# The Basic Status and Future Development of The Hydrogen Economy

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**Abstract.** As the world tackles climate change by reducing greenhouse gas emissions, hydrogen energy is believed to play a crucial role in the global shift to cleaner energy sources. Collaborative efforts across sectors are currently propelling the hydrogen energy industry to overcome obstacles and challenges, transitioning from pilot projects to widespread commercialization, thus advancing a cleaner, low-carbon, safer, and more efficient energy system. This article provides an in-depth examination at the hydrogen energy industry's current development. We will then examine the hydrogen energy industry chain, providing an in-depth analysis at each link and its projected development. We anticipate future hydrogen energy industry trends and hope this information improves everyone's understanding of it.

**Keywords:** Hydrogen energy, Hydrogen production, Hydrogen energy storage and transportation.

## 1. Introduction

As the world grapples with the urgent need to reduce greenhouse gas emissions and combat climate change, hydrogen energy has emerged as a pivotal power in the global transition toward a sustainable and low-carbon future.According to statistics, since 1850, the concentration of carbon dioxide in the atmosphere has increased from $280\times10^{-6}$ to $450\times10^{-6}$,the global temperature has increased by 0.9 ~ 1.2℃, and the sea level has risen by 20 cm[1-3]. In particular, in the past 30 years, the global temperature and sea level have increased rapidly, with the temperature rising rate reaching 0.2℃ every 10 years and the sea level rising rate reaching 0.32 cm/a[4-6]. By the end of this century, if global climate warming reaches 2°C, the sea level rise will reach 36 ~ 87 cm, 99% of coral reefs will disappear, about 13% of terrestrial ecosystems will be destroyed, and many plants and animals are at risk of extinction. [7] Hydrogen offers a versatile and clean energy carrier capable of decarbonizing multiple sectors, including transportation, industry, and energy storage. Hydrogen can abate 80 gigatons of $CO_2$ by 2050. Setting our energy system on a trajectory to net zero requires firm commitment and rapid acceleration. It is estimated that the deployment of 75 MT of clean hydrogen is needed by 2030 – an ambitious, yet achievable target. This supply of clean hydrogen can replace 25 MT of grey hydrogen in ammonia, methanol, and refining; 50 billion liters of diesel in ground mobility; and 60 MT of coal used for steel production.[8] Despite its potential, hydrogen faces challenges such as high production costs, immature storage and transportation technologies, and environmental concerns related to leakage and resource consumption. For example,at present, gray hydrogen accounts for more than 95% of global hydrogen production, hydrogen production from coal or natural gas costs only 10-15 yuan /kg, and the cost of green hydrogen production from renewable energy electrolytic water exceeds 30 yuan /kg.[9]This paper explores the current state of hydrogen production, storage, transportation, and applications, alongside the policies and market dynamics driving its adoption. By analyzing the environmental impacts and technological advancements, this study aims to provide a comprehensive understanding of hydrogen's role in achieving global carbon neutrality and shaping a sustainable energy future.

# 2. Hydrogen production

## 2.1. Green Hydrogen

Green hydrogen production is the production of hydrogen through the electrolysis of water by renewable energy sources such as solar, wind, water, etc,and the entire process produces almost no carbon emissions. The main place for hydrogen production by electrolysis is the electrolytic cell, which electrolyzes water into hydrogen and oxygen under the action of direct current. According to IRENA statistics, taking the 1MWALK water electrolysis system as an example, the cost of the electrolyzer in the entire water electrolysis hydrogen production system accounts for about 45%. Each electrolytic cell is divided into an anode cell and a cathode cell. The cathode cell produces hydrogen and the anode cell produces oxygen. The main components and materials of the electrolyzer include the electrode, the diaphragm and the electrolyte, of which the electrode is mainly composed of metal materials, accounting for about 57% of the cost of the electrolyzer. The overall reaction is:$H_2O \rightarrow H_2 + 1/2O_2$. The leading current hydrogen production technologies through water electrolysis are as follows.

Proton Exchange Membrane water electrolysis for production(PEM): Using a proton exchange membrane as the electrolyte produces hydrogen, it can operate at a relatively low temperature and has high efficiency and hydrogen purity. Specifically, PEM electrolysis of water to produce hydrogen is divided into four steps: First, water ($2H_2O$) undergoes a hydrolysis reaction on the positive electrode, and splits into protons ($4H^+$), electrons ($4e^-$) and gaseous oxygen ($O_2$) under the action of electric fields and catalysts. Then, $4H^+$ passes through a solid PEM containing sulfonic acid functional groups and reaches the negative electrode under the action of an electric field. Next, the $4e^-$ pass from the positive to the negative electrode through the external circuit. Finally, the $4H^+$ at the negative electrode accepts $4e^-$ to form $2H_2$.The Electrolysis principle of PEMEC is shown in Figure 1 below.[10]

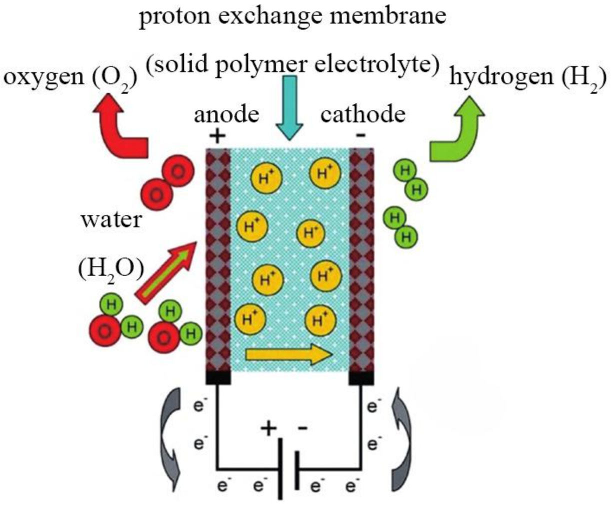


**Fig. 1** Scheme of the operating principle of a proton exchange membrane (PEM) electrolysis cell

During the operation of the PEM electrolyzer, the proton exchange membrane provides a transmission channel that only allows water molecules and hydrated hydrogen ions to pass through, transporting protons from the anode of the electrolyzer to the cathode of the electrolyzer, forming an ion transferpath inside the electrolyzer. The main components of PEM water electrolyzer are proton exchange membrane, catalyst layer, gas diffusion layer and bipolar plate from inside to outside, in which the diffusion layer, catalytic layer and proton exchange membrane form the membrane electrode assembly (MEA), which is the main site of the material transmission and electrochemical reaction of the entire water electrolyzer. The characteristics and structure of the membrane electrode directly affect the performance and lifetime of PEM electrolyzer.Proton exchange membrane in PEM electrolytic cell has the following three functions: 1. As a solid electrolyte, it conducts the protons generated by the anode reaction to the cathode to participate in the cathodic Hydrogen Evolution Reaction, providing a channel for proton transfer. 2. Isolate the reaction products (hydrogen and oxygen) on the cathode side and the anode side, to avoid the mutual penetration of hydrogen and oxygen. 3. Provide physical support for the catalyst layer on the cathode side and the anode side.

