
Review

Hydrogen energy technologies for net-zero transitions: Progress, bottlenecks, and future pathways across production, storage, transport, and applications

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Abstract: Hydrogen energy, distinguished by its high energy density, superior combustion calorific value, and environmental benignity, represents a highly promising low carbon energy carrier for the 21st century energy transition and serves as a critical technological pillar supporting global energy restructuring and the attainment of carbon peaking and carbon neutrality objectives. In this paper, we systematically reviewed the current landscape and core technological bottlenecks of the hydrogen industry, structured along its three fundamental value chain segments: hydrogen production, storage and transportation, and end use applications. Our findings indicated that water electrolysis constitutes a pivotal route for green and sustainable hydrogen generation. Moreover, alkaline water electrolysis attained a technology readiness level (TRL) of 9 and exhibited a hydrogen storage efficiency of approximately 60%–75%. Nevertheless, the intrinsic intermittency and fluctuations inherent in wind and solar power generation tended to induce performance degradation and shortened the operational lifespan of electrolysis units, thereby critically undermining the stability and economic viability of green hydrogen production. With respect to storage and transportation, the dominant high pressure gaseous hydrogen technology likewise reached TRL 9; however, it was constrained by a relatively low volumetric storage density (20–40 kg/m³) and notable safety concerns. Liquid hydrogen storage offered a substantially higher volumetric density, exceeding 60 kg/m³, albeit at the expense of considerable energy consumption and elevated costs during liquefaction and transportation. In

contrast, solid state hydrogen storage combined enhanced safety with high volumetric densities in the range of 50–110 kg/m³, rendering it a primary focus of research and development efforts. In terms of applications, hydrogen was predominantly deployed in the transportation sector, industrial decarbonization of steelmaking and chemical production, and hydrogen based energy storage and power generation.

Keywords: hydrogen energy; hydrogen production; hydrogen storage and transportation; hydrogen energy application; green hydrogen

1. Introduction

Hydrogen is considered a central element in the architecture of future sustainable energy systems, due to its versatility and potential for integration with renewable sources [1]. With the increasingly severe global environmental problems and the intensifying demand for energy transformation, hydrogen is widely recognized by countries as a critical pillar for deep decarbonization, and policy attention is increasingly transitioning from the question of “whether” to develop hydrogen to the more pragmatic concerns of “how” to achieve efficient, cost-effective, and large-scale deployment. The U.S. Department of Energy issued the “U.S. National Clean Hydrogen Strategy and Roadmap” in 2023 [2], proposing a comprehensive development framework to accelerate the production, processing, delivery, storage, and application of clean hydrogen. It is projected that by 2030, the green hydrogen production capacity will reach 10 million tons per year, increasing to 20 million tons per year by 2040, and 50 million tons per year by 2050. Moreover, the European Commission issued the “REPowerEU Plan” in 2022 [3], where the REPowerEU set a target of 10 million tons of domestic renewable hydrogen production and 10 million tons of renewable hydrogen imports by 2030. Furthermore, Japan, South Korea, etc. also successively issued the “Basic Energy Plan [4]” and “Roadmap for Hydrogen Energy economy [5]” to accelerate the layout of the hydrogen energy industry. The National Development and Reform Commission of China promulgated the “Medium- and Long-Term Development Plan for the Hydrogen Energy Industry (2021–2035) [6]” in 2022 to promote the sustainable and healthy development of the hydrogen energy industry. The multi-scenario forecasting study by Okonkwo et al. [7], who adopted a hybrid time-series model, further confirmed the long-term exponential growth trend of global hydrogen demand under energy-transition pathways. Under the Global aggressive transformation scenario (AGS), hydrogen demand is projected to grow exponentially. By 2050, China’s hydrogen demand will increase from 3341 PJ in 2023 to 10641 PJ, a more than threefold increase; the United States will also increase from 1530 PJ to 6134 PJ, and Japan will increase from 217 PJ to 933 PJ [7].

Moreover, significant breakthroughs have been achieved across key technological domains of hydrogen energy utilization, including hydrogen production, storage and transportation, and hydrogen energy application. However, bottlenecks exist in key links such as hydrogen production efficiency, hydrogen storage density, and hydrogen service life [8,9]. Moreover, systemic integration challenges at the industry level, including the intermittency mismatch with renewable energy sources [10], high infrastructure costs [11], and incomplete safety standards across the full value chain, continue to impede the large-scale application of hydrogen energy. These bottlenecks do not exist in isolation but are interconnected and mutually influential, forming a “bottleneck” closed-loop in the hydrogen energy industry chain. Only by accurately solving the core pain points of each link, promoting the collaborative

iteration of technology and the improvement of the industrial ecosystem, can we accelerate the transformation of hydrogen energy from demonstration application to large-scale popularization.

