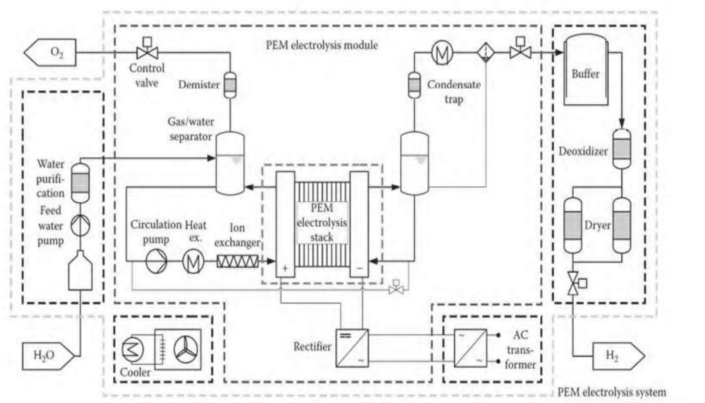


- Alkaline is most developed but growing interest in green hydrogen boosting further development. Manufacturers are focused on performance improvement, cost reduction and upscaling. Where the established alkaline technology was mainly atmospheric, pressurized systems have also entered the market. Pressurized systems require less compression which is generally needed for most applications. Pressurized systems are also better equipped to respond to changes in power input (e.g., from renewable energy). This gives pressurized alkaline the advantage to still compete with other technologies such as PEM when combined with renewable energy.

Green Hydrogen Production Technologies - PEM

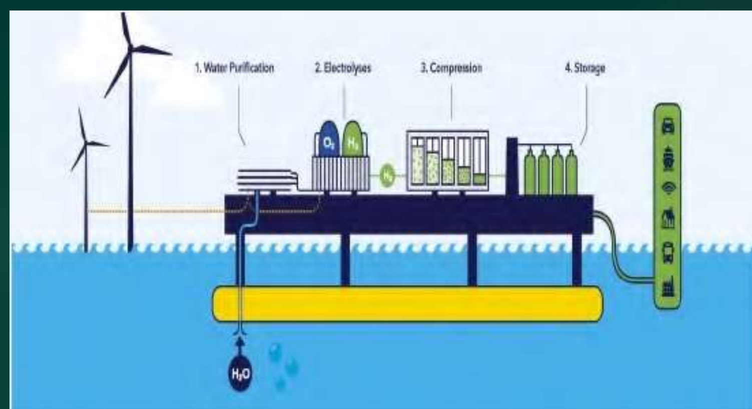






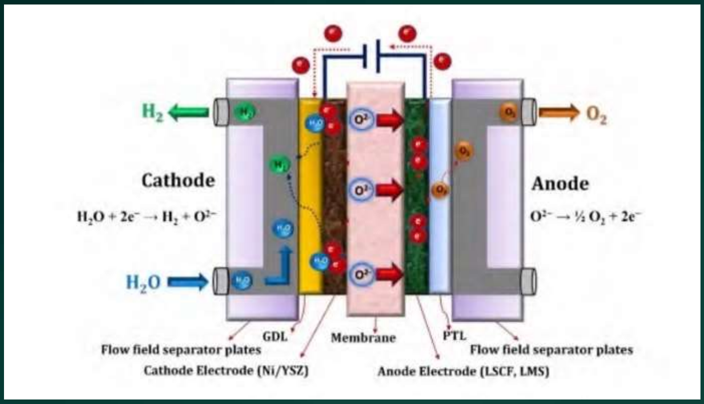
- PEM refers to the using the proton exchange membrane as a solid electrolyte to replace the diaphragm and liquid electrolyte used in the alkaline , and using pure water as the raw material for electrolysis. Compared with alkaline electrolysis, PEM electrolysis has the advantages of high current density, high hydrogen purity, fast response speed. PEM water electrolysis working efficiency is higher and easy to combine with the consumption of renewable energy. However, because the PEM electrolytic cell needs to operate in a strong acid and high oxidation working environment, the equipment needs to use electrocatalyst and precious metal (platinum, iridium) as special membrane materials, therefore the cost is higher and the service life is not as longer as alkaline water electrolysis.

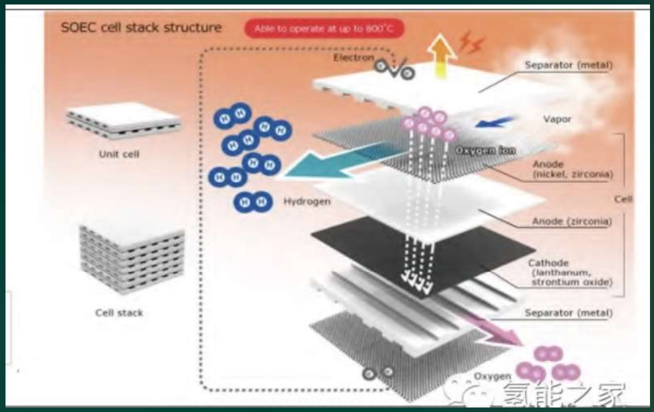
Green Hydrogen Production Technologies - PEM



PEM has seen much development over the last decade and has an established position in the electrolyser market. PEM is known for its ability to ramp up and down very quickly, making it a suitable technology to follow changes in power input from renewable energy. The focus areas for development are very similar to alkaline but are expected to follow a steeper learning curve to catch up to costs of alkaline. Additional development with PEM goes to the reduction and recycling of iridium and platinum, rare materials which could limit very large-scale expansion of PEM.

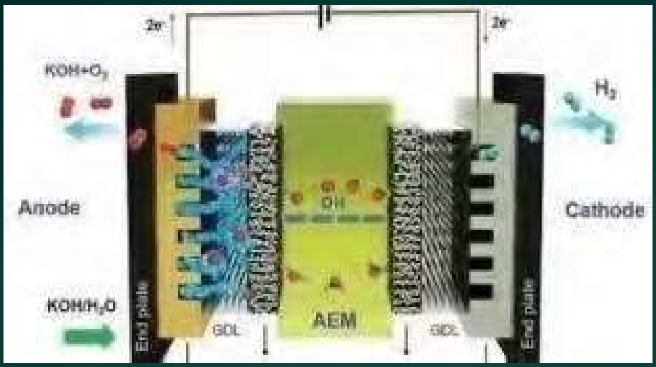
Green Hydrogen Production Technologies - SOEC

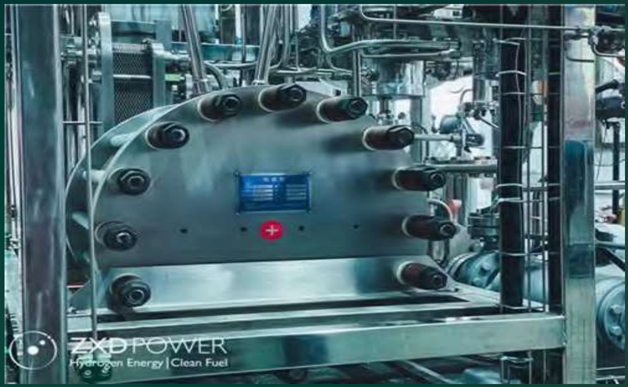




SOE is mainly recognized for high operating temperatures (500-900°C), high efffciencies, and the use of steam instead of liquid water. The technology is commercially available but is still far behind alkaline and PEM in terms of scale and maturity. The current focus for development, is commercialization, upscaling, lifetime improvement and cost reduction. A unique advantage of SOE is its capability to directly form syngas using co-electrolysis of steam and CO2, and to produce a mixture of hydrogen and nitrogen with co-electrolysis of steam and air. The latter is advantageous combined with ammonia production, saving costs on air separation units to produce nitrogen and the possibility to use waste heat for steam production. SOE is also capable of operating in reverse, acting as a fuel cell. But the mechanical performance of the electrode is not stable at high temperature;high temperature also shortens the life of glass-ceramic sealing material in the electrolytic cell;the heating rate under high-temperature reaction needs to improve when using renewable energy power.

Green Hydrogen Production Technologies - AEM





AEM' s fundamental difference from PEM is that the exchange ions of the membrane change from proton to hydroxide ions. The relative molecular mass of hydroxide ions is 17 times that of protons, which makes their migration much slower than protons。The advantage of AEM is that there are no metal cations and no carbonate precipitation to block the hydrogen production system. The electrodes and catalysts used in AEM are non-precious metal materials such as nickel, cobalt and iron, and it produce high hydrogen purity, good air tightness and rapid system response, which is very compatible with the current characteristics of renewable energy. AEM is the latest developed technology and has not yet commercialized at relevant scale. It shares many similarities with PEM in terms of design but uses cheaper materials. The main focus of development is lifetime improvement before it will enter commercialization, cost reduction and further improvements.

Green Hydrogen Storage Technologies

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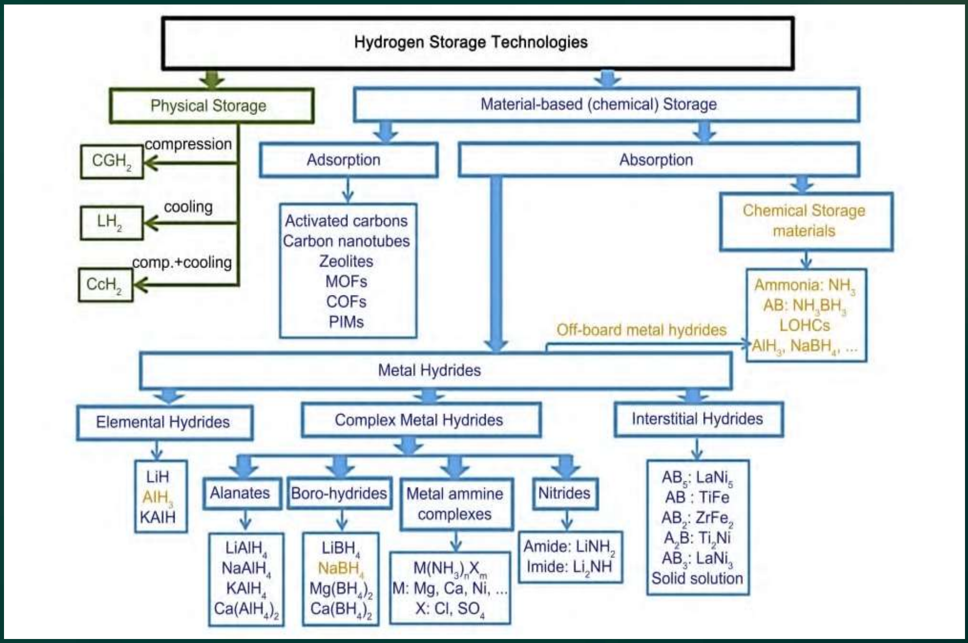
In General, Hydrogen can be stored either as pure hydrogen or integrated into a carrier which makes it easier to transport and store. As the demand for hydrogen is increasing , there are four mainstream of hydrogen storage technologies available:

- High pressure gaseous hydrogen storage
- Low temperature liquid hydrogen storage
- Liquid organic hydrogen carrier storage
- Solid state hydrogen storage



Green Hydrogen Storage Technologies

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- **High pressure gaseous hydrogen storage:**

High-pressure gaseous hydrogen storage is a technology to compress hydrogen and store it in a pressure-resistant tank. The amount of hydrogen storage is directly proportional to the pressure. Compressed gas hydrogen (CGH_2) has been used in various industries such as petroleum, syngas fermentation, ammonia production, medical field and metal production. It can also replace natural gas for combustion and heating and as fuel for transport units, reducing greenhouse gas emissions.