Hydrogen is produced via alkaline water electrolysis (ALK) using alkaline electrolytes like NaOH or KOH; this mature, low-cost technology has relatively low efficiency. The main body of the ALK electrolytic cell is assembled by the end pressure plate, gasket, plate, electroplate, diaphragm, and other parts, including dozens or even hundreds of electrolytic cells, which are pressed together by the screw and the end plate to form a cylinder or square. Two adjacent plates, including positive and negative plates, an anode electrode, diaphragm, sealing washer, and cathode electrode 6 parts delimit each electrolytic cell. In the electrolyte material of ALK, in the industrial application, KOH solution with a mass fraction of 30% or NaOH solution with a mass fraction of 26% is widely used.The working principle of ALK electrolytic cell is shown in Figure 2 below.[11]

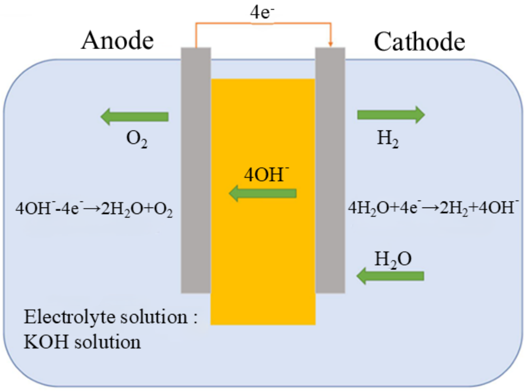


**Fig. 2** Working principle of ALK electrolytic cell

Solid Oxide water electrolysis for hydrogen production (SOE): Using solid oxides at high temperatures as the electrolyte, it has high efficiency and low energy consumption, but the cost and technical requirements are high.[12] The typical construction scenario of SOEC electrolyzer is shown in Figure 3 below.[13]

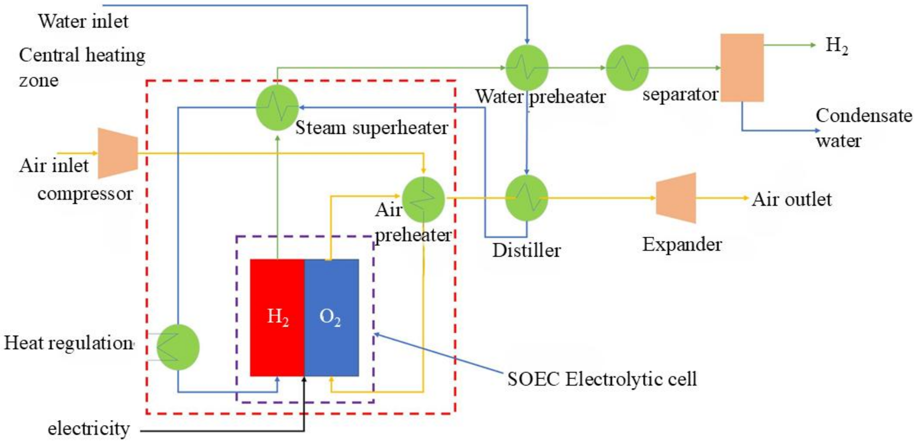


**Fig. 3** Typical construction scenario of SOEC electrolyzer

Other technologies also include: Anion Exchange Membrane water electrolysis for hydrogen production (AEM): Using an anion exchange membrane, combines the advantages of Alkaline and PEM electrolysis. The working principle of the AEM anion exchange membrane is shown in Figure 4below.[14]

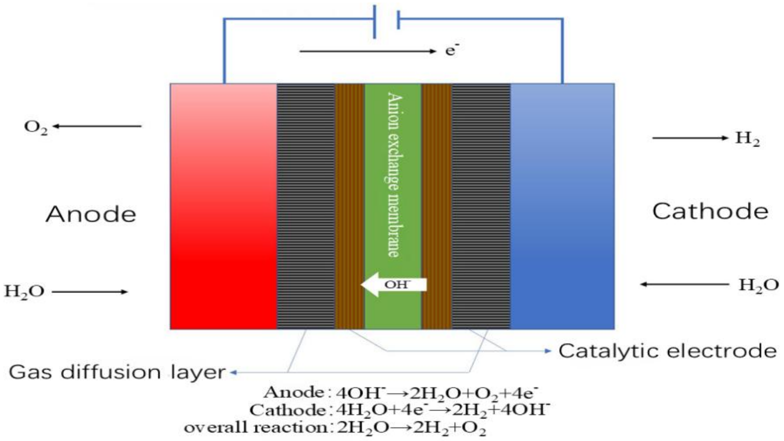


**Fig. 4** Sehematic diagram of A EM anion exchange membrane

Currently, the technology for green hydrogen production remains in its nascent stages, characterized by relatively low maturity and high costs, and it will require a considerable period before widespread adoption can be achieved.