Despite the wealth of hydrogen-related review studies, most researchers primarily focus on independent technical progress or individual segment optimization while neglecting systematic analysis of value chain coupling mechanisms across hydrogen production, storage, transportation, and application. In particular, comprehensive interpretation of the interactive constraints, synergistic relationships, and chain-wide bottleneck coupling effects remains insufficient. Furthermore, reviews lack a unified evaluation framework for horizontal comparison of technology readiness levels (TRLs) among mainstream hydrogen technical pathways, making it difficult to quantitatively distinguish the maturity, application potential, and commercialization barriers of technologies.

Against this background, in this review, we provide distinct value addition compared with other studies. We not only systematically sort out the technical status and problems of each node in the hydrogen industry chain, but also further focus on the coupling coordination characteristics and chain-wide restrictive mechanisms of the hydrogen energy value chain. Moreover, we conduct a targeted cross-technology comparison of TRLs for key hydrogen technologies, clarifying the technical gaps and development priorities of different pathways. This chain-coupling-oriented and TRL-comparison-based analytical framework can provide more targeted references for subsequent technological iteration and industrial layout optimization.

2. Review methodology

In this narrative review, we investigated technical advances and industrial bottlenecks throughout the hydrogen-energy value-chain, encompassing hydrogen production, storage-transportation, and end-use applications, with particular emphasis on TRL evaluation and cross-segment coupling mechanisms [8,12]. Relevant literature was retrieved from Web of Science, Scopus, and ScienceDirect, complemented by Chinese-language sources from the CNKI database, publicly accessible authoritative reports released by the IEA, U.S. DOE, and the European Commission. Publications published between 2015 and 2026 were prioritized, alongside seminal foundational studies. Boolean operators were utilized to combine search keywords covering hydrogen-related technologies and industrial-scale constraints [13,14].

Quantitative performance indicators were extracted to facilitate comparative analysis among alternative technical pathways (Tables 1–3). No meta-analysis or harmonized life-cycle assessment was performed in this work. Given divergent boundary assumptions across primary studies, cross-technology comparisons should be interpreted prudently. Cross-cutting bottlenecks restricting industrial deployment were synthesized, based on which practical implications, inherent review limitations, and prospective development pathways were elaborated. Potential selection bias introduced by subjective literature filtering is discussed in the Limitations section.

3. Hydrogen production

Hydrogen production is a key strategic link in the upstream of the hydrogen energy industry chain. Its clean and large-scale development is a prerequisite for promoting the penetration of hydrogen energy from industrial raw materials into diverse scenarios such as transportation and energy storage and is an important technical support for achieving the “dual carbon” goal. Furthermore, the primary methods for hydrogen production include fossil-based hydrogen production, hydrogen from industrial

by-product, water electrolysis, and photocatalytic water splitting.

3.1. Fossil-based hydrogen production

Hydrogen production from fossil fuels is the most mainstream hydrogen production technology path globally due to its mature technology and low hydrogen production cost. The commonly used fossil energies for hydrogen production mainly include coal, natural gas, petroleum, methanol, etc. Among them, coal and natural gas hydrogen production are the main methods of fossil energy hydrogen production [16]. However, fossil fuels are non-renewable fossil resources and a large amount of carbon dioxide is generated during hydrogen production. For example, the carbon emission per unit of hydrogen production from coal and natural gas reforming can reach 17.8–21.6 kg CO₂/kg H₂ and 8.9–9.8 kg CO₂/kg H₂, respectively [13], which does not meet the requirements of low-carbon transformation and development, and has difficulty in meeting long-term emission reduction targets. Based on lifecycle-emission considerations, fossil-fuel-based hydrogen can be classified into grey hydrogen, blue hydrogen, turquoise hydrogen, and other low-carbon pathways. The blue hydrogen route coupled with carbon capture, utilization, and storage (CCUS) technology can greatly reduce carbon emissions, and it is the core path for low-carbon transformation of fossil hydrogen production. However, it has problems such as high equipment investment, high operation and maintenance cost, and limited carbon capture efficiency, and there are bottlenecks in large-scale applications.

3.1.1. Hydrogen production from coal

Coal is one of the fossil energies with the largest reserves, and coal-to-hydrogen is a widely used and relatively mature method for hydrogen production. The coal-to-hydrogen process includes two steps: coal gasification and gas purification. Coal gasification refers to the process of converting coal into gas under high temperature and high pressure conditions [17]. The reactions occurring during coal gasification are:

Gasification reaction: $C + H_2O \rightleftharpoons CO + H_2$, $2C + O_2 \rightleftharpoons 2CO$

Water-gas shift reaction: $CO + H_2O(g) \rightleftharpoons CO_2 + H_2$

In addition to H₂, coal gasification also includes CO₂, CO, and CH₄. High-purity hydrogen needs to be obtained through gas purification. The coal gas purification process is to purify hydrogen from the mixed gas through CO conversion, acid gas removal, and pressure swing adsorption (PSA) processes [18]. The process route of coal-to-hydrogen is shown in Figure 1.