- **There are two major equipments used in this process**
  - **hydrogen gas compressor**
  - **high pressure hydrogen storage cylinder**

Green Hydrogen Storage Technologies

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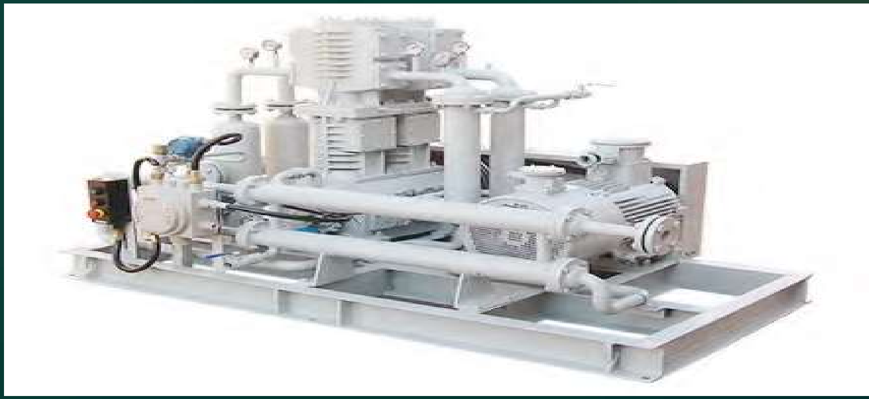
➢ hydrogen gas compressor

The compressor used in the field of hydrogen energy has many different types of products, such as raw gas compressor for hydrogen production， hydrogen filing compressor and hydrogen refuelings tation compressor according to the different uses.The application of hydrogen compressor in the field of green hydrogen mainly refers to the hydrogen filling compressor． The hydrogen filling compressor is mainly used in the hydrogen production plant to fill the tube trailer .The working principle of hydrogen filling compressor is similar to that of hydrogen station compressor. From the technical point of view，there are three different types of filling compressor:

- diaphragm compressor
- hydraulicdrive compressor
- ion compressor.

At present, the diaphragm compressor has a large number of applications.



Green Hydrogen Storage Technologies

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- **high pressure hydrogen storage cylinder - 5 types**

	Type 1	Type 2	Type 3	Type 4	Type 5
Components	All metal construction	Steel vessel with glass fibre composite	Full composite overwrap with metal (aluminium) liner	Full carbon fibre or carbon–glass fibre composite with HDPE liner and metallic boss	Full composite without liner
Structural load	Metal body withstands the whole load	Steel and composite materials share the load equally	The composite structure bears the most load, and the metal liner takes only about 5% mechanical load	Composite material carries the load	Composite material carries the load
Storage pressure	Up to 50 MPa	Highest pressure tolerance	Typically, around 45 MPa and showed problems for 70 MPa	Up to 100 MPa	Under development
Gravimetric density	~1 wt%	≤2.1 wt%	≤4.2 wt%	4.4–5.7%	Under development
Weight	Relative weight is high	30–40% less than Type I	Around half the weight of Type II	Lighter than Type III	It has the potential to be the lightest
Cost (differs with application)	83 USD/kg H_2	86 USD/kg H_2	700 USD/kg H_2	633 USD/kg H_2	Under development

Green Hydrogen Storage Technologies

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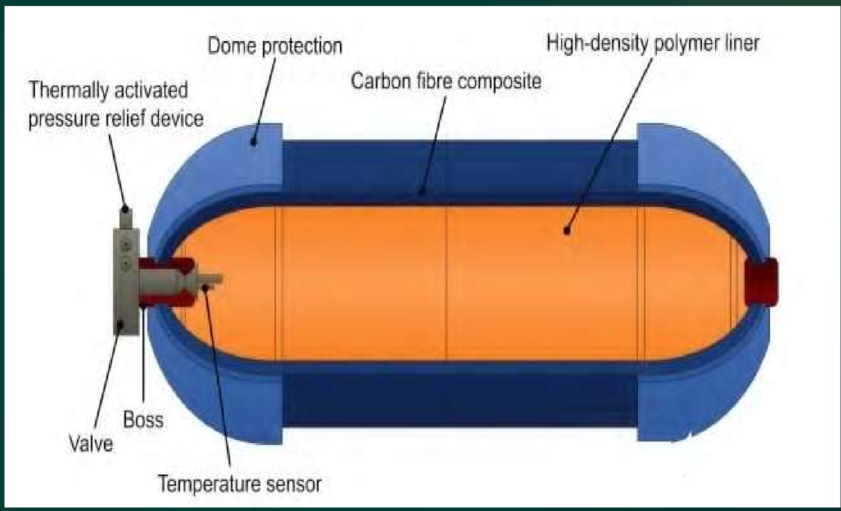
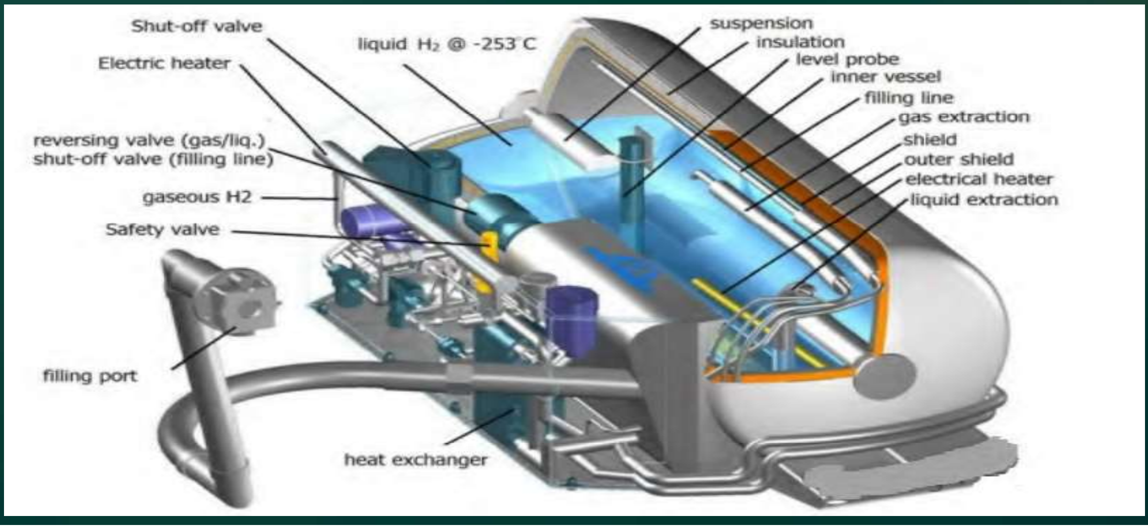
- high pressure hydrogen storage cylinder - type 4



Green Hydrogen Storage Technologies

● Low temperature liquid hydrogen storage

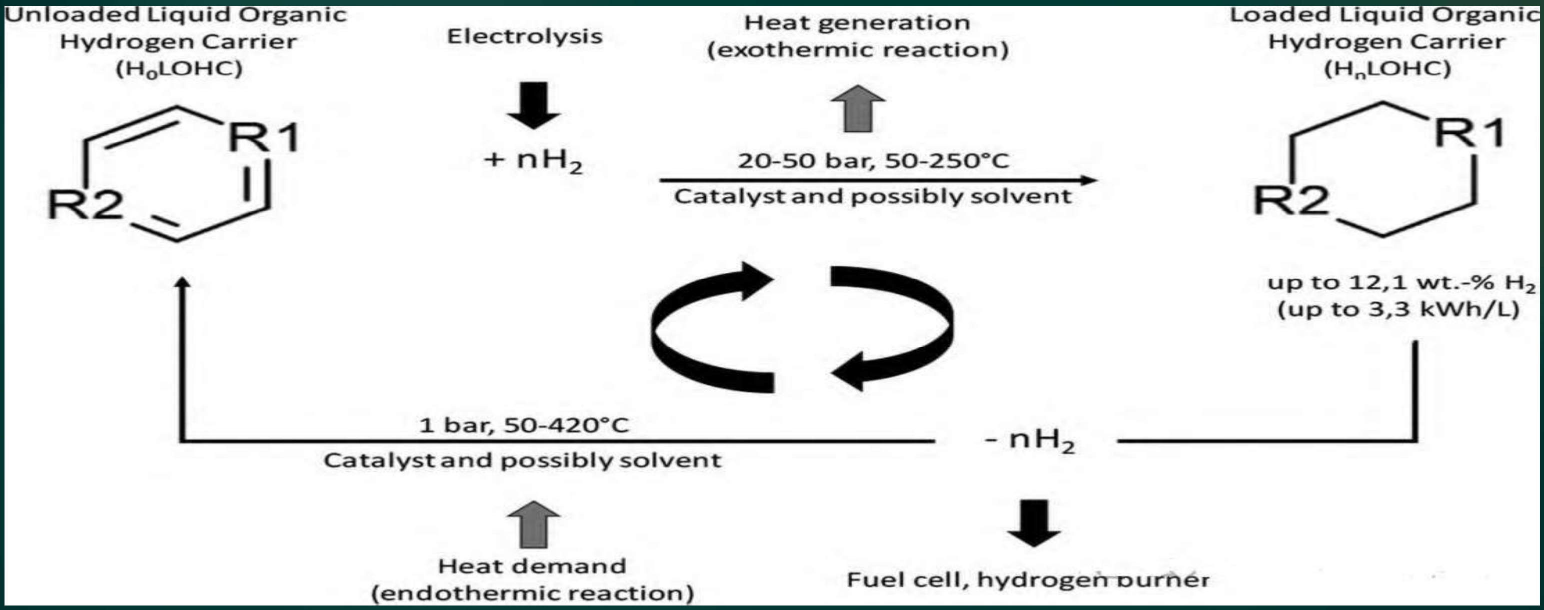
The main reason for making low-temperature liquid hydrogen is that the bulk energy density is higher compared to compressed hydrogen. Liquid hydrogen ($LH_{2)}$ has a density of up to 71g / L at the temperature of-253 C, which brings it to a volume energy density of 8 MJ / LH_2, while gaseous hydrogen has a volume density of only 42 g / L at 70MP. However, the liquefaction process requires a large amount of energy, or about 30% or more of the stored energy,.The associated cost of liqufication is about $1 / kg of hydrogen. Therefore, liquid hydrogen is mainly used in air and space mobility applications that require high volume energy density.



Green Hydrogen Storage Technologies

- **liquid organic hydrogen carrier storage**

Basically, LOHC is to realize the hydrogen storage and transportation through the reversible hydrogenation and dehydrogenation reaction of unsaturated liquid organics.