## 2.2. Gray hydrogen

Gray hydrogen is hydrogen produced from fossil fuels, such as natural gas or coal.Gray hydrogen is mainly produced by steam methane reforming (SMR), which reacts natural gas with water vapor to produce hydrogen, or coal gasification, which reacts coal with oxygen and water vapor to produce syngas and further convert to hydrogen. The following is the specific reaction equation:Main reaction Methane ($CH_4$) reacts with water vapor ($H_2O$) at high temperatures (700-1000°C) with a catalyst (nickel based) to form hydrogen gas ($H_2$), carbon monoxide (CO),and a small amount of carbon dioxide($CO_2$):$CH_4 + H_2O \rightarrow CO + 3H_2$.Water gas conversion reaction:The carbon monoxide reacts with water vapor to produce more hydrogen $CO + H_2O \rightarrow CO_2 + H_2$.Overall reaction formula: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$.The production process of this method has high carbon emissions.Especially,in the case of producing pure hydrogen, it is necessary to convert all the CO (42% to 60%, volume fraction) in the syngas into CO2 in the conversion stage to generate the target product H2, which is the most important source of CO2 produced by the hydrogen production process from fossil resources, accounting for 70% to 85% of the carbon emissions in the entire process. The Hydrogen production from fossil resources is shown in Figure 5 below. [15]

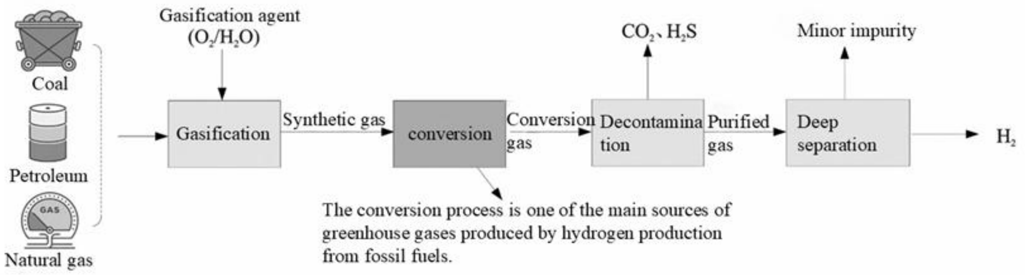


**Fig. 5** Hydrogen production from fossil resources

These two methods have mature technology and low cost, but high carbon emissions, emitting 9-12 kg and 18-20 kg of carbon dioxide per 1 kg of hydrogen production, respectively. Although gray hydrogen is currently the main source of hydrogen, due to its negative impact on the environment, it will gradually be replaced by blue hydrogen combined with carbon capture technology and green hydrogen made from renewable energy in the future, becoming a transitional choice in the energy transition.

### 2.3. Blue Hydrogen

Blue hydrogen production is the production of hydrogen through technologies such as Steam Methane Reforming (SMR) or Autothermal Reforming (ATR) and a process equipped with Carbon Capture and Storage (CCS) technology to reduce carbon emissions. As described in 2.2 When hydrogen is produced by SMR, the main reaction and water gas conversion reaction will release a large amount of $CO_2$.And then $CO_2$ is separated from the smoke of the SMR unit.Commonly the capture efficiency can reach 85-95%.CCS can be divided into three main segments, carbon capture, transport and carbon storage. First, there are three main methods of carbon capture.

Pre-combustion $CO_2$ capture: separation of $CO_2$ before fuel combustion such as coal gasification hydrogen production process. Pre-combustion $CO_2$ capture process diagram is shown in Figure 6 below.

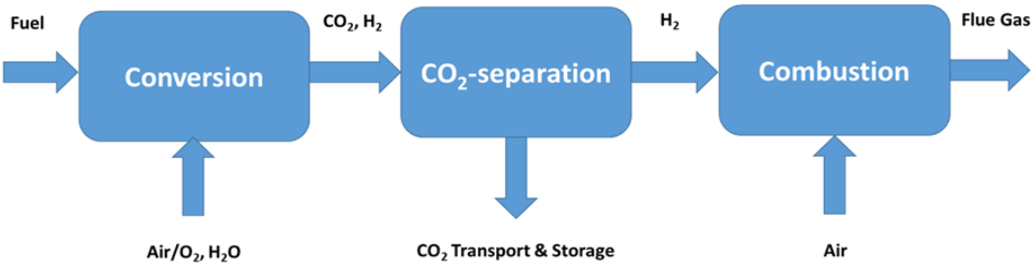


**Fig. 6** pre-combustion $CO_2$ capture

Source: IEAGHG Technical Report 2019

Post-combustion $CO_2$ capture: Separation of $CO_2$ from the flue gas, commonly used chemical absorption method, such as amine liquid absorption. Post-combustion $CO_2$ capture process diagram is shown in Figure 7 below.

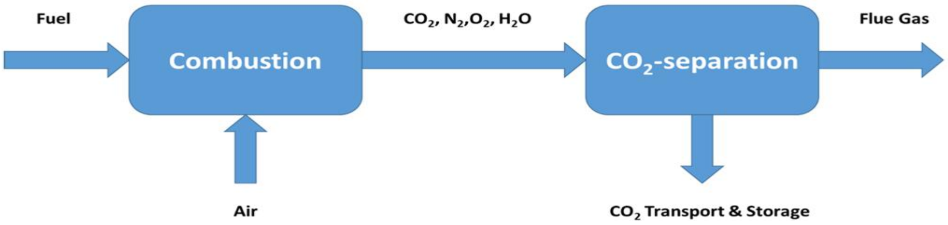


**Fig. 7** Post-combustion $CO_2$ capture

Source: IEAGHG Technical Report 2019

Oxyfuel combustion processes: Use pure oxygen instead of air combustion, so that the $CO_2$ concentration in the flue gas is higher. Oxyfuel combustion processes diagram is shown in Figure 8 below.

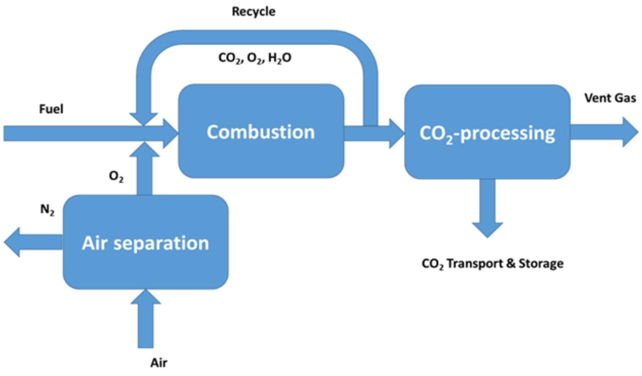


**Fig. 8** Oxyfuel combustion processes

Source: IEAGHG Technical Report 2019

Then transportation is mainly through pipelines, ships or trucks to transport liquid or supercritical $CO_2$ to the storage site. Finally, storage. There are mainly three kinds of storage methods.

Geological storage: Injection into deep underground geological structures such as depleted oil and gas fields, salt water layers, and unexploitable coal seams. For example,Norway's Sleipner project: The $CO_2$ produced by hydrogen production from natural gas in the North Sea is sequestered into the salt water layer of the sea floor, with a cumulative storage of more than 20 million tons.