Improving the utilization efficiency of coal and reducing environmental pollution during hydrogen production are still research topics. Moreover, the absorption-enhanced water gas shift technology [18] integrated with CCUS technology and coal supercritical water gasification technology [19,20] have attracted much attention and will be the key research directions for coal-to-hydrogen technology.

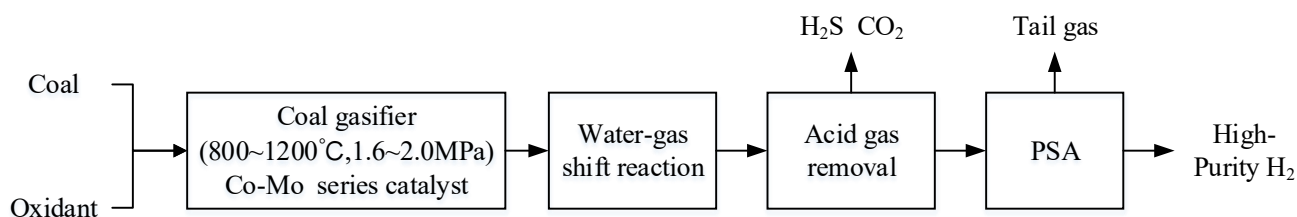


Figure 1. Schematic diagram of the hydrogen-production processes from coal.

3.1.2. Hydrogen production from natural gas

The main component of natural gas is methane (CH₄). Methane is a hydrocarbon with the highest hydrogen element ratio. The steam methane reforming (SMR) hydrogen production technology is the most mature and widely used technology in natural gas hydrogen production. It is used to prepare hydrogen by reforming methane with steam under high temperature and the action of a catalyst [21,22]. The main reactions occurring during hydrogen production are:

Reforming reaction: $\text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3\text{H}_2$

Water-Gas shift reaction: $\text{CO} + \text{H}_2\text{O(g)} \rightleftharpoons \text{CO}_2 + \text{H}_2$

The SMR hydrogen production technology includes: natural gas desulfurization and purification, high-temperature reforming and conversion of methane and steam to produce syngas of CO and H₂, CO and steam forming a mixture of CO₂ and H₂ through the water gas shift reaction, and preparing high-purity hydrogen through pressure swing adsorption technology. The flow chart of natural gas reforming hydrogen production is shown in Figure 2 [12].

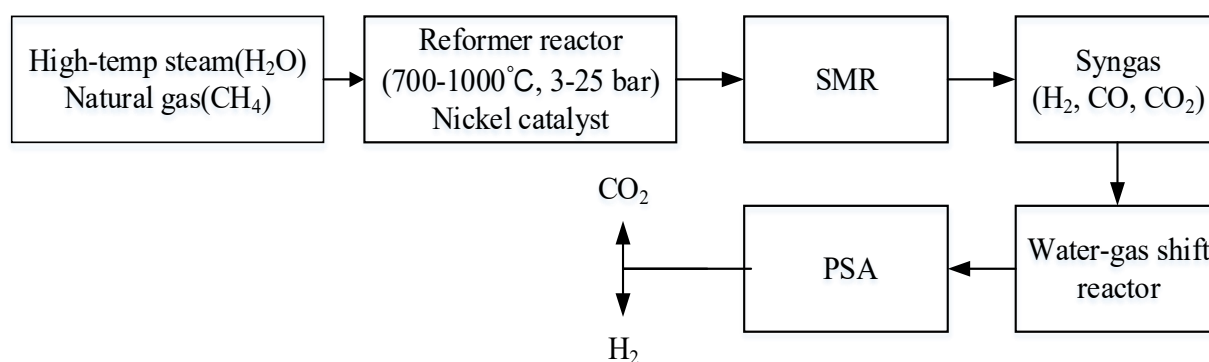
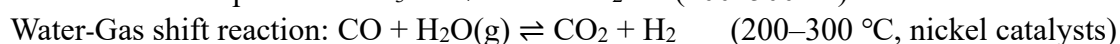


Figure 2. Workflow of natural gas-to-hydrogen production.

Similar to hydrogen production from coal, hydrogen produced via methane reforming is also classified as grey hydrogen. The research directions mainly focus on the deep integration of CCUS technology, electrocatalytic methane reforming technology, and natural gas high-temperature cracking hydrogen production technology [23] to achieve the transformation from gray hydrogen to blue hydrogen. In addition, the research and development of high-performance catalyst technology play a key role in reducing reaction energy consumption [22].