Green Hydrogen Storage Technologies

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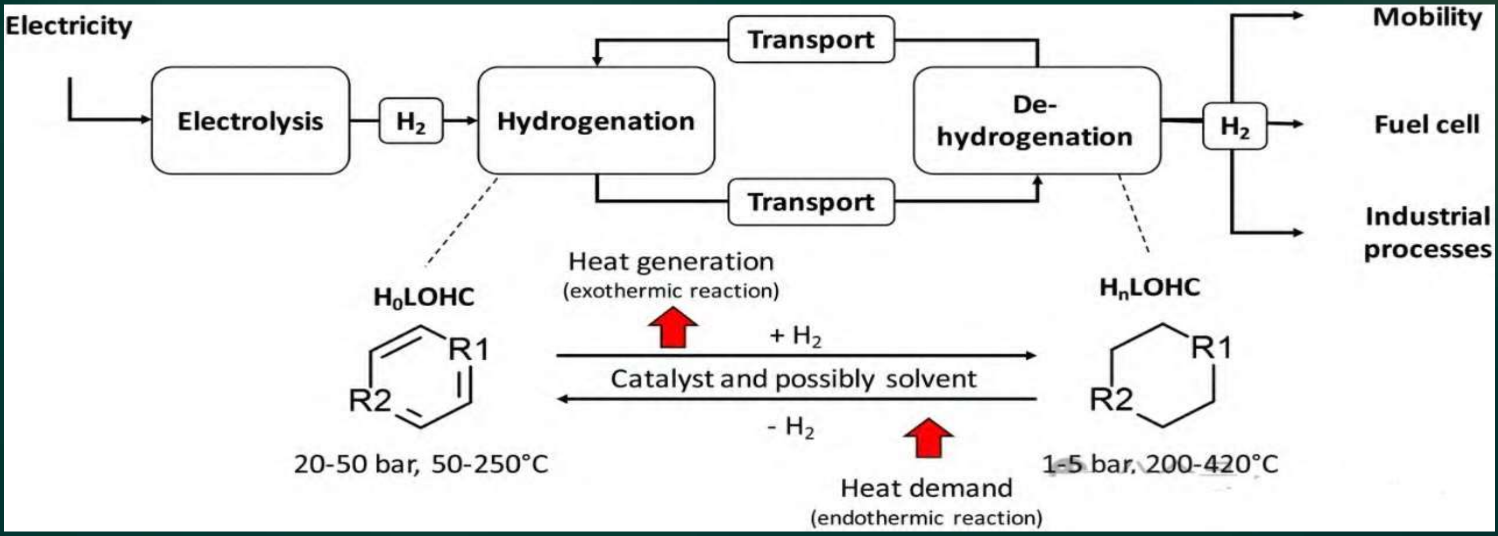
- **liquid organic hydrogen carrier storage**

First, the hydrogen produced is added to the organic liquid hydrogen carrier by catalytic hydrogenation; next, the organic liquid hydride is transported through existing pipelines and storage equipment; finally, at the hydrogen application terminal, the stored hydrogen is released by the dehydrogen reaction device.



Green Hydrogen Storage Technologies

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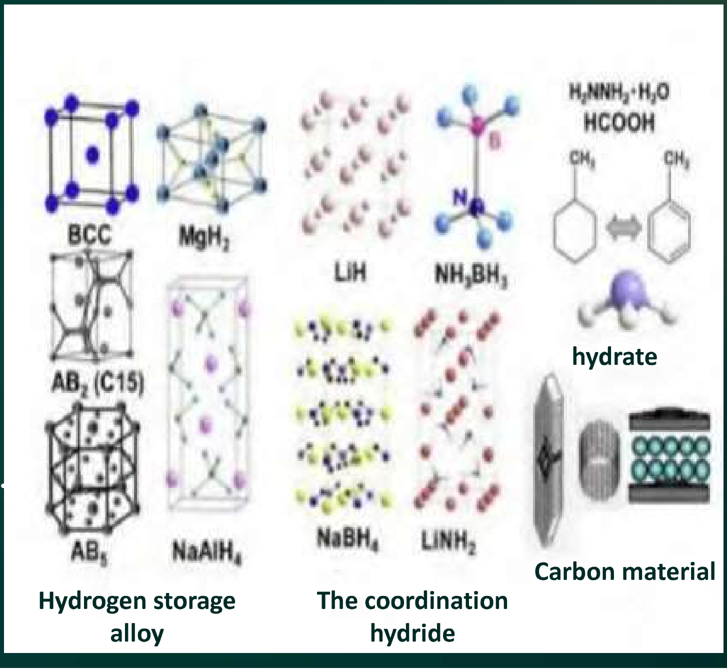
● Solid state hydrogen storage

Solid-state hydrogen storage technology is a physical or chemical way to combine hydrogen and hydrogen storage materials to achieve hydrogen storage. The materials are metal alloy, carbon materials and so on.Metal hydride alloy can be subdivided into rare earth, titanium / manganese, vanadium and magnesium,etc.

Metal hydride is the mainstream technique of solid hydrogen storage, involving materials including magnesium, titanium, vanadium, rare earth and composite hydrogen storage alloy, etc. magnesium alloy has the biggest capacity (up to 7.6%), but the hydrogen discharge temperature is high, usually 300℃;



Green Hydrogen Storage Technologies

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Comparsion of the four main hydrogen storage methods and present main application

Methods	Hydrogen Density	Advantages	Disadvantages	Main Application
high pressure gaseous	1-3wt%	mature technology, simple structure, fast filling and discharging speed, low cost and energy consumption。	low energy density by volume, poor safety performance.	Ordinary cylinders, light high-pressure hydrogen storage tank, mostly used in fuel cells
low temperature liquid	>10wt%	high storage density, has a cost advantage after planning	high energy consumption and storage requirements, heat leakage problems cannot be applied to civil use temporarily due to regulations	large quantities, long-distance storage and transportation, mainly used for rocket low-temperature propellant
liquid organic carrier	5-10wt%	large storage volume, high safey, recyclable, low energy consumption	high cost, many technical difficulties, harsh technical operation, certain toxic hazards	practical application is insufficient
solid state	1-18wt%	lower energy consumption, good safety, high hydrogen purity, reversible cycle	Immature technology, low efficiency of filling and discharging, easy to pulverize and heavy metal poisoning	laboratory experiment

Green Hydrogen Storage Technologies - Pros and Cons

Advantages of Hydrogen Storage:

- **High energy density**

Hydrogen has a high energy density by weight, making it an attractive option for energy storage. When compared to batteries, hydrogen can store more energy in a smaller and lighter package.

- **Long-term storage**

Unlike batteries, which can lose their charge over time, hydrogen can be stored indefinitely without significant energy loss. This makes it an ideal solution for long-term energy storage and seasonal energy balancing.

- **Scalability**

Hydrogen energy storage systems can be scaled up or down to meet the needs of various applications, from small residential systems to large-scale grid storage.

- **Environmentally friendly**

When hydrogen is converted back into electricity, the only by-product is water, making it a clean and environmentally friendly energy storage solution.

- **Grid stability**

Hydrogen energy storage can help stabilize the electrical grid by providing a buffer between supply and demand, reducing the need for peaking power plants and improving the overall efficiency of the grid.

Green Hydrogen Storage Technologies - Pros and Cons

Back-draws of Hydrogen Storage:

- **Low Efficiency**

The process of converting electrical energy into hydrogen and back into electricity is not as efficient as other energy storage technologies, such as batteries. The round-trip efficiency of hydrogen energy storage is typically around 40 % to 50 %, while the round-trip efficiency of battery storage can range from 70 % to 90 % depending on the type of battery and its operating conditions.

- **High capital costs**

The equipment required for hydrogen energy storage, such as electrolysers and fuel cells, can be expensive, leading to higher initial capital costs compared to other energy storage solutions.

- **Infrastructure**

The lack of existing hydrogen infrastructure, such as pipelines and refuelling stations, can be a barrier to widespread adoption of hydrogen energy storage.

- **Safety concerns**

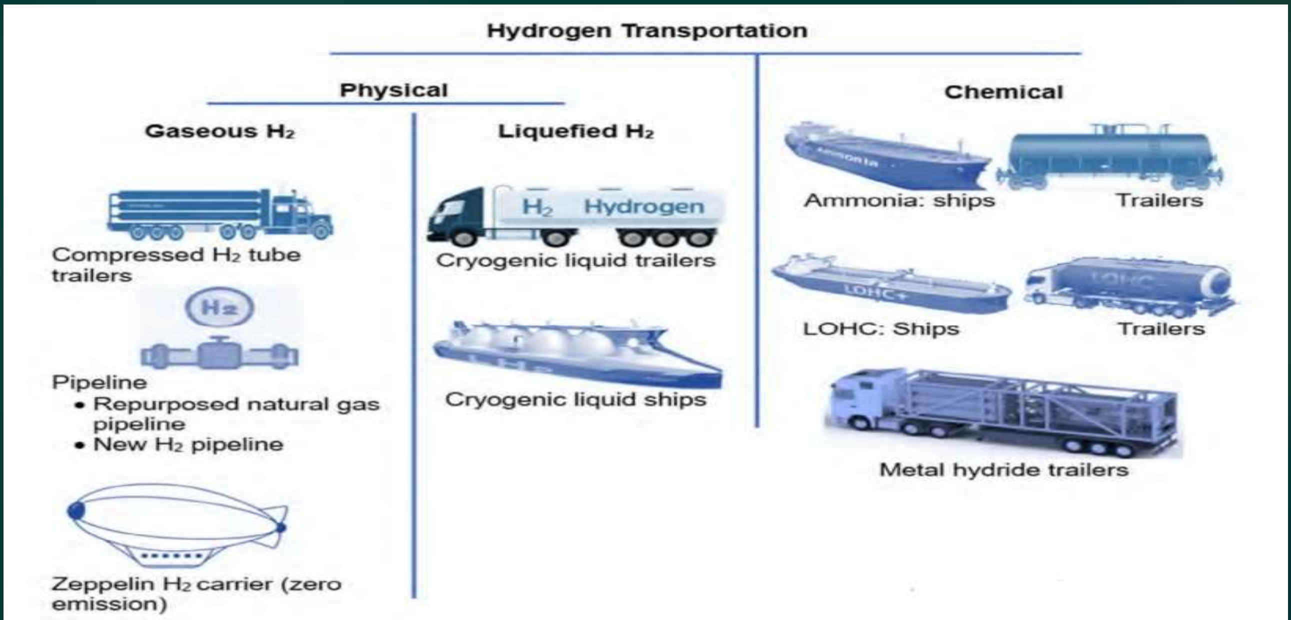
Hydrogen is a highly flammable gas, and its storage and transportation require strict safety measures to prevent accidents.

- **Energy density by volume**

Although hydrogen has a high energy density by weight, its energy density by volume is relatively low. This means that large storage tanks or high-pressure systems are required to store hydrogen in a compact form.

Green Hydrogen Transportation Technologies

The transportation of hydrogen can be divided into gaseous transportation, liquefied transportation and solid hydrogen transportation. The transportation technologies are selected accordingly to different hydrogen states。



Green Hydrogen Transportation Technologies

- **Gaseous transportation: often adopts long tube trailer and pipeline.**

➢ **long tube trailer: The purified product hydrogen is compressed to 20-70MPa through the compressor, and the loaded long tube trailer is currently only suitable for short distance (transport radius 300 km) and low volume scenarios. As the transport distance increase from 50 km to 500 km, costs of operating long tube trailer will increase from ＄0.6 / kg to ＄2.6 / kg, the labor cost and oil are the main factors affecting the rapid increasing cost. Long tube trailers are the most common way of transporting hydrogen, but it is not efficient.**

Green Hydrogen Transportation Technologies

- **Pipeline transport: has irreplaceable economy under large-scale and long-distance conditions, and it is the priority and realistic choice to solve the problem of large-scale and low-cost transportation of hydrogen energy. Through the design, construction, operation, maintenance ,ect it can achieve stable hydrogen energy or hydrogen mixed natural gas pipeline transportation**

Green Hydrogen Transportation Technologies

- **Liquefied Transportation: Cryogenic Liquid Trailers**

The transportation capacity of cryogenic liquid trailers is more than 10 times that of gaseous long tube trailer, and it has high efficiency and low comprehensive cost in long distance transportation. In general, the volume of cryogenic liquid trailers does not exceed $100m^3$ The liquid trailers is composed of three parts: power locomotive, vehicle towing tray and liquid hydrogen storage tank. The liquid hydrogen storage tank shall be equipped with discharge pipeline system, gasification pressurization system, monitoring system, safety discharge device, etc.

- **Brand：US Chart，Kawasaki Heavy Industries，Russian JSC，etc.**

Green Hydrogen Transportation Technologies

- **liquefied transportation: Cryogenic Liquid Ships**

Ship transportation is an effective mode of transportation for distributing hydrogen sources worldwide, which has the advantages of low transportation cost and large carrying capacity. In view of the physical characteristics of liquid hydrogen, there are two difficulties in the process of ship transportation:

- **the severe shaking of liquid hydrogen due to the complex sea environment, and the design difficulty of low temprature tank**
- **due to the small density of liquid hydrogen which reduce the hull load and displacement, it is difficult to meet the waterline requirements.**

Therefore, the technical threshold of liquid hydrogen carrier is high. At present, only the United States, Europe, Japan and other developed countries have the technology to built the ship.