Mineral sequestration: $CO_2$ reacts with metal oxides to form stable carbonates.For example,basalt mineralization.

Marine sequestration: Sequestration of $CO_2$ in deep sea or seabed sediments.

A visual overview of each step in the CCUS process is shown in Figure 9 below.[16]

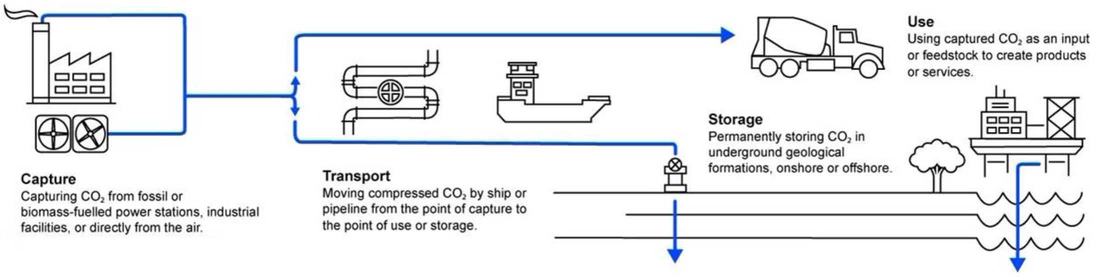


**Fig. 9** CCUS process

Source:Carbon Capture Utilisation and Storage - Energy System - IEA

It has already reached a certain scale and relies on carbon capture and storage technology.

## 2.4. Other methods

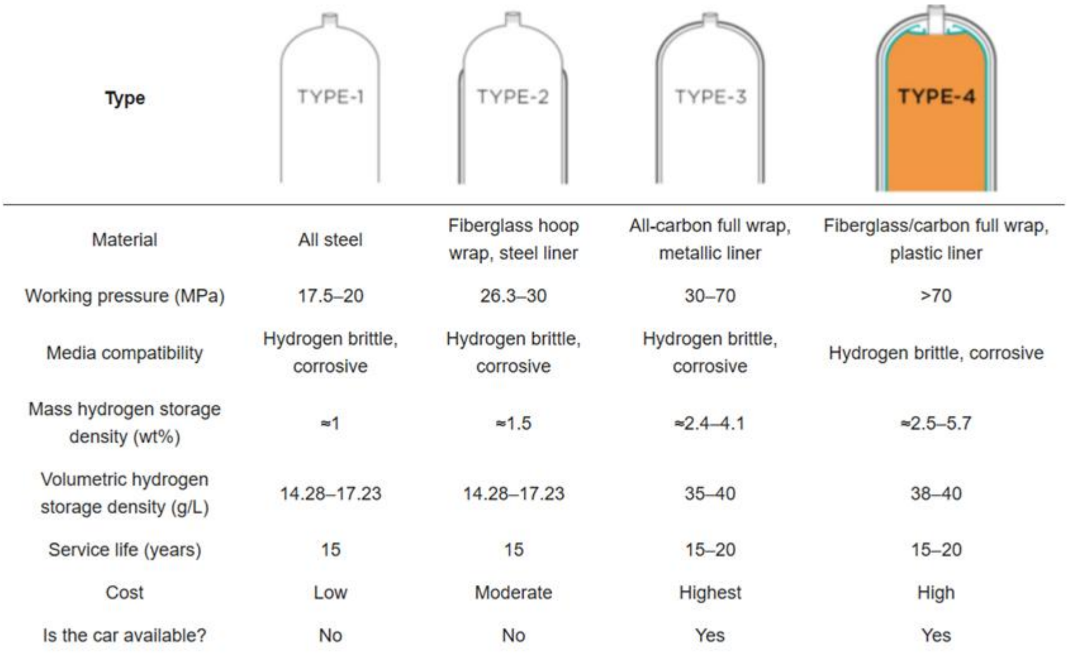
Biological hydrogen production and photocatalytic hydrogen production are two kinds of clean hydrogen production technologies. The former uses microorganisms to convert water or organic matter into hydrogen through photobiological hydrogen production, dark fermentation, or photo fermentation, which is suitable for waste treatment and resource recycling. To be more specific, according to the difference between microorganisms, hydrogen-containing substrate, and hydrogen production mechanism, the hydrogen production method can be divided into three categories. Photolysis of aquatic hydrogen. Green algae and Bacteria such as cyanobacteria decompose water under light and anaerobic conditions to produce hydrogen. Hydrogen production by light fermentation. Photosynthetic bacteria decompose organic matter to produce hydrogen under light and anaerobic conditions. Dark fermentation hydrogen production. Anaerobic fermentation bacteria break down organic matter to produce hydrogen in dark, anaerobic conditions.[17] This method uses a photocatalyst to split water into hydrogen under light; it relies on solar energy, and its raw material is clean. The photolysis process has three steps. Light excites the semiconductor. When the energy absorbed by the semiconductor is equal to or greater than its own band gap, the electrons in the valence band transition to the conduction band after excitation, and free electrons appear in the conduction band, while holes are left in the valence band. Recombination and migration of photo-generated carriers. Due to thermal vibration and other reasons, most of the photo-generated electrons will re-transition to the valence band, the electron-hole pairs will be recombined, and the remaining few photo-generated carriers will migrate to the semiconductor surface. Surface reaction. Some of the carriers that reach the surface will still recombine on the surface, and the rest will be captured by the water molecules adsorbed on the semiconductor surface, thus triggering the decomposition of water molecules.[18]Although the two are currently inefficient and the technology is not fully mature, they provide an important direction for a sustainable, low-carbon hydrogen economy in the future, and have broad application prospects.