3.1.3. Hydrogen production from methanol decomposition

Hydrogen production from methanol decomposition has the advantages of easy storage of raw materials, low reaction temperature (400–500 °C, 1.0–5.0 MPa), and easy separation of hydrogen, showing great application potential [19]. In methane decomposition, carbon is produced in the form of solid carbon black. The resulting carbon emissions lie between those of grey hydrogen and blue hydrogen, which is why this route is termed turquoise hydrogen. The methanol reforming method is the most widely used methanol-to-hydrogen method, which is a method of preparing hydrogen by chemically reacting methanol and steam under the action of a catalyst [24]. Commonly employed catalysts are selected from copper-based, nickel-based, or molybdenum-based systems. Generally, it is considered to include two processes: methanol decomposition and water gas shift reaction [25]. The main reaction equations are:



The catalyst is the core technology of the methanol reforming hydrogen production process [26]. Developing new and efficient catalysts is the technical core to improve methanol conversion and efficient utilization and is the current research focus of methanol-to-hydrogen.

3.1.4. Hydrogen production from petroleum

Petroleum-to-hydrogen is the by-product of petroleum cracking (such as naphtha, heavy oil, petroleum coke) to produce hydrogen through high-temperature cracking reactions [21]. The petroleum by-products form syngas (mainly hydrogen and carbon monoxide) after high-temperature cracking. The syngas reacts with steam under the action of a catalyst to form hydrogen and carbon monoxide, and then through water gas shift and purification processes, high-purity hydrogen is obtained.

3.2. Hydrogen production from industrial by-products

Hydrogen production from industrial by-products refers to the technology of separating and purifying hydrogen from hydrogen-rich gases generated during industrial production processes [27]. Compared with fossil fuel hydrogen production, it has the advantages of shorter process, lower energy consumption, and lower incremental carbon emission, which can effectively utilize resources, and plays an important role in promoting the sustainable development of industrial production [28]. However, its production capacity is dependent on the original industrial production load, with uncontrollable output and insufficient gas source stability. Along with the upgrading and iteration of traditional high energy-consuming industries, its long-term production capacity has weak sustainability, so it is suitable for only regional and phased hydrogen supplementary applications. Hydrogen production from industrial by-products generally uses pressure swing adsorption gas separation technology, temperature swing adsorption gas separation technology, or membrane separation technology [29] to separate hydrogen from industrial by-products to achieve hydrogen production. Figure 3 is a typical process flow chart of recovering hydrogen from coke oven gas.

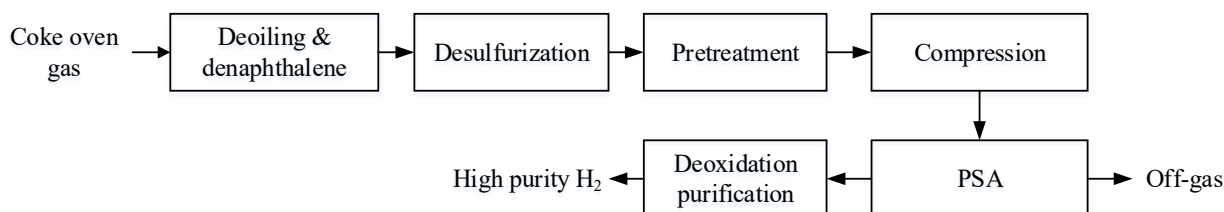


Figure 3. Typical process flow chart of recovering hydrogen from coke oven gas [27].

3.3. Hydrogen production from water electrolysis

Hydrogen production from water electrolysis is an important way to achieve green and sustainable hydrogen production. Hydrogen generated from water electrolysis with nearly zero CO₂ emissions is referred to as green hydrogen. Water electrolysis hydrogen production mainly depends on electrolyzers. According to the operating mechanism of electrolyzers, it can be divided into: alkaline water electrolysis (AWE), proton exchange membrane water electrolytic (PEMWE), solid oxide electrolysis cell (SOEC), and anion-exchange membrane water electrolysis (AEMWE) [30]. AWE features mature commercialization, low capital cost, and long service life, which is suitable for large-scale hydrogen production under stable power conditions, while it suffers from slow dynamic response and poor adaptability to fluctuating renewable energy. PEMWE electrolysis possesses fast response, high current density, and high hydrogen purity, making it highly compatible with intermittent wind and photovoltaic power, though it relies on precious metal catalysts with high equipment cost. AEMWE electrolysis combines the low-cost advantage of alkaline systems and the compact structure of membrane electrolysis without precious metal catalysts, showing great development potential, but it is limited by insufficient membrane stability and is in the demonstration and research stage. SOEC can achieve ultra-high electrolysis efficiency by coupling industrial waste heat with low energy consumption, which is applicable to industrial scenarios with high-temperature heat sources, whereas it has poor start-stop performance, complex system configuration, and the lowest commercial maturity.

The performance characteristics of the four electrolytic water hydrogen production technologies are shown in Table 1.