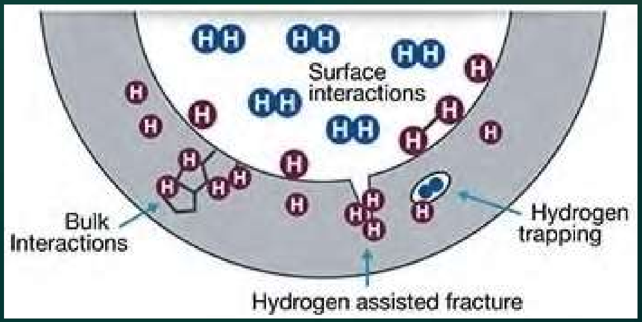
Green Hydrogen Transport Technologies

- solid hydrogen transportation. Lightweight hydrogen storage materials (such as magnesium-based hydrogen storage materials) have high volume storage density and weight hydrogen storage ratio. The low-pressure and high-density solid storage tank is only used as the on-board hydrogen transport container, and the heating medium and device are fixed on the hydrogen filling and hydrogen use site, which can realize the rapid charging of hydrogen and safe transportation. However, because of the price of storage alloy is high and it also need to be heated before use, so the long-distance transportation is not economical.

Hydrogen Embrittlement - The invisible killer of the metal

On the night of January 16,1943, there was a loud noise from the Swan Island shipyard in Oregon. A newly finished oil tanker, standing still, suddenly split into two sections without any warning. This is not a drama, but a Hydrogen Embrittlement (HE).

HE also known as hydrogen-assisted cracking or hydrogen-induced cracking, is a phenomenon that reduces material mechanical properties,. When hydrogen atoms penetrate into the solid metal, the stress threshold for crack generation and extension is reduced. Hydrogen brittlement is widely found in various structural parts, pressure vessels, storage and transportation containers and other metal devices.



Hydrogen Embrittlement - How to tackle

- **Choose the right metal material.** Different metals have different reactivity to hydrogen, some metals are more prone to hydrogen embrittlement, some metals are more stable. For example, steel and aluminum alloy are more susceptible to hydrogen embrittlement, while metals such as chromium, titanium and vanadium are more resistant . Therefore, when using hydrogen, we should try to choose those metal materials that are not sensitive to hydrogen, or apply a protective layer on the metal surface to prevent the penetration of hydrogen.
- **Control of the temperature and pressure.** Hydrogen embrittlement generally occurs between-50℃ and 100℃. In this range, hydrogen spreads more slowly and tends to accumulate inside the metal. In high or low temperatures, the hydrogen diffuses faster and can easily escape from the metal. At the same time, we also need to control the pressure of hydrogen to avoid excessive penetration of hydrogen.
- **Hydrogen Removal.** In the process of metal manufacturing or processing, hydrogen can be removed the from the metal, thus reducing the risk of hydrogen embrittlement. Baking warms the metal to a certain temperature and allows the hydrogen to escape from the metal. Another method is to place metal in a vacuum environment where the suction force can withdraw the hydrogen from the metal.
- **Improve the metal structure.** Generally speaking, small, uniformed grains are more resistant to hydrogen embrittlement than those with large and non-uniform grains. Therefore, in the process of metal manufacturing or processing, annealing, quenching, forging, etc can be used to improve the structure of the metal.

Green Hydrogen Applications

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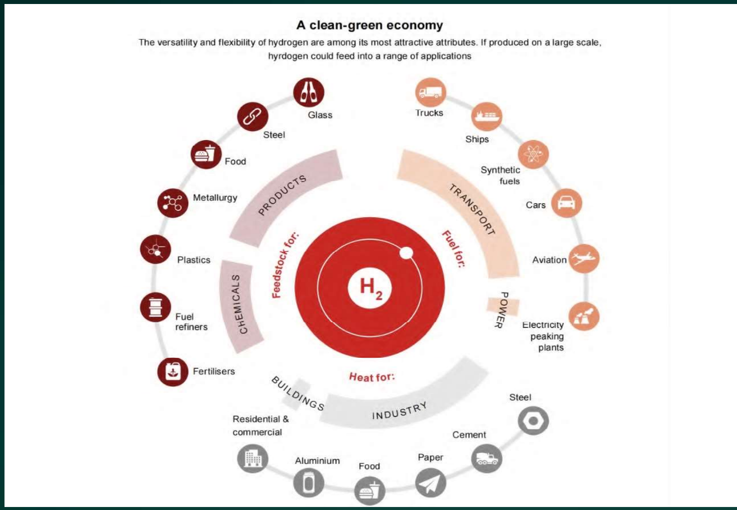
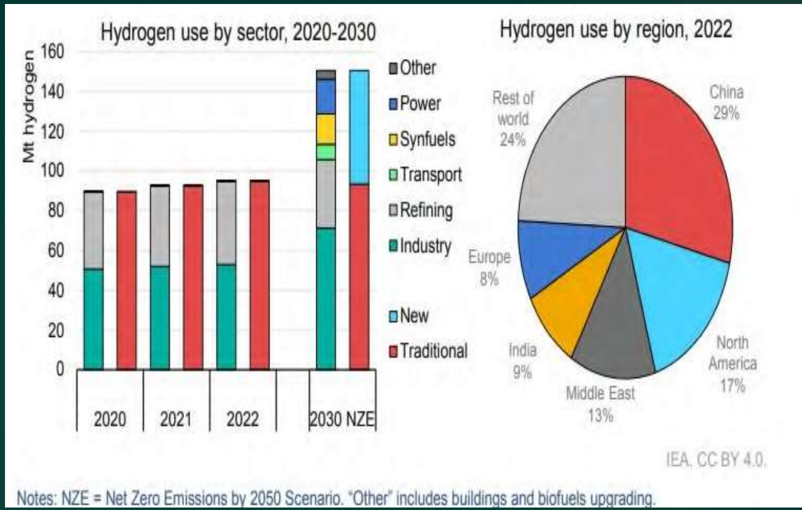
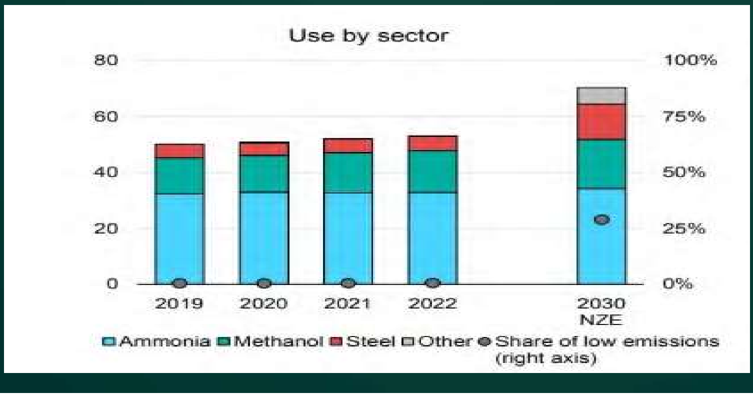




Green Hydrogen, like other Hydrogen, can be used as raw material, fuel or energy storage carrier. It is widely used in transportation, industry, power and construction fields, and can help to achieve low carbon emission. At present, it is mainly used in the field of industry and transportation, and it is still in the exploratory stage in the fields of construction and power generation

Green Hydrogen Applications - Industry

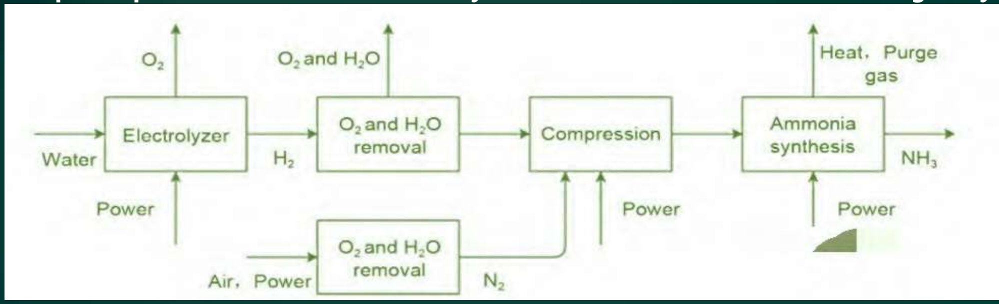
- Hydrogen is an important industrial raw material, which has been widely used in synthetic ammonia, synthetic methanol, petrochemical and metallurgy and other industrial fields. Under the constraint of the Net-Zero target, it is expected that the application scale of hydrogen-based energy in the industrial field will grow rapidly.



According to IEA, Of the 53 Mt of hydrogen used in industry in 2022, about 60% was for ammonia production, 30% for methanol and 10% for Direct Reduced Iron (DRI) in the iron and steel subsector .

Green Hydrogen Applications - Industry

- **Synthetic Ammonia** is the main raw material of chemical fertilizer and an important industrial raw material . Also it can be used for organic or inorganic chemical products such as amine, dye, explosive, synthetic fiber and synthetic resin; in the electronics industry, high purity ammonia can be used for large-scale integrated circuit decompression or plasma chemical vapor deposition; in the food industry, ammonia can be used as alkaline agent, yeast nourishment, food pigment dilution, etc.

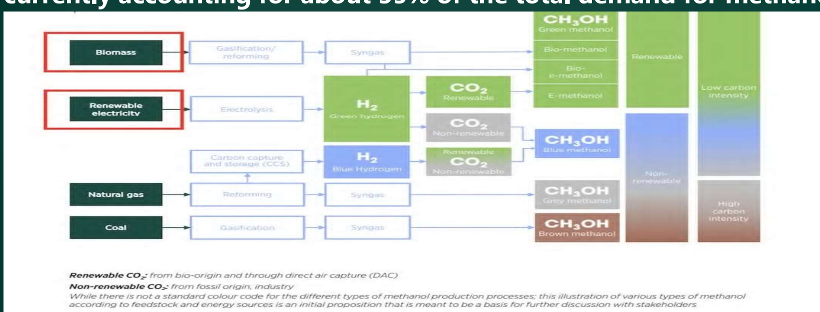


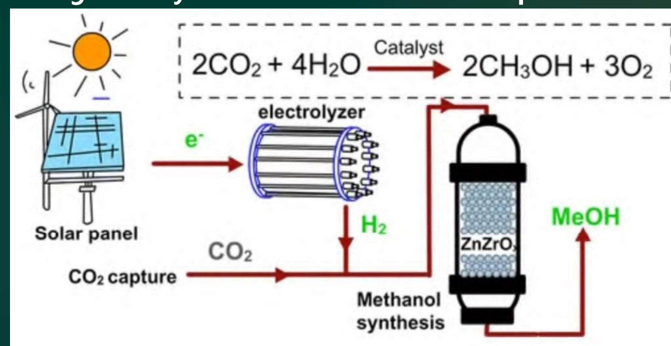
$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

The main raw materials for ammonia synthesis are nitrogen and hydrogen. Theoretically, 0.18 tons of hydrogen and 0.82 tons of nitrogen are needed to synthesize 1 ton of ammonia. The source of nitrogen gas required for ammonia synthesis is relatively simple and can generally be obtained by air separation. The sources of hydrogen required for ammonia synthesis are relatively diverse. At present, it mainly comes from gray hydrogen prepared by coal and natural gas. In view of the green hydrogen produced by water electrolysis from renewable energy has the characteristics of low carbon emission and high purity, green hydrogen will become the main source of hydrogen in the future.