# 3. Hydrogen energy storage and transportation

## 3.1. Hydrogen energy storage

Hydrogen storage technologies are divided into two directions: physical hydrogen storage and chemical hydrogen storage [19-20]. Physical hydrogen storage mainly includes :Room-temperature high-pressure hydrogen storage, Cryogenic liquid hydrogen storage,Cryogenic high-pressure hydrogen storage and Porous material adsorption hydrogen storage. High-pressure gaseous hydrogen storage equipment is convenient and has achieved mature commercialization. The storage of gaseous hydrogen uses high-pressure gas cylinders as containers, there are four main types: Type I cylinders are made of steel or aluminum and other metal materials, have relatively simple structures, and mainly rely on the strength of the metal to withstand the internal high pressure, although strong but relatively heavy and weak pressure bearing capacity; To solve the limitations of the weight and pressure bearing capacity of the type I hydrogen storage cylinder; Type II bottles use metal material as the inner liner and wrap composite material around the outside as reinforcement, which doubles the load capacity of the storage tank, but the pressure of hydrogen storage generally does not exceed 20MPa.. The type III bottle also uses metal material as the inner liner, but the cladding form of the external composite material changes to a combination of annular winding and longitudinal winding. The metal inner liner provides air tightness, and the fully wrapped composite material improves the strength of the hydrogen storage tank. In order to further reduce the weight of the hydrogen storage tank, increase the hydrogen storage density and reduce the cost, the type IV bottle replaces the original metal inner liner with a plastic inner liner.[21] Several types of high-pressure hydrogen storage vessels are shown in Table 1.[22]

**Table 1.** Different types of hydrogen storage vessels



| Type | TYPE-1 | TYPE-2 | TYPE-3 | TYPE-4 |
|---|---|---|---|---|
| Material | All steel | Fiberglass hoop wrap, steel liner | All-carbon full wrap, metallic liner | Fiberglass/carbon full wrap, plastic liner |
| Working pressure (MPa) | 17.5–20 | 26.3–30 | 30–70 | >70 |
| Media compatibility | Hydrogen brittle, corrosive | Hydrogen brittle, corrosive | Hydrogen brittle, corrosive | Hydrogen brittle, corrosive |
| Mass hydrogen storage density (wt%) | ≈1 | ≈1.5 | ≈2.4–4.1 | ≈2.5–5.7 |
| Volumetric hydrogen storage density (g/L) | 14.28–17.23 | 14.28–17.23 | 35–40 | 38–40 |
| Service life (years) | 15 | 15 | 15–20 | 15–20 |
| Cost | Low | Moderate | Highest | High |
| Is the car available? | No | No | Yes | Yes |

However, it has low hydrogen storage density and poses safety risks such as leakage, making it a less preferred option for hydrogen storage technology in the long term [23]. Cryogenic liquid hydrogen storage requires liquefaction of hydrogen, which can significantly increase hydrogen storage density. In the process of storage of liquid hydrogen, the spin isomer conversion of hydrogen is particularly important. Orthohydrogen and Parahydrogen are two forms of hydrogen molecules with parallel and antiparallel nuclear spin arrangements, respectively. [24-25]Figure 10.[26] shows the change law of the ratio of Orthohydrogen and Parahydrogen hydrogen in equilibrium hydrogen with temperature and the change law of the specific enthalpy of Orthohydrogen and Parahydrogen hydrogen with temperature.

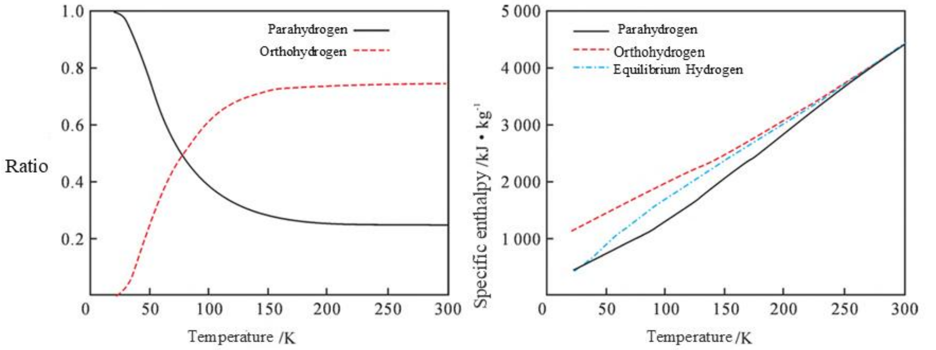


**Fig. 10** The variation law of the ratio of positive and secondary hydrogen in equilibrium hydrogen with temperature(left), and the variation law of the ratio of positive and secondary hydrogen with temperature (right)

Orthohydrogen hydrogen is relatively stable at higher temperatures, while Parahydrogen hydrogen is stable at low temperatures, and is the main form of liquid hydrogen and solid hydrogen. The conversion of Orthohydrogen hydrogen to Parahydrogen hydrogen will release heat, which is the main source of self-heating of liquid hydrogen. However, the energy consumption and cost of liquid hydrogen storage are high [27]. Commercial liquid hydrogen storage and transport technologies are mature in Europe, the US, and Japan, unlike China, where high costs and limited core technology restrict its use in aerospace [28]. Cryogenic high-pressure hydrogen storage technology improves hydrogen storage density compared to high-pressure gaseous hydrogen storage and reduces energy consumption compared to liquid hydrogen storage [29], although it is still in the research and development stage. Porous materials, such as carbon nanomaterials [30-31] and metal-organic frameworks (MOFs) [32-33], have large specific surface areas and can adsorb hydrogen through van der Waals forces. However, their adsorption performance and hydrogen storage capacity at room temperature and pressure need improvement. Solid-state metal hydrogen storage offers high safety and maintains high purity of hydrogen, but its hydrogen absorption/desorption performance and cycling stability need enhancement. Chemical hydrogen storage primarily includes metal hydride hydrogen storage and organic liquid hydrogen storage. Metal hydrogen storage materials store hydrogen in alloys in the form of metal hydrides, including magnesium series, titanium series, vanadium series, rare earth series and composite hydrogen storage alloys, etc. The hydrogen storage capacity of magnesium alloy is large (up to 7.6%), but the hydrogen discharge temperature is high, usually 300℃; The hydrogen storage capacity of titanium series, vanadium series and rare earth series hydrogen storage alloys ranges from 1.4% to 2.4%, and the hydrogen discharge temperature is significantly lower than that of magnesium series. The coordination hydride route requires alkali metals (lithium, sodium, potassium, etc.) or alkaline earth metals (magnesium, calcium, etc.) or third major group elements (aluminum, boron, etc.). In the process of hydrogen absorption, the alloy hydrogen storage material takes on exothermic reaction to absorb hydrogen and form metal hydride under certain temperature and hydrogen pressure. In the process of hydrogen dehydrogenation, the metal hydride undergoes an endothermic reaction under heating to release the absorbed hydrogen. A list of selected metal hydrides along with their hydrogen capacities is shown in Table 2.[34]