Table 1. Main characters of hydrogen production technologies by water electrolysis [14].

Technical Characteristics	AWE	PEMWE	SOEC	AEM
Diaphragm Material	Asbestos cloth	Proton-exchange membrane	—	Anion-exchange membrane
Electrolyte	5–7mol/L KOH	Pure water	Solid oxide	1mol/L KOH/ Pure water
Operating temperature/°C	70–90	70–80	600–1000	65–85
Hydrogen-production efficiency/%	60–75	70–90	85–100	60–90
Current density/(A/cm ²)	0.2–0.4	1–2	1–10	0.8–2.2
DC power consumption (kWh/Nm ³)	4.5–5.5	3.8–5.0	2.6–3.6	4.2–4.6
Technology readiness level	TRL 9	TRL6–8	TRL 5	TRL 2–3

3.3.1. Alkaline water electrolysis (AWE)

The AWE working principle is shown in Figure 4. Using an aqueous solution of KOH or NaOH as the electrolyte, under the action of direct current, a hydrogen evolution reaction occurs at the cathode, and an oxygen evolution reaction occurs at the anode. The chemical reactions occurring during electrolysis are:

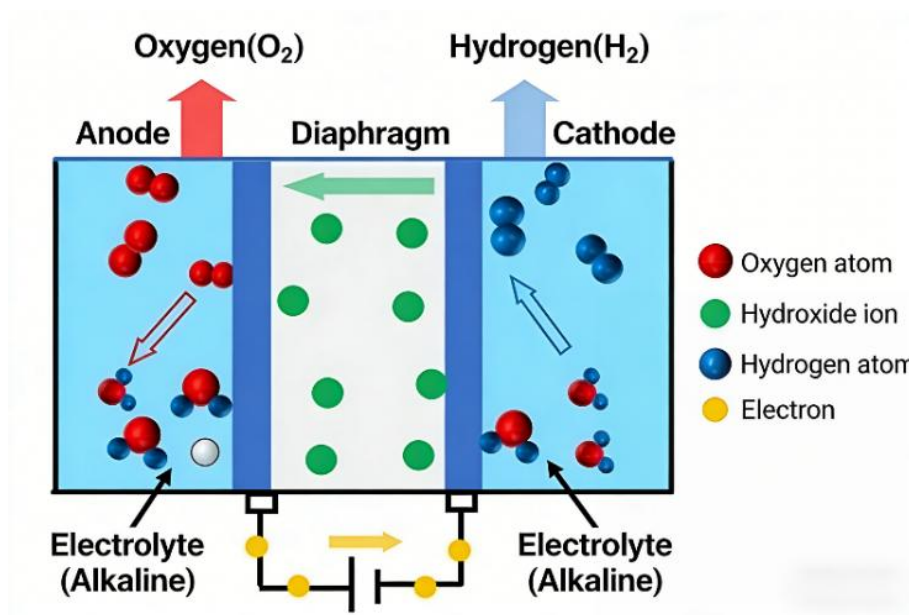
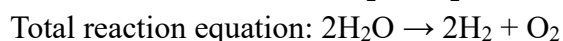


Figure 4. Principle structure diagram of AWE hydrogen production [31].

The conversion efficiency of AWE is generally about 70%. Improving the electrolysis conversion efficiency is the key to reducing hydrogen production costs [32]. The research core is to develop efficient and stable inexpensive metal catalytic materials. Demnitz et al. [33] studied the effect of adding iron to the electrolyte on the electrolysis efficiency. The research results showed that iron can simultaneously promote the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) by lowering both overpotentials by at least 100 mV at high current densities. As the iron ion concentration increases, the Tafel slope gradually decreases in the low current density range ($0.5\text{--}20\text{ mA}\cdot\text{cm}^{-2}$), and the catalytic activity is improved. Wang et al. [34] studied the effect of Ce-doped Ni-based catalysts on AWE hydrogen production. The research results showed that the electrocatalyst is synthesized with highly dispersed cerium in a nickel matrix, showing an overpotential of 169 mV for HER at a current density of $500\text{ mA}\cdot\text{cm}^{-2}$, about 137 mV lower than that observed without cerium. Jia et al. [35] developed a $\text{Ru}/\text{Ti}_3\text{C}_2\text{O}_x@\text{NF}$ electrocatalyst that was fabricated by electrodepositing ultra-low (0.54 wt%) Ru nanoclusters onto $\text{Ti}_3\text{C}_2\text{O}_x$ MXene nanosheets deposited on nickel foam. The electrocatalyst demonstrates excellent bifunctional activity and operational stability under constant current conditions. Ashfaq et al. [36] fabricated $\text{Cr}_2\text{S}_3\text{-Fe}_2\text{S}_3$ composite nanosheets via a hydrothermal method. The results revealed that the as-prepared material exhibited outstanding oxygen evolution reaction (OER) performance, with an overpotential (η) of 290 mV and a Tafel slope of 39 mV/dec. It can operate