Green Hydrogen Applications - Industry

Production of Methanol: Methanol is another major way of hydrogen application. Methanol is the basis of organic chemical raw materials, can be used to produce olefin, formaldehyde, dimethyl ether, acetic acid, methyl tert-butyl ether, dimethyl methamide, methylamine, methane chloride, terephthalic acid, methacrylic acid, synthetic rubber and a series of organic chemical products, is widely used in chemical industry, light industry, textile, pesticide, medicine, electronics, food. By using methanol to olefin, it has a strong cost advantage compared with traditional naphtha to olefin. It has gradually become the main consumption market , currently accounting for about 55% of the total demand for methanol.



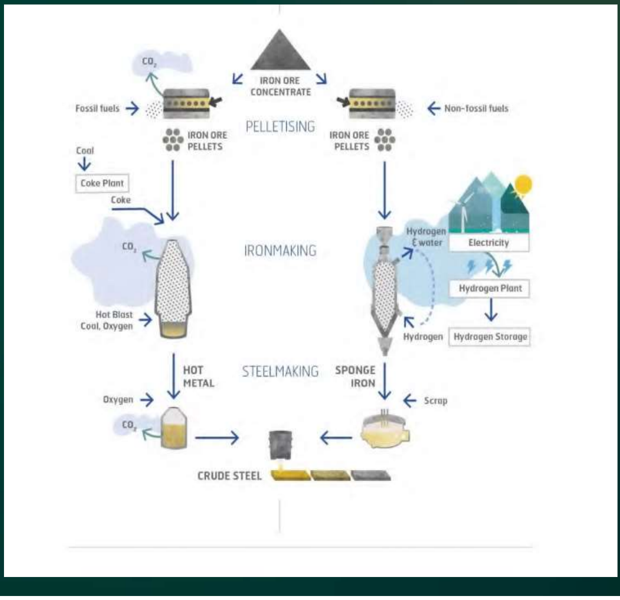


In the long run, using green methanol as raw material is an important means to reduce carbon emissions in the chemical field. Green methanol, refers to the zero carbon emissions in the process of production of methanol,mainly has two production ways: one is biomass Productionof green methanol, the other is green electric green methanol which through synthesis of green hydrogen and carbon dioxide. This technical route can realize large-scale utilization of carbon dioxide and it is an important technical route of green methanol in the future.

Green Hydrogen Applications - Industry

Petrochemical: Hydrogen is one of the indispensable raw materials in the field of petrochemical industry. Hydrocracking, hydrorefining and other processes can convert heavy oil into light oil and effectively improve the oil refining efficiency. At present, hydrogen in petrochemical industry mainly relies on fossil energy to produce hydrogen or industrial byproduct hydrogen, and there is great potential to replace it with green hydrogen in the future.

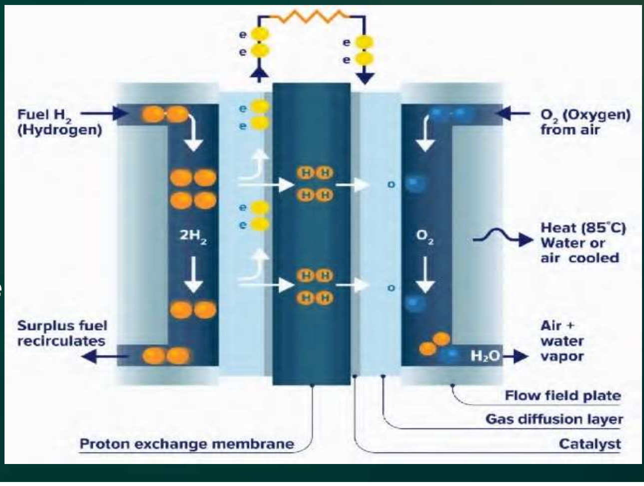
Metallurgy: Hydrogen can replace carbon as a reducing agent in the metallurgical industry. At present, the mainstream hydrogen metallurgical technology route is divided into two ways which are blast furnace hydrogen-rich metallurgy and gas-based direct reduction vertical furnace metallurgy. Green hydrogen is regarded as the key to carbon emission reduction in the metallurgical industry. The traditional blast furnace ironmaking is a smelting method based on coal, and the carbon emission accounts for about 70% of the total emission of the whole process. Hydrogen can replace the reduction effect of carbon in the metallurgical process, so that the metallurgical industry can get rid of the dependence on coal and achieve carbon reduction at the source.



Green Hydrogen Applications - Transportation

Highway transportation: is the absolute main body of carbon emission. The application of hydrogen-based energy in the field of highway transportation mainly includes hydrogen-based energy fuel cell and hydrogen-based energy internal combustion engine. Hydrogen fuel cell is a relatively mature green solution used in highway transportation. The development of hydrogen fuel cell vehicles adopts the route of commercial vehicles before passenger vehicles in most countries. Hydrogen fuel cell vehicles mainly start with passenger cars, heavy trucks, tractors and urban logistics vehicles, and gradually transit to the field of passenger vehicles. Compared with the mature electric vehicles, hydrogen fuel cell vehicles are suitable for fixed routes, medium and long distance trunk lines and high load scenarios.

Fuel cell has 5 different types which are Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell(PAFC),Molten Carbonate Fuel Cell(MCFC), Alkaline Fuel Cell(AFC) and Solid Oxide Fuel Cell(SOFC). Take PEMFC as an example, the basic principle is a reverse reaction of water electrolysis , the hydrogen with oxygen supplies the cathode and the anode respectively, and hydrogen passes through the cathode and make electrolyte reaction. Then The electrons released and reach the anode via an external load.



Green Hydrogen Applications - Transportation

Railway transportation : The application of hydrogen-based energy in the field of railway transportation is mainly to replace the traditional internal combustion engine with the hydrogen-based energy fuel cell to provide new power sources for trains. The advantage of the hydrogen-based power train is that it can realize the emission reduction without the electrification of the existing railway tracks. France, Germany, the United Kingdom and other European countries have introduced national railway network cleaning and upgrading plans, but in the background of high electrification rate of railways in China, the demand for hydrogen-based power trains is relatively limited. In terms of technology, hydrogen-powered trains are still in the experimental development phase. In 2022, the world's first pure hydrogen powered passenger train was officially operated in Germany with a range of 1000 km and a maximum speed of 140 km. In 2021, China launched the first hydrogen fuel cell hybrid train, full hydrogen can run continuously for 24.5 hours, and the maximum straight load can exceed 5000 tons.

Green Hydrogen Applications - Transportation

Aviation: Carbon reduction in aviation is difficult to achieve through electrification, and hydrogen-based energy provides possible carbon reduction solutions . The hydrogen aircraft power mainly includes hydrogen fuel cell, hydrogen engine, etc. Compared with hydrogen fuel cells, the development of the hydrogen engine is relatively slow. Hydrogen engine shares many characteristics of aviation kerosene and hydrogen fuel and its’ structural design, especially the design of the combustion chamber has brought great challenges. Hydrogen-powered aircraft may become a carbon reduction scheme for short and medium distance aviation flights, but in the long distance aviation still depends on aviation fuel. So the development of green jet fuel will be the most important measure to achieve the carbon reduction target. Green aviation kerosene refers to C8~15 liquid hydrocarbon fuels derived from non-fossil resources. According to the life cycle analysis of Global Oil Products Company, the greenhouse gas emissions of green jet fuel are reduced by 65%~85% less than that of oil-based jet fuel.

Green Hydrogen Applications - Transportation

Shipping: The 2023 IMO Ship GHG Emission Reduction Strategy clearly proposes that the international shipping industry will reduce GHG emission by more than 30% compared with 2008, and net zero emissions will be achieved around 2050. As an important carbon emission reduction plan in the shipping field, hydrogen-based fuel will have an important development opportunity. At present, the application of hydrogen-based fuel in shipping mainly includes two solutions: fuel cell and methanol fuel. Green methanol is internationally recognized as a clean fuel, and methanol can achieve partial or complete replacement of diesel oil at low modification cost of ships. At present, Japan, Singapore and other countries have clearly used green methanol as the fuel for ship transportation. According to IEA, the global demand for green methanol will reach 6 million tons, and green methanol has a huge market space in the shipping field.

Green Hydrogen Applications - Power

Electricity Generation: Hydrogen as fuel in the power sector is virtually non-existent today, with a share of less than 0.2% in the global electricity generation mix (and largely not from pure hydrogen, but mixed gases containing hydrogen from steel production, refineries or petrochemical plants).Technologies to use pure hydrogen for electricity generation are commercially available today, with some designs of fuel cells, internal combustion engines (ICE) and gas turbines able to run on hydrogen-rich gases or even pure hydrogen. Using hydrogen in the form of ammonia could be another option for electricity generation. Co-firing of ammonia in coal-fired power plants has been successfully demonstrated in trials in Japan and China. Ammonia could also become a fuel for gas turbines.

Gas-electric hydrogen-mixed combustion refers to a certain proportion of hydrogen in natural gas for gas turbine combustion power generation. Gas-electric hydrogen-mixed combustion can significantly reduce the total emission of gas-electric greenhouse gases, and reduce the consumption of natural gas as a fossil fuel. It is one of the main ways to achieve carbon emission reduction for natural gas power generation in the future.

Green Hydrogen Applications - Buildings

Buildings: The energy demand in the construction field is mainly heating (space heating and domestic hot water). Traditional heating mainly relies on the combustion of fossil energy such as coal and natural gas. Taking hydrogen-based energy as the main carrier can effectively promote the low-carbon and green development in the building field. The application of hydrogen-based energy in the field of construction mainly includes natural gas pipeline hydrogen mixing and building heating and electricity co-generation system. According to IEA, the contribution of hydrogen to meeting energy demand in the buildings sector remains negligible. As part of efforts to meet climate goals, there is a need to shift the use of fossil fuels in buildings towards low-carbon alternatives, but options such as electrification via heat pumps, district heating, and distributed renewables appear to be well ahead of hydrogen technologies. The use of hydrogen for decarbonisation in the buildings sector is therefore negligible in the NZE Scenario.

Green Hydrogen Cost Analysis

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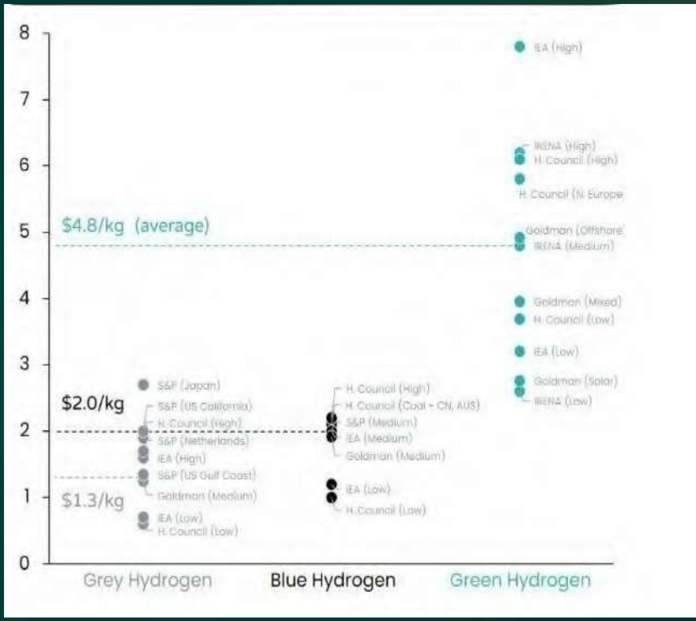
A major barrier to the deployment of green hydrogen to date has been the higher costs of production compared to unabated (i.e., which causeshigh carbon emissions) fossil-based hydrogen. At present, the average cost of green hydrogen is about $4.8/kg (The cost of green hydrogen ranges from $2.5 to $8 per kilogram, with a global average price of about $4.8), which is obviously far above US $2/kg for blue hydrogen and US $1.3/kg for gray hydrogen, the apparent price difference is also the main reason why the competitiveness of the green hydrogen is still weak. At present, the world produces about 90 million tons of hydrogen per year, of which 80% is made from fossil fuels and 90% of the hydrogen is used in the oil refining and chemical industries.