**Table 2.** Hydrogen storage characteristics of metal hydrides

| Metal hydride | $H_2$ capacity (wt%) | Desorption temperature (°C) | Desorption enthalpy (kj/mol $H_2$) |
|---|---|---|---|
| $MgH_2$ | 7.6 | >300 | 75 |
| $Mg_2NiH_4$ | 3.59 | >280 | 65 |
| $Mg_2FeH_6$ | 5.5 | >300 | 77.6 |
| $FeTiH_2$ | 1.89 | >30 | 28 |
| $LaNi_5H_6$ | 1.4 | >100 | 31 |
| $MgH_2$-$LiAlH_4$ (1:1M) | 9.4 | >250 | 45 |
| $MgH_2$-$NaAIH_4$ (1:1M) | 7.6 | >175 | — |
| $MgH_2$-$LiBH_4$ | 11.4 | >350 | 45 |

Microscopic mechanism: Hydrogen molecules are first adsorbed on the surface of the metal, and are dissociated into hydrogen atoms with the hydrogen bond breaking. The hydrogen atoms enter the gap of metal atoms through internal diffusion to form metal solid solution, and then the hydrogen atoms in the solid solution further diffuse to the inside of the metal, reaching the solid solution and transforming into the activation energy of chemical adsorption to form hydrides. Simplified model of metal-hydrogen interaction is shown in Figure 11 below.[35]

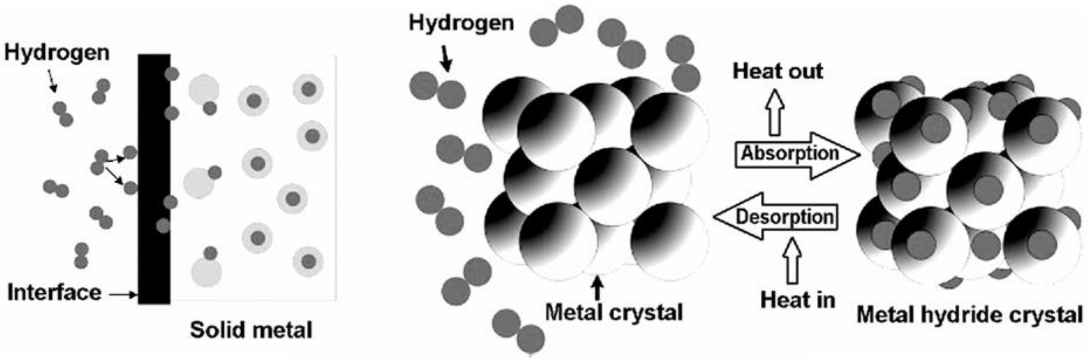


**Fig. 11** Simplified model of metal-hydrogen interaction

In recent years, unsaturated hydrocarbon organic solutions have been regarded as promising hydrogen carriers. They store hydrogen through hydrogenation reactions and release hydrogen through dehydrogenation reactions, offering high hydrogen storage density and the potential to utilize existing liquid fuel transportation infrastructure for hydrogen transport[36-37].The basic principle of this technology is catalytic hydrogenation reaction, loading hydrogen onto specific organic liquid molecules to form hydrogen-rich organic matter to achieve efficient hydrogen storage.When hydrogen is needed, it is released by catalytic dehydrogenation. In the hydrogenation stage, the liquid organic hydrogen carrier such as aniline, methylcyclohexane, etc, reacts with hydrogen under the action of a catalyst, and the hydrogen atoms are combined into the molecular structure of the organic carrier to form a stable hydrogen-rich compound, at which time the hydrogen is "stored" in the liquid. When hydrogen is needed, the hydrogen stored in the organic liquid is released by heating and catalytic dehydrogenation.[38] Currently, this technology is still in the research and development stage, with catalysts requiring further optimization, and the hydrogen released after dehydrogenation needing additional purification. The performance comparison of several typical hydrogen storage technologies is shown in Table 3.

**Table 3.** Performance Comparison of Hydrogen Storage Technologies

| **Hydrogen Storage Technology** | **Storage Density (Mass/Volume)** | **Operating Conditions** | **Key Advantages** | **Key Limitations** | **Applcations** |
|---|---|---|---|---|---|
| Room-Temperature High-Pressure | 1-5 wt%<br>20-40kg/$m^3$ | Ambient temperature,<br>35-70 MPa | Mature technology, simple equipment, fast hydrogen charge/discharge | High-pressure safety risks,low volumetric density,heavy containers | Fuel cellvehicles, stationary storage |
| Cryogenic Liquid Hydrogen | ≈100%liquid $H_2$ density<br>70.8　kg/$m^3$ | Ultra-low temperature(-253℃).ambient pressure | Extremely high volumetric density,no high-pressure containers required | High liquefaction energy(≈30%of $H_2$ energy),evaporation loss,strict insulation | Aerospace, large-scale hydrogen transport |
| Cryogenic High-Pressure Composite | 5-8 wt%<br>50-80 kg/$m^3$ | Low temperature(-50~-150℃).<br>15-35 MPa | Combines low temperature and moderate pressure for enhanced storage density | Requires simultaneous temperature/pressure control,complex system design | Industrial storage, laboratory use |
| Porous Material Adsorption | 1-3 wt%<br>10-30 kg/$m^3$ | Ambient to cryogenc(-196℃).<br>3-10 MPa | Low-pressure operation,high safety. tunable materials(e.g.MOFs,activated carbon) | Low storage density,high adsorbent cost,requires pre-cooling/regeneration | Smal-scale devices, R&D |
| Metal Hydride | 1-7 wt%<br>50-150 kg/$m^3$ | Ambient-200℃,<br>0.1-5 MPa | Safe low-pressure storage,high volumetric density,reversible reactions | Low gravimetric density.thermal managemen required,material degradation | Portable power, submarine storage |
| organic Liquid Hydrogen Storage | 5-7 wt%<br>50-60 kg/$m^3$ | Ambient conditions 200(storage) -300℃ (release) | Ambient storage, compatible with existing oilinfrastructure, high safety | High dehydrogenation energy, costly catalysts, limited cycle life | Long-distance transport,chemical industry |