steadily for more than 40 h at a current density of $10 \text{ mA}\cdot\text{cm}^{-2}$, and no degradation in catalytic activity has been observed after 3000 cyclic voltammetry (CV) cycles, demonstrating its excellent long-term durability. Alqarni et al. [37] fabricated $\text{CoTiO}_3/\text{rGO}$ nanocomposite catalyst via a hydrothermal route. The catalyst exhibits superior electrocatalytic activity, achieving a low overpotential (η) of 185 mV and a Tafel slope of 35 mV/dec at $10 \text{ mA}/\text{cm}^2$, while maintaining stable operation up to 38 h. Majeed, et al. [38] fabricated a novel CuO/PANI nanocomposite that exhibits significantly enhanced OER electrocatalytic performance and durability, achieving a low overpotential (η) of 209 mV and a Tafel slope of 36 mV/dec at $10 \text{ mA}\cdot\text{cm}^{-2}$ current density (Cd) with excellent stability over 40 h.

3.3.2. Proton exchange membrane water electrolysis (PEMWE)

The working principle of PEMWE is shown in Figure 5. Using a solid polymer electrolyte as a conductor, under the action of a direct current electric field, an oxidation reaction occurs at the anode to form O_2 and H^+ , and H^+ transfers through the proton exchange membrane to the cathode to undergo a reduction reaction to form H_2 . The efficiency of PEMWE can reach over 85%, and it is considered one of the most promising water electrolysis hydrogen production technologies [40]. However, due to the strong acidic environment at the anode, the electrocatalysts of PEMWE electrolyzers mainly use precious metals such as Ir and Ru, which greatly increases the cost of PEMWE hydrogen production. Developing non-precious metal catalysts to reduce the cost of PEMWE hydrogen production is one of the current research hotspots. Chong et al. [41] studied a nanofiber cobalt spinel catalyst doped with La and Mn. Yang et al. [42] deposited Co_3O_4 nanowire arrays on carbon paper to study their catalytic effect on water electrolysis, Li et al. [43] studied the catalytic effect of $\gamma\text{-MnO}_2$ on water electrolysis hydrogen production, and Liu et al. [44] prepared bulk-phase S-doped Ni_3Se_4 and bulk-phase Se-doped Ni_3S_2 catalysts.

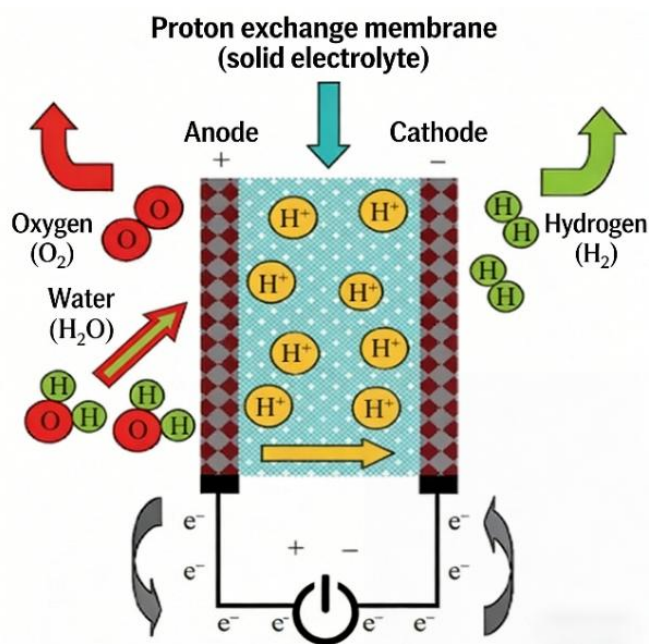


Figure 5. Schematic diagram of the principle structure of PEMWE for hydrogen production [39].

3.3.3. Solid oxide electrolysis cell (SOEC)

SOEC uses solid oxide as the electrolyte and electrolyzes water vapor at high temperature and under an applied voltage to produce hydrogen [45]. It has the advantages of high energy conversion efficiency (over 90%), no use of precious metal catalysts, and can utilize industrial waste heat, etc. It is one of the very promising green hydrogen production technologies. However, due to working at high temperatures, the service life of the electrode and electrolyte materials will be greatly reduced. Developing high-temperature-resistant electrode and electrolyte materials is the research focus of this technology [21]. Yttria-stabilized zirconia-based electrolytes [46], cerium-based electrolytes [47], barium zirconate/barium cerate-based solid solution electrolytes [48], perovskite-based material electrodes [49], etc. have become the key research objects for solving the problem of high-temperature failure of materials and improving the long-term operation reliability of electrolytic cells due to their excellent high-temperature tolerance and comprehensive electrochemical performance.