Green Hydrogen Cost Analysis

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The cost of green hydrogen is mainly composed of three parts:

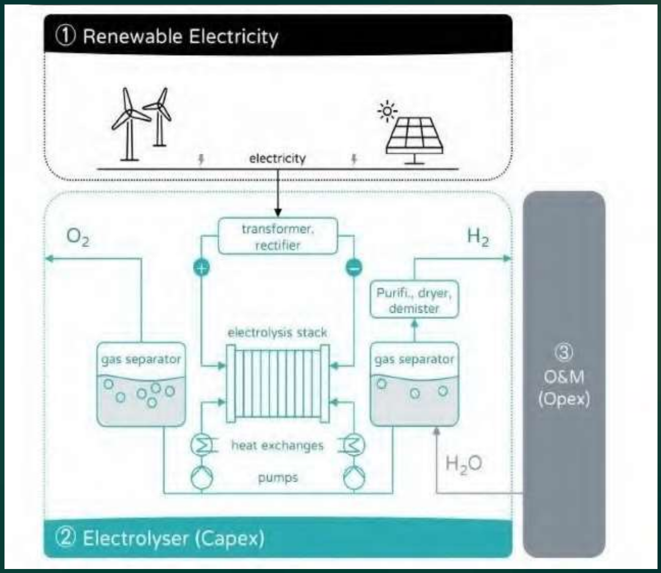
① Electricity generated by renewable energy - The energy cost accounts for the largest proportion, generally is 40%~60% (ALK / PEM) or even up to 80%.

② Electrolyser - electrolytic separation site.

③ Operation and maintenance - full life cycle cost of equipment.

➢ Electricity generated from renewable energy is used as an energy raw material to produce green hydrogen, usually generated by solar power or wind power.

➢ The Electrolyser reflects the capital expenditure (Capex) for the production of green hydrogen. The right panel shows the alkaline electrolyser system.



The Electrolyser system is made of two parts：Electrolysis stack (where water electrolyzed into hydrogen and oxygen) and Balance of Plant system (BOP to ensure proper operation of the stack under the required operating conditions ,e. g. temperature and pressure, and to provide reactants for the reactor and remove by-products).

Green Hydrogen Cost Analysis

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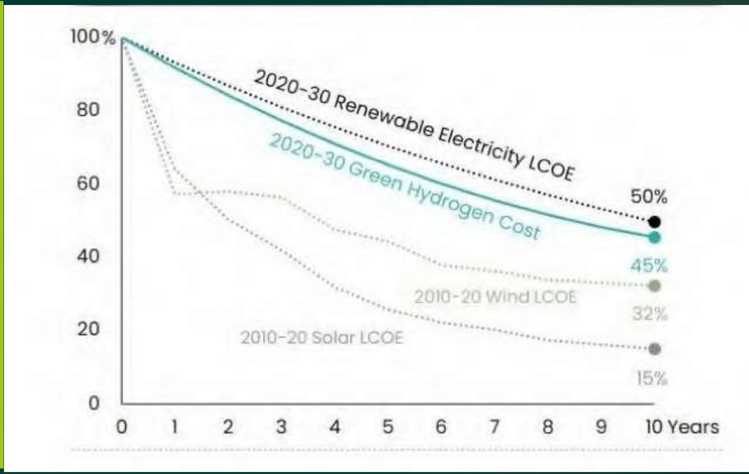
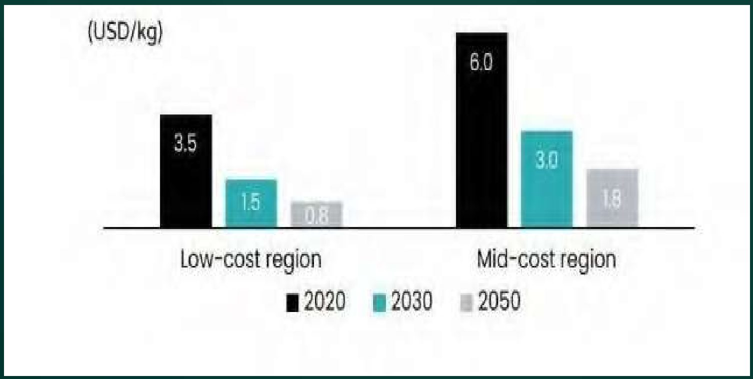
The rapid decline in the cost of green hydrogen is expected, but it is always limited by the cost of renewable electricity.

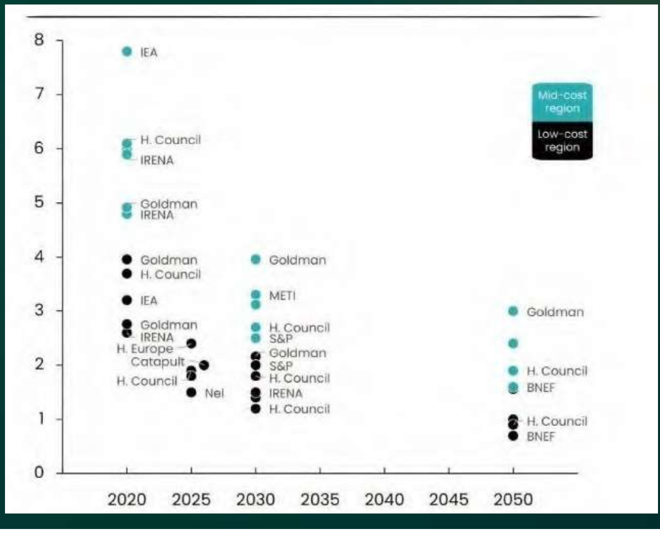


The cost of electricity generated from renewable sources such as solar and wind has fallen sharply over the past decade. At present, as the technology matures, the rate of decline will slow down significantly in the next 10 years, which also causes the curvature of hydrogen energy is relatively flat.

Green Hydrogen Cost Analysis

According to market forecasts, by 2030, with increased capacity, technological advances and the falling cost of renewable power, the average cost of green hydrogen is expected to fall down to between $1.5 and $3. Areas with low costs of green hydrogen will tend to have abundant solar and terrestrial wind resources, such as the Middle East / North Africa, Western Latin America and Australia. Medium-cost areas cover most key areas with rich offshore wind resources, such as Northwest Europe and East China. Higher-cost areas are those with limited renewable energy potential, such as Japan and South Korea.





Green Hydrogen Cost Analysis

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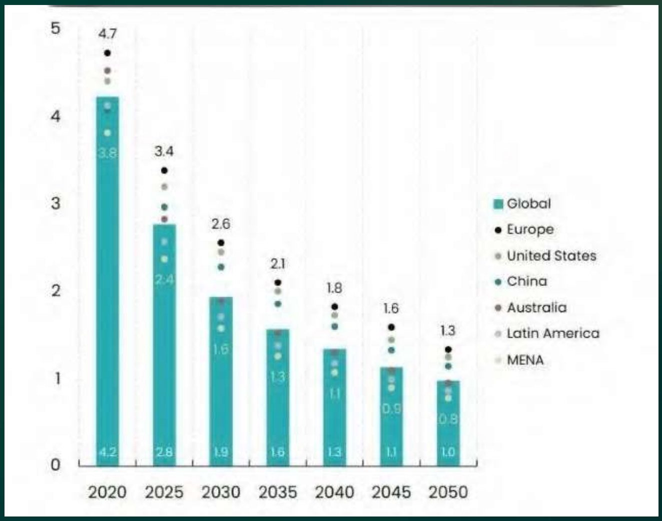
Green electricity costs vary in different regions, leading to regional differences in green hydrogen costs. As the cost of electricity in the total cost increases, the green hydrogen costs will show more significant difference between renewable energy low costs regions and high costs regions.

- **By 2030, it is expected that green hydrogen costs in Europe will be 62% higher than that in the Middle East / North Africa region.**

- **The cost of green hydrogen in Europe is the highest in the forecast, but it is by no means the highest cost of green hydrogen in Europe in the world. The cost of green will not drop to $2/kg even until around 2050 in countries like Japan or South Korea.**

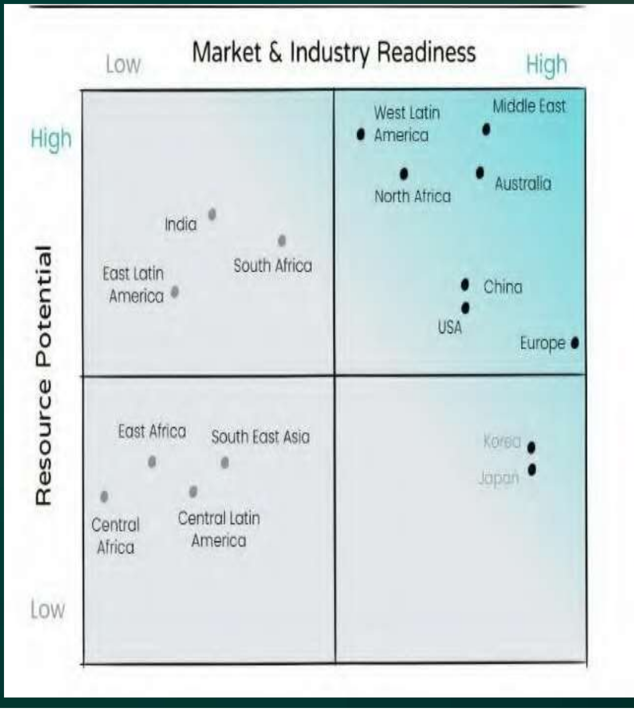
- **In the long term, the large-scale development of green hydrogen will be at the Middle East / North Africa, Latin America and Australia which will become an eye-catching hydrogen export center with a price advantage of less than $0.8/kg**



Green Hydrogen International Trade Analysis

Europe, the Middle East and Australia will have broad market prospects:

- The European Union published a landmark strategy late last year to support the development of green hydrogen production.The green hydrogen production capacity is set to reach 6GW by 2024 and 40GW by 2030. In addition, the EU is considering an additional 40GW to be achieved through exports from neighbouring countries.
- The Middle East has one of the best renewable resources in the world. Solar energy is abundant during the day and wind resources are abundant at night. Last year, Saudi Arabia formed a joint venture with a US contractor to build the world's largest green hydrogen and ammonia plant.
- Australia has launched a "hydrogen below 2" target (production costs less than \$2 / kg or US \$1.4 / kg), triggering A \$370 millionin national support and multiple GW-scale project proposals.



Green Hydrogen International Trade Analysis

The Middle East and North Africa, Australia and Western Latin America may become green hydrogen export centers.