## 3.2. Hydrogen Energy

Transportation: Key methods for moving hydrogen include high-pressure gas, cryogenic liquid, pipeline, and solid-state transport, plus options like liquid organic hydrogen carriers (LOHC) and ammonia**.** Each involves a different technology for transporting hydrogen. At present, the most mature hydrogen transport method is the high-pressure long tube trailer, which is suitable for transportation in the city and meets the needs of short-distance hydrogen transport. The key equipment technology of low-temperature liquid hydrogen transportation has been gradually industrialization, and will become an important mode of hydrogen transportation in the civilian hydrogen energy field in the future. In addition, pure hydrogen pipeline transportation has not been popularized due to high cost, and will gradually be applied with the expansion of industrial applications in the future. It is worth paying attention to the natural gas mixed hydrogen transport mode, which can use existing natural gas pipelines to transport hydrogen, especially for civil construction, and can achieve the purpose of reducing natural gas consumption without replacing household cookware. Compared with the construction of pure hydrogen transport pipeline, hydrogen blending technology of natural gas pipeline is more economical. In the future, with the growth of hydrogen demand in developed regions such as the east of China, the use of cheap renewable power resources in the northwest region of the "Hydrogen Energy Huyong Line" to produce hydrogen and incorporate it into natural gas pipelines is expected to achieve large-scale long-distance transmission of hydrogen, which will help solve problems such as the imbalance of regional distribution of energy in China and promote the rapid development of the hydrogen energy industry.[39] In Germany,there have been engineering cases of 20% mixed hydrogen in the natural gas pipeline network. The Gestion des Réseaux par l'Injection d'Hydrogène pour Décarboner les Énergies (GRHYD) project in France started injecting natural gas containing hydrogen (blending rate of 6%) into the gas network in 2018, and the blending rate of hydrogen reached 20% in 2019. In the United Kingdom, zero-carbon hydrogen production is implemented in the HyDeploy project, government has laid out that by 2023 it wishes to The hydrogen value chain work with industry to complete testing necessary to allow up to 20% blending of hydrogen into the gas distribution grid for all homes on the gas grid. This is supported by a Value for Money assessment being undertaken by BEIS in 2022.[40] The incorporation of hydrogen into the existing natural gas pipeline system is an effective way to achieve large-scale and low-cost hydrogen energy transportation and increase the consumption of renewable energy, but the hydrogen embrittleness (HE) effect caused by hydrogen is a serious threat to pipeline safety. Current studies mostly focus on the transportation conditions of hydrogen-doped natural gas, but due to the differences in natural gas components, pipeline working conditions and storage and transportation materials in different countries, the research results lack universality, and the law of the influence of hydrogen-doped proportion on the pipeline network system is not clear. According to the relevant data, it can be summarized that the focus should be carried out in three aspects: first, according to the development level of hydrogen mixing technology in various countries, targeted hydrogen embrittance research; The second is to establish a hydrogen mixing demonstration project to systematically evaluate the impact of different hydrogen mixing ratios on the hydrogen embrittance resistance of infrastructure; The third is to strengthen the research on the mechanism of hydrogen embrittlement resistance of materials, build a material compatibility test platform, optimize the compatibility of pipe network equipment and hydrogen-doped natural gas in terms of technical indicators, user needs and economy, and provide theoretical support for the large-scale safe transportation of hydrogen-doped natural gas.[41]

# 4. Hydrogen application

## 4.1. Transportation

Hydrogen energy plays an important role in transportation, and its core advantage is to achieve low carbon and efficient energy transition. As a zero-emission clean energy source, hydrogen fuel cell vehicles only emit water vapor, which can significantly reduce greenhouse gases and pollutants, especially for long-distance freight, public transportation and other traditional fuel consumption areas. The high energy density of hydrogen gives it potential in heavy trucks, ships and aviation, overcoming the limitations of battery life and charging time of pure electric vehicles. At the same time, hydrogen can be produced by electrolyzing water from renewable sources, reducing dependence on fossil fuels, improving energy security, and supporting localized energy supply. The commercialization of hydrogen transportation continues to accelerate as technological advances drive fuel cell efficiency and hydrogen storage costs down, and as national policies accelerate the promotion through subsidies and infrastructure investments (such as hydrogen refueling stations). In the future, with the breakthrough and large-scale application of green hydrogen production technology, hydrogen energy is expected to become a key path for the decarbonization of multi-mode transportation and help achieve the goal of global carbon neutrality.

**Table 4.** The performance of the hydrogen systems in the transport sector is presented[42]

| Application | Capacity | Energy efficiency* | Investment cost** | lifetime | Maturity |
|---|---|---|---|---|---|
| Fuel cell vehicle | 80-120 kW | Tank to wheel 43-60% (HHV) | $ 60 K-100 K | 150,000 km | Early market |
| Hydrogen retail station | 200 kg/day | -80% inc. compression to 70 MPa | $1.5-2.5 M | - | Early market |
| Tube trailer (gaseous) | Up to 1000 kg | -100% (without compression) | $1M ($ 1000 per kg payload) | - | Maturity |
| Liquid tankers | Up to 4000 kg | Boil-off stream: 0.3% loss per day | $ 75 K | - | Maturity |

Lower heating value*, $=USD
All power specific investment costs refer to the energy output**
HHV-higher heating value

### 4.2. Industrial application

Hydrogen energy has a wide range of important uses in the industrial sector and is the key to promoting the decarbonization of traditional high-carbon industries. In the chemical and oil refining industries, hydrogen is used in ammonia synthesis, fertilizer production, refinery desulfurization and methanol manufacturing, and is the core raw material of the chemical industry chain. In steel manufacturing, hydrogen as a reducing agent (hydrogen direct reducing iron technology) can replace coke, greatly reducing carbon emissions in the steelmaking process. In addition, hydrogen, as a high caloric value fuel, provides high temperature heat sources for glass, ceramics, cement and other industries, and gradually replaces fossil fuels for industrial boilers. In electronics and semiconductors, high-purity hydrogen is used as a protective gas in chip manufacturing and liquid crystal panel production.

### 4.3. Other industries

In energy storage and power systems, hydrogen energy can be used as a large-scale energy storage medium, through electrolytic water to convert surplus solar energy into hydrogen storage, solve the intermittent problem of renewable energy, and in the grid peak load through fuel cells or gas turbines to generate electricity, improve the flexibility of the energy system. For example, the German "Hybridge" project uses hydrogen energy to achieve cross-season storage of solar energy. In building heating and power supply, hydrogen can be mixed with natural gas (up to 20% hydrogen) for home heating, or fuel cells to provide combined heat and power to buildings, reducing carbon emissions. Japan's Tokyo Gas Company pilot hydrogen energy housing, to achieve heating, and power integration. In the medical field, hydrogen has also been proved to be effective in removing oxidation groups and treating oxidative damage [43-44]. In the food industry, hydrogen is often used to hydrogenate fats and fats to improve the use value of fats and fats [45-46].