3.3.4. Anion exchange membrane water electrolysis (AEMWE)

The diaphragm in AEMWE uses a solid polymer anion exchange membrane, and non-precious metals such as Fe, Ni, and Co are used as electrode catalysts, which have higher conversion efficiency [45] and lower cost. However, the AEMWE technology is in the laboratory research stage and has not been commercially applied on a large scale.

3.4. Hydrogen production from biomass

Hydrogen production from biomass is a technology that uses agricultural waste and municipal waste as raw materials and converts biomass into hydrogen through biological or thermochemical methods. Due to the characteristics of clean, environmental protection, and renewable of hydrogen production from biomass, it has become a research hotspot for green hydrogen production in recent years [50].

Biological hydrogen production is a process of converting biomass into hydrogen through microbial metabolism, including: dark fermentation hydrogen production, photofermentation hydrogen production, and photolysis of water hydrogen production. Dark fermentation hydrogen production entails using anaerobic bacteria to decompose organic matter to produce hydrogen under lightless conditions. This technology has simple process and low energy consumption, but there are technical challenges in aspects such as strain cultivation and waste liquid treatment [21]. Photofermentation hydrogen production is a technology that uses photosynthetic bacteria to convert organic matter into hydrogen under light and anaerobic conditions. This technology has higher hydrogen production efficiency than dark fermentation bacteria and better cleanliness, and is an important direction for the future development of biological hydrogen production technology. Moreover, the research hotspots of photofermentation hydrogen production focus on the screening of high-efficiency hydrogen-producing strains, the optimization of hydrogen production conditions, etc. [51]. Photolysis of water hydrogen production is a process in which green algae and cyanobacteria directly split water into hydrogen and oxygen under anaerobic light conditions [21]. No CO₂ is generated during hydrogen production, but the O₂ produced during the hydrolysis process has an inhibitory effect on the hydrogenase in biological photolysis, seriously reducing the hydrogen production efficiency [52].

Thermochemical hydrogen production refers to the process of decomposing and reforming biomass under high temperature or high pressure conditions to obtain hydrogen-rich gas [14]. This

includes steam gasification hydrogen production, supercritical water gasification hydrogen production, and pyrolysis reforming hydrogen production. Biomass steam gasification hydrogen production uses steam as the gasifying agent to gasify biomass into hydrogen-rich gas and then obtains high-purity hydrogen through the water gas shift reaction and gas separation technology. The research hotspots of steam gasification hydrogen production technology focus on the development of high-efficiency anti-coking catalysts and the high-efficiency removal and conversion technology of tar and other core fields, aiming to break through the technical bottleneck of “high cost-low efficiency-weak stability” [53,54]. Biomass supercritical water gasification hydrogen production is a process in which biomass undergoes catalytic cracking reaction in supercritical water to obtain hydrogen-rich gas, which has the advantages of high conversion rate and no tar formation, and is a green hydrogen production path with great potential under the background of carbon neutrality [55]. The research hotspots of supercritical water gasification hydrogen production technology focus on the development of high-efficiency anti-deactivation catalysts [56], process optimization, and intensification technology [57]. Biomass pyrolysis reforming hydrogen production is a process of converting biomass into high-purity hydrogen through pyrolysis and catalytic reforming processes in an oxygen-free environment. The hydrogen production by this method has the characteristics of controllable tar and high hydrogen selectivity, and is one of the important ways to produce green hydrogen. The main research hotspots are to develop high-efficiency anti-coking catalysts to improve the carbon conversion efficiency and hydrogen production efficiency [58].

3.5. Photocatalytic water splitting for hydrogen production

Photocatalytic decomposition of water for hydrogen production is to directly decompose water into hydrogen and oxygen under sunlight irradiation through a semiconductor photocatalyst [59]. When the energy of the photons absorbed by the photocatalyst exceeds its band gap width, the electrons (e^-) on its valence band will be excited and jump to the conduction band, and at the same time, positively charged holes will be left on its valence band. The excited electrons and holes migrate to the surface of the catalyst and react with water molecules. The electrons on the conduction band reduce the hydrogen in water to produce hydrogen, and the holes on the valence band oxidize water molecules to produce oxygen [60]. Photocatalytic decomposition of water is an ideal method for hydrogen production. At present, it is in the laboratory research stage. The research and development of low-cost and high-activity semiconductor catalysts are the keys to promoting the practical application of photocatalytic water splitting hydrogen production technology [21].

The comparison of energy efficiency and production cost for different hydrogen-production pathways are depicted in Table 2.

Table 2. Comparison of energy efficiency and production cost for different hydrogen-production pathways.