- **The United States and China are expected to be self-sufficient in hydrogen energy through the development of green hydrogen and blue hydrogen.**

- **Japan and South Korea are likely to import green hydrogen from Australia, Latin America and the Middle East.**

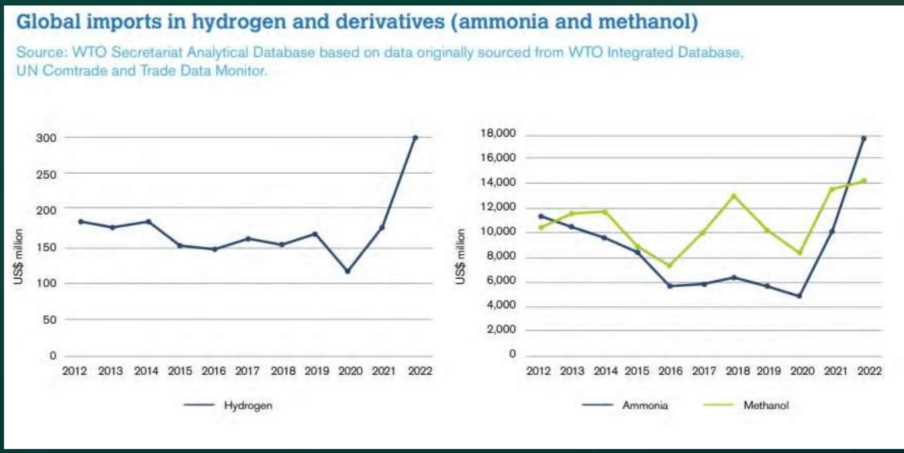
		50% Resource Potential		30% Market Readiness		20% Industry Readiness	
	Score	Solar	Wind	Hydrogen Initiative	Demand Proximity	Energy Value Chain	Industry Infrastructure
Europe	**3.6**	2	3	5	5	4	4
Middle East	**3.6**	5	4	2	2	4	3
Australia	**3.4**	4	3	3	3	4	3
West Latin America	**3.2**	5	4	2	2	1	2
USA	**3.1**	3	3	2	3	4	4
China	**3.0**	3	2	3	3	4	4
North Africa	**2.7**	4	3	1	3	2	1
Japan	**2.4**	1	1	3	5	3	4
Korea	**2.4**	1	1	3	5	3	4

- **Chile, in Western Latin America, that is rich in low-cost renewable resources, has set a target of 25GW of hydrogen by 2030.**

Green Hydrogen International Trade Analysis

The value of global hydrogen imports (of all colours, but mostly those that are fossil-fuel-based) amounted to around US$ 300 million in 2022. While hydrogen trade has seen relatively modest fluctuations over most of the past decade, it saw a sharp increase of 71 per cent in 2022 compared to 2021, mostly reffecting an increase in the value of hydrogen imports by the Netherlands from Belgium (i.e., one of the largest global hydrogen exporters and one of the top markets). It is likely that this increase and, more broadly, the value of hydrogen trade have been driven to a signiffcant extent by fluctuations in the price of natural gas, which is the dominant source in current hydrogen production.

Global trade in hydrogen is very small compared to that in commodities that can be produced as derivatives. For example, global imports of ammonia and methanol have registered strong growth over the past two years, reaching US$ 17.5 billion and US$ 14.1 billion in 2022 . As described above, the expansion of green hydrogen production is expected to lead to an increase in hydrogen trade from the current low levels.

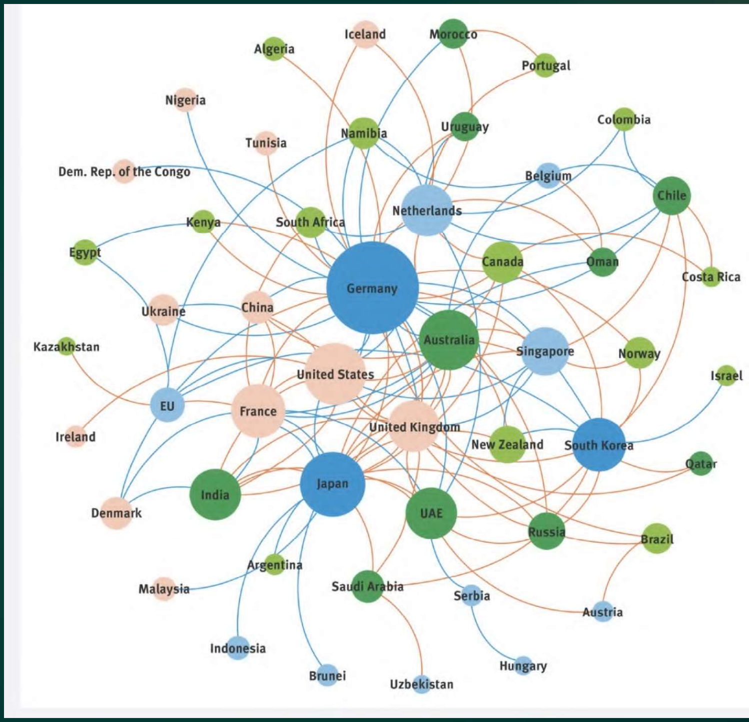


Green Hydrogen International Trade Analysis

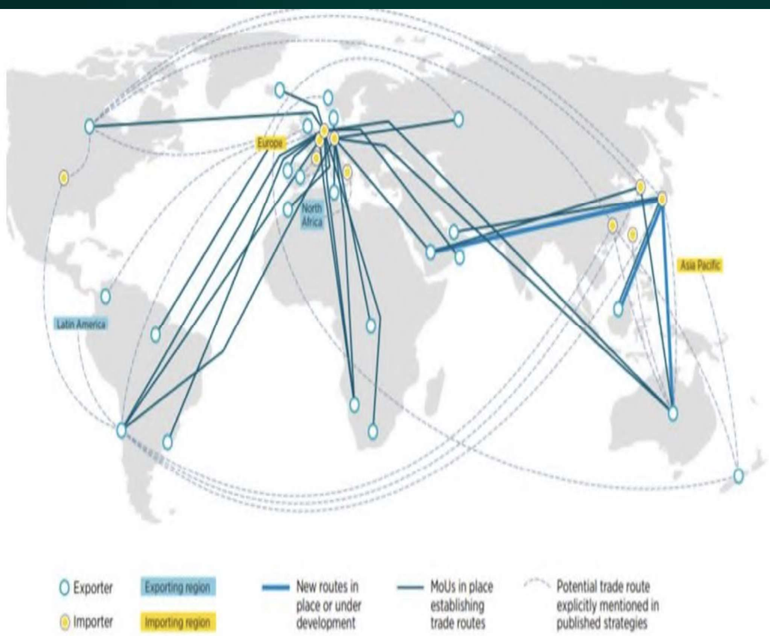
- Currently, demand for GH_2 is particularly high in Germany, Japan and South Korea. These economies have actively forged hydrogen partnerships with potential export-ing countries. Germany has signed MoU with countries in sub-Saharan Africa(e.g. South-Africa, Namibia), Latin America(e.g. Chile)the MENA region(e.g. Morocco, Saudi Arabia, Egypt and the United Arab mirates).

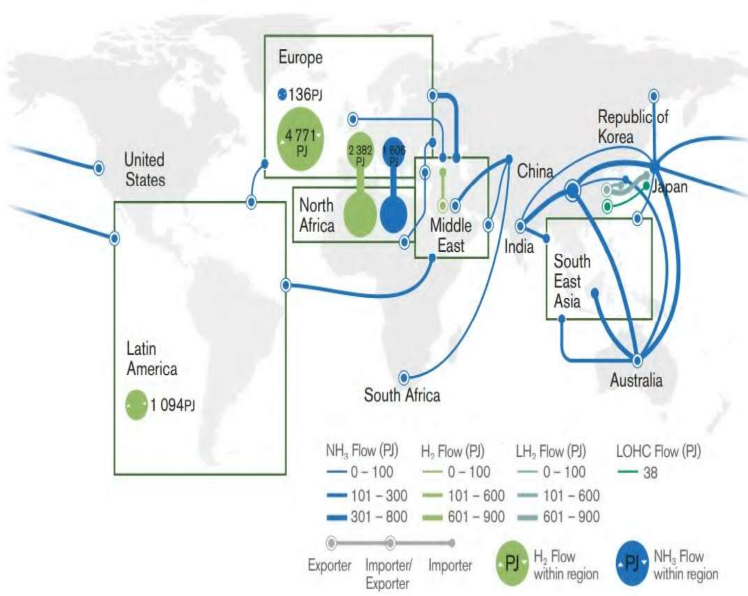
- On the other hand, Japan and South Korea are focusing on Oceania, South America and North Africa to find suitable partners.

- On the export side, Australia,India, the UAE, Saudi Arabia, Chile and the Russian Federation have also established a robust network with other countries. Even countries that will not necessarily rely heavily on GH_2 trade in the future, such as the United States, the United Kingdom, France and China, have entered into partnerships.



Green Hydrogen International Trade Analysis





04 Hydrogen Future Development Outlook

Hydrogen Future Development Outlook - Investment

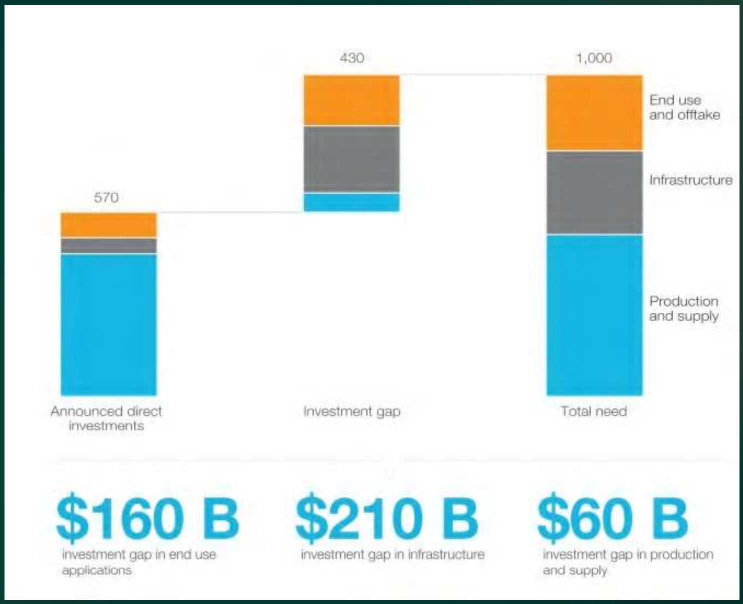
According to Hydrogen Council and McKinsey:

- **Investment Gap:**

There is still an investment gap of about $43 billion in the hydrogen industry to achieve the 2030 zero emission target.

- **Infrastructure Investment Gap:**

In hydrogen infrastructure, the announced investment accounts for only 20% of the investment required, with an absolute gap of about $21 billion. This was followed by investment gaps in end-use and offshore (end use and offtake) and production and supply (production and supply), at about $16 billion and $6 billion, respectively.



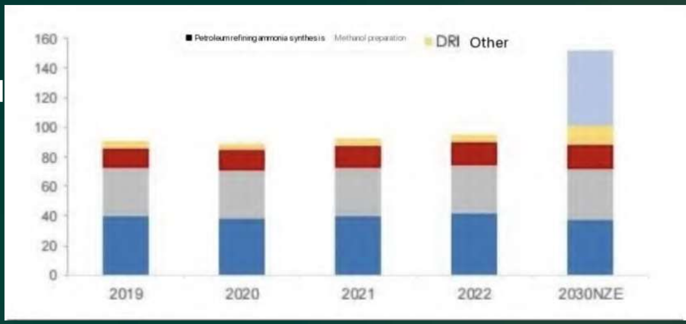
- **Project Maturation and Deployment:**

More projects are still needed to fill the remaining investment gap. Also, The currently announced projects need to be matured and deployed to grow from $39 billion (FID) to more than $1 trillion by 2030.

Hydrogen Future Development Outlook - Demand&Supply

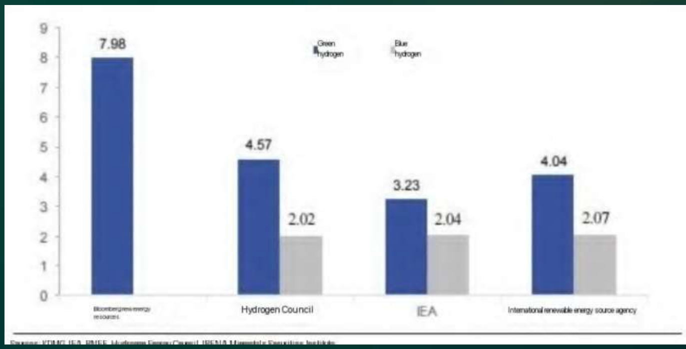
Demand Side：

According to the IEA，the hydrogen demand in 2022 is 95 million tons，42 million tons of which are used for petroleum refining and 53 million tons are used for industrial use.