## 5. Policy and market

### 5.1. Policy

With the increasing global energy demand and the increasingly severe problem of climate change, it is inevitable to accelerate the transition from traditional energy to clean and sustainable energy.The world's major economies see hydrogen as an important option for energy security and carbon neutrality. By the beginning of 2021, more than 30 major economies, including the United States, the European Union, Japan, and Australia, have formulated hydrogen development strategies and related policies.The 2020 Fraunhofer Society's vision of the German Hydrogen Economy Development Route [47] predicts that the expansion of hydrogen production capacity by electrolytic water in Germany alone will require a capacity of 50-80 GW by 2050. Taking China as an example, China has published a medium and long-term plan for the development of the hydrogen energy industry (2021-2035). According to the plan, we can see that by 2025, a relatively complete system and policy environment for the development of the hydrogen energy industry will be formed, the industrial innovation capacity will be significantly improved, the core technology and manufacturing process will be basically mastered, and a relatively complete supply chain and industrial system will be initially established. Remarkable achievements have been made in the demonstration and application of hydrogen energy, great progress has been made in clean energy hydrogen production and hydrogen energy storage and transportation technologies, and the market competitiveness has been greatly improved. A hydrogen energy supply system has been initially established that focuses on industrial by-production of hydrogen and nearby utilization of hydrogen production from renewable energy sources. The number of fuel cell vehicles is about 50,000, and a number of hydrogen refueling stations have been deployed. Hydrogen production from renewable energy reaches 100,000 to 200,000 tons/year, becoming an important part of new hydrogen energy consumption, and achieving carbon dioxide emission reduction of 1 to 2 million tons/year.After another five years of development, by 2030, a relatively complete hydrogen industry technology innovation system, clean energy hydrogen production and supply system will be formed, the industrial layout will be reasonable and orderly, and renewable energy hydrogen production will be widely used, which will strongly support the realization of the carbon peak goal.By 2035, a hydrogen energy industrial system will be formed to build a multi-component hydrogen energy application ecology covering transportation, energy storage, industry and other fields. The proportion of hydrogen production from renewable energy sources in terminal energy consumption has increased significantly, which plays an important supporting role in the development of green energy transformation.[48]

### 5.2. Market

The hydrogen economy faces enormous challenges that cannot be solved by the market alone. High production costs, low-cost performance for storage and transportation, market forces influenced by vested interests in fossil fuels and existing profitable renewable technologies often hinder the competitiveness and development of hydrogen. To overcome these problems, heavy government intervention is therefore essential. According to Hydrogen Insights 2024, it is expected that by 2030, the global hydrogen energy market will exceed 680 billion US dollars, the proportion of green hydrogen will be significantly increased, and the hydrogen energy industry chain will gradually mature, providing important support for the global carbon neutrality goal.[49] The gas hydrogen is suitable for short distances with medium and low transportation volumes or long distances with low transportation volumes. Liquid hydrogen and liquid organic hydrogen carriers are both suitable for long distances with large transportation volumes. Liquid organic hydrogen carriers have advantages in daily transportation demand of more than 20,000 kg/day. Pipeline gas hydrogen is suitable for short distances of less than 100 km with large transportation volumes. Then the economic analysis under the 1-to-N hydrogen storage and transportation scenario is conducted to decrease the economic cost. At 25 km, 1-to-N gas hydrogen transport can reduce the cost by up to 26.2% (300 kg H2/day) and 1-to-N liquid hydrogen transport can reduce the cost by up to 69.5% (3000 kg H2/day). To step further, the 1-to-N relay hydrogen storage and transportation scenario is proposed for high daily transportation demand and long transportation distances. [50]

## 6. Environmental impact

The impact of hydrogen economy on the environment is dual, with both significant positive impacts and potential challenges. On the positive side, the hydrogen economy can significantly reduce greenhouse gas emissions, especially green hydrogen produced through the electrolysis of water from renewable energy sources, which produces almost no carbon emissions throughout the life cycle, becoming a key path to decarbonization in industry, transportation and other fields. For example, hydrogen energy can replace fossil fuels in high-carbon industries such as steel and chemicals, and hydrogen direct reduced iron ($H_2$-DRI) technology can reduce carbon emissions in the steel industry by 90%. In the field of transportation, hydrogen fuel cell vehicles emit only water vapor, which can significantly improve urban air quality. In addition, hydrogen energy, as a large-scale energy storage medium, can solve the intermittent problem of wind and solar energy, promote the development of renewable energy, and realize the cross-regional transmission of clean energy through hydrogen carriers. However, the hydrogen economy also faces some environmental challenges. At present, 80% [51]of the world's hydrogen comes from fossil fuels (gray hydrogen), and the production process has high carbon emissions, even when combined with carbon capture technology (blue hydrogen), there is still a risk of carbon leakage. Hydrogen itself is an indirect greenhouse gas, and leakage into the atmosphere can exacerbate the greenhouse effect. Overall, the environmental benefits of a hydrogen economy depend on how hydrogen is produced and how well it is managed. As the cost of green hydrogen falls, carbon capture technology improves, and leakage control technology improves, the hydrogen economy has the potential to be an important support for achieving global carbon neutrality, but its sustainable development requires a balance between technological progress, policy support, and ecological management.

## 7. Conclusion

Hydrogen energy holds immense promise as a cornerstone of the global energy transition, offering a pathway to decarbonize industries, transportation, and energy systems. Green hydrogen, produced from renewable sources, represents the ideal solution for achieving zero emissions, while blue hydrogen serves as a transitional option with reduced carbon footprints. However, the hydrogen economy faces significant challenges, including high costs, technological barriers, and environmental risks such as hydrogen leakage and resource consumption. Despite these hurdles, rapid advancements in electrolysis, storage, and transportation technologies, coupled with strong policy support and growing market investments, are accelerating the adoption of hydrogen. As nations strive to meet their carbon neutrality goals, hydrogen is poised to play a critical role in bridging the gap between renewable energy and sustainable development. By addressing current limitations and fostering innovation, hydrogen can unlock its full potential, contributing to a cleaner, more resilient, and equitable energy future.

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