Hydrogen type	Technology route	Energy efficiency	Production cost (USD/kg H ₂)	CO ₂ emission intensity (kg-CO ₂ /kg-H ₂)	Technology readiness level
Grey hydrogen	Coal gasification	60–70%	1.5–2.3	9–12	TRL 9
Grey hydrogen	SMR	70–75%	2.1–2.7	8–11	TRL 9
Blue hydrogen	Coal gasification + CCUS	52–62%	2.4–3.3	1–4	TRL 7
Blue hydrogen	SMR + CCUS	62–68%	2.7–3.7	1–3	TRL 7
Green hydrogen	Renewable power	Electrolysis: 65–75%; Whole chain: 35–55%	1.3–4.8	0–0.5	TRL 4–5

4. Storage and transportation

Hydrogen storage and transportation is a key link in the hydrogen energy industry chain. Safe and economical storage and transportation technologies are crucial for the development of hydrogen energy [61]. The main methods of hydrogen storage and transportation are high-pressure gaseous hydrogen storage, liquid hydrogen storage, and solid-state hydrogen storage. High-pressure gaseous hydrogen storage has the advantages of the most mature technology, fast hydrogen charging and discharging, and low equipment cost, and it is the main hydrogen storage method for fuel cell vehicles and hydrogen refueling stations. However, the hydrogen storage density of high-pressure gaseous hydrogen storage is only 1–6 wt%, the hydrogen storage capacity is greatly affected by pressure and the material of the hydrogen storage cylinder, and there are potential safety hazards such as leakage and explosion, putting extremely high requirements on the manufacturing process and safety of the container. The cryogenic liquid hydrogen storage density is 5–8 wt%, which is the method with the highest volumetric energy density among hydrogen storage technologies, and is suitable for large-scale and long-distance hydrogen transportation. However, cryogenic liquid hydrogen storage has high technical thresholds, and the liquefaction process consumes much energy, resulting in relatively high hydrogen storage costs. In addition, the cryogenic temperature environment imposes extremely high requirements on storage tank materials and sealing technologies, and problems such as low-temperature embrittlement, evaporation, and leakage are prone to occur, making safety prevention and control difficult. Moreover, this is mainly limited to aerospace, ocean transportation, and other fields. Solid-state hydrogen storage has become a core solution for safe hydrogen storage due to its advantages such as high volumetric energy density, storage at room temperature and low pressure, and low risks of leakage and explosion. However, the adsorption and release rate of hydrogen is relatively slow, which makes it difficult to meet the requirements of high-frequency and rapid charging and discharging scenarios such as vehicle-mounted hydrogen storage. Furthermore, technical problems, including material cost, hydrogen absorption and desorption kinetics performance, and cycling stability, need to be overcome [62].

The comparisons of different hydrogen storage technologies are depicted in Table 3 [12,63].

Table 3. Comparison of different hydrogen storage technologies

Hydrogen storage method	Volumetric Density kg/m ³	Gravimetric densities wt%	Safety	Maturity (TRL)	Cost USD/kg H ²	Use case
Compressed gas	25–40	1–6	Potential safety hazards including hydrogen leakage and deflagration	TRL 7–9	0.6	Fuel cell vehicles, hydrogen refueling stations
Liquid hydrogen	40–60	5–8	Safety challenges arise from hydrogen boil-off, cryogenic embrittlement, insulation failure and complex operational requirements	TRL 7–8	4.87	Aerospace, ocean transportation
LOHC	55–64	5–7.5	Excellent safety performance under ambient-temperature storage and transport	TRL 5–7	5.2	Large-scale, long-distance storage and transportation
Solid-state hydrogen storage	50–110	1.5–7.6	High inherent safety; hydrogen is chemically-bonded with low-pressure operation	TRL 4–5	—	Distributed energy storage, special equipment

*Note: United States Department of Energy (DOE) targets: the mass hydrogen storage density reaches 7.5 wt% and the volume hydrogen storage density reaches 40 g/L [64].

4.1. High-pressure gaseous hydrogen storage and transportation

Gaseous hydrogen storage and transportation are the most mature and the widely applied hydrogen storage-transportation technologies. Usually, gaseous hydrogen is compressed and stored in a hydrogen storage tank, and the hydrogen is transported through a tube trailer or a hydrogen pipeline. The hydrogen storage capacity of the hydrogen storage tank is proportional to the pressurization pressure and depends on the pressure resistance of the hydrogen storage tank. As the pressure increases, the safety of hydrogen storage decreases. The technologies of type I 20 MPa pure steel metal tank, type II 45 MPa steel inner liner fiber-wound tank, type III 35 MPa and 70 MPa aluminum inner liner fiber-wound tank, etc. are relatively mature and have been industrialized. However, the hydrogen storage density has not reached the research and development goals of on-vehicle hydrogen storage technology proposed by DOE. Improving the hydrogen storage density, light weight, and ultra-high pressure are the development directions of hydrogen storage cylinders. Foreign car companies such as Toyota in Japan have applied type