The IEA forecasts that hydrogen demand will increase to 150 Mt by 2030, up about 40% from today and 527Mt of low-carbon hydrogen is needed globally by 2050.

The BloombergNEF gives the most optimistic number that is 798 Mt of green hydrogen is needed globally by 2050.

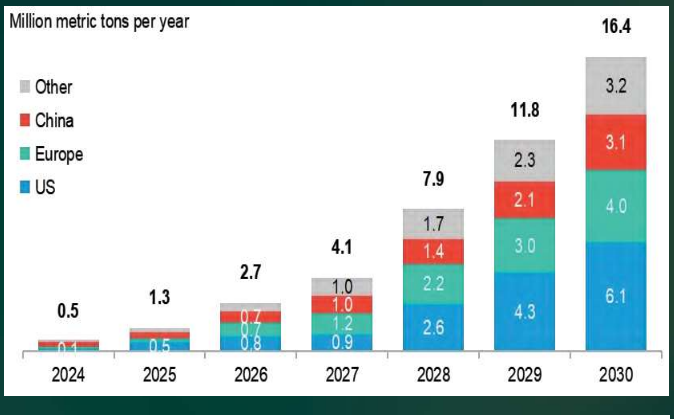


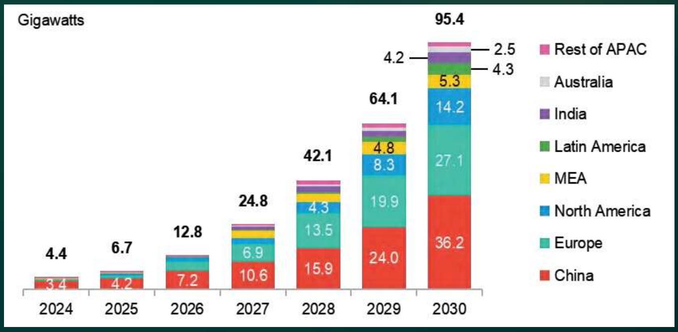
Green hydrogen demand in Europe is expected to reach 20 million tons per year by 2030.

Hydrogen Future Development Outlook - Demand&Supply

Supply Side forecast by BloombergNEF：

- ➢ Green hydrogen supply could reach 16.4Mt per year by the end of 2030.This represents 17% of today's gray hydrogen demand (95Mt) and just around 25% of the announced Green H_2 project capacity by 2030(64.6Mt). Production is highly likely to undershoot most governments 2030 targets. The main reasons for this are long project development timelines (over 70% of forecasted projects will be delayed), lower than expected technology maturity and delays to government regulation.
- ➢ Up to 95.4 gigawatts (GW) of electrolyzer capacity could be cumulatively installed by the end of 2030, of which 54GW is associated with projects announced by April 2024.This compares to the 481.5GW of electrolyzer capacity publicly announced to come online by 2030.





Hydrogen Future Development Outlook - Technologies

- **Green Hydrogen Production Pathways:**

- **PEM Electrolysis:** Optimized Membrane Systems, comprising multiple elements such as membrane polymers, reinforcements, radical scavengers, and gas recombination catalysts.

- **Liquid Alkaline Electrolysis:** Advanced Cells compatible with scalable manufacturing processes, including electrodes and support structures with high surface areas, high catalytic activity, and high conductivity to improve performance; optimized for reverse-current tolerance and intermittent operations.

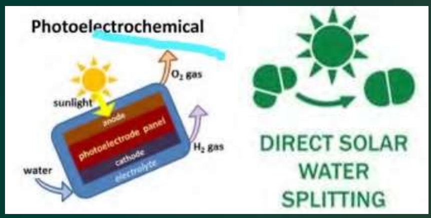
- **SOE Electrolysis:** Advanced Engineered Materials and Interfaces compatible with scalable synthesis and manufacturing processes, addressing degradation mechanisms such as thermal stresses under temperature cycling, Ni coarsening and Cr poisoning.

- **AEM Electrolysis:** Advanced AEM Membranes that enable high electrolyzer efficiency with enhanced durability at expected stack operating temperatures above 60°C, including improved mechanical stability addressing degradation due to swelling from water uptake and edge failures.

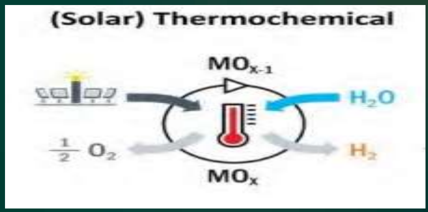
Hydrogen Future Development Outlook - Technologies

- **Advanced Green Hydrogen Production Pathways:**

➤ **PEC:** is a low-temperature process that bythe demand for electricity and directly uses sunlight to decompose water into hydrogen and oxygen. PEC has been widely demonstrated at a laboratory scale, utilizing different semiconductor material systems and catalysts, and early scale-up work is under way.



➤ **STCH**(solar thermochemical)： is another promising technology with the potential to achieve high theoretical solar-to-hydrogen conversion efficiency. The STCH process can be divided into two categories: (1) direct cycling, using concentrated solar heat (usually> 1000℃); (2) mixing cycle, using lower temperature thermochemical reduction (<800℃) plus secondary electrochemical steps.



➤ **Biological Conversion**: The biotransformation process utilizes the ability of microorganisms to consume and digest biomass and waste streams while releasing hydrogen. In direct hydrogen fermentation, the microbes produce hydrogen by themselves.

Hydrogen Future Development Outlook - Technologies

- **Next-Generation Fuel Cell concepts include:**
- **PEM fuel cells containing PGM-free catalysts:** allow for significant cost reduction, as the PGM catalyst is projected to be the most critical PEM fuel cell stack cost component. The development of high-performing and durable PGM-free catalysts also alleviates reliance on foreign imports for PGM materials.
- **Anion-exchange membrane fuel cells:** present the opportunity to achieve the high powerdensity of PEM fuel cells with alkaline conditions that are less harsh for many materials, and therefore offer possible compatibility with less expensive catalyst and bipolar plate materials.
- **Bipolar membrane fuel cells:** offer the potential for integrating the high hydrogenelectrode kinetics in acid systems with the advantages of anion-exchange membrane fuel cells. Bipolar membranes also provide potential for self-humidifying membranes that can operate under drier conditions.
- **Direct liquid-fueled fuel cells:** operate by electrochemically converting liquid fuels (e.g., methanol, ammonia, dimethyl ether) directly to electricity, thereby alleviating hydrogen delivery and storage challenges and offering fuel flexibility for a range of applications (e.g., maritime, rail, data centers).
- **Fuel cells and hybrid concepts for polygeneration:** including cogeneration (combined heat and power), present the opportunity to utilize diverse feedstocks to generate multiple value streams. In tri-generation, power, heat, and hydrogen are produced with low emissions and high efficiency

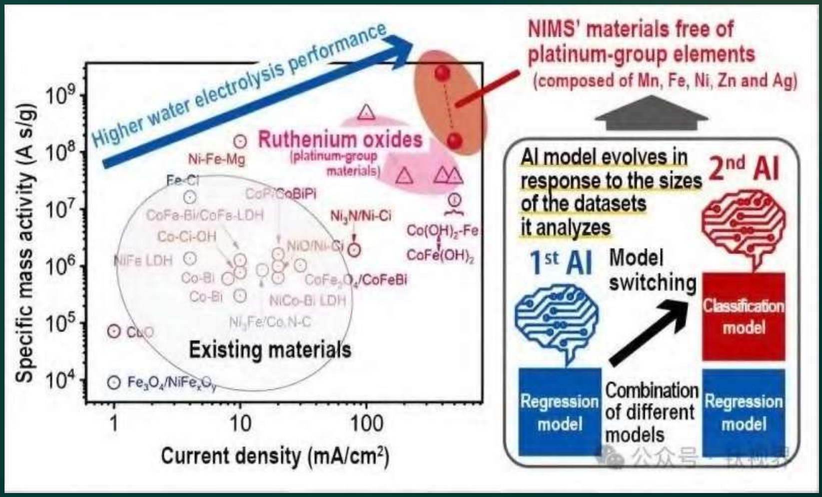
Hydrogen Future Development Outlook - Technologies

● **Artificial intelligence (AI) application - Identify The ideal Materials**

Currently, the mass production of green hydrogen using electrolyzer rely on expensive, scarce platinum group elements as their main catalyst components to accelerate slow oxygen evolution reactions (OER) .The National Institute for Materials Science (NIMS) of Japan has developed an AI technology that accelerates the identification of materials that do not contain platinum group elements.

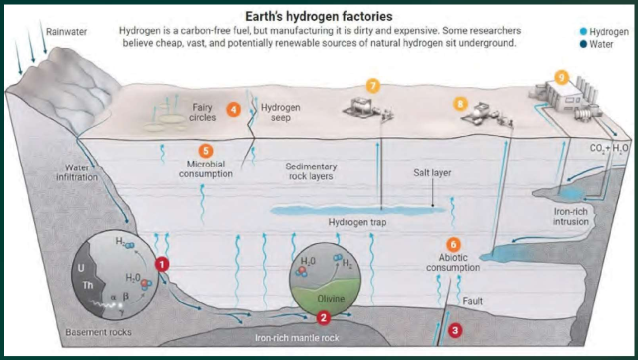
Using this AI, the team was able to identify new, effective OER materials from about 3,000 candidates in just one month. For reference, a comprehensive manual evaluation of these 3,000 materials is about six years.

These newly discovered materials are synthesized using relatively cheap and abundant metal elements: manganese (Mn), iron (Fe), nickel (Ni), zinc (Zn), and silver (Ag).



Hydrogen Future Development Outlook - New Source

- **Natural Hydrogen (aka geological hydrogen, white hydrogen, or gold hydrogen) :**



➢ "The search for natural hydrogen sources" was listed as one of the top10 scientific breakthroughs of 2023 by Science Magazine. Natural hydrogen is becoming one of the most significant scientific discoveries and future trends of the year.

➢ It forms naturally through geological tectonic movements and geochemical processes in the crust and mantle. It is a primary energy source(remeber Elon Musk), similar to fossil fuels and a renewable energy sources.

➢ According to GoldmanSachs, the market will more than double to $250 billion by 2030 and will be $1 trillion by 2050.

➢ Natural hydrogen deposits have been found in many places around the world, including the United States, Eastern Europe, Russia, Australia, Oman, France and Mali. Some of them are discovered incidentally, while others are discovered by searching for clues, such as hydrogen moving from deep to the surface, forming circular surface depressions called "fairy circles".

➢ The challenge now for natural hydrogen seekers is to turn hypothetical promises into commercial reality. The United States Geological Survey also pointed out that although geological hydrogen brings hope, further research is still needed to truly excavate natural hydrogen.

Hydrogen Future Development Outlook - INT Cooperation

- **Options for international cooperation to support national policymaking are need:**

Countries in the Global North have a significant advantage in terms of financial and human resources as regards the development of hydrogen policies compared to countries in the Global South. Policymakers in countries in the Global South face resource limitations, including a lack of qualiffed personnel and competing priorities for other, more pressing issues. International collaboration is crucial for addressing these challenges and accelerating the development of a comprehensive hydrogen policy framework in many countries. This can be achieved through :

- **Co-financing the development of a policy framework**
- **Multilateral cooperation in science, technology and innovation to accelerate global GH_2 production and application**
- **Knowledge sharing: Dialogue and capacity development**
- **Policy to support financing from the Global North to the Global South**
- **International coordination for hydrogen trade routes**
  1. **Inter-governmental Memoranda of Understanding**
  2. **International standards and certiffcation**
  3. **International collaboration for trade corridors**
  4. **International collaboration for trading green products**

THANKS FOR YOUR TIME

Email:liuyihua@eximbank.gov.cn
Tele: 0086 10 8357 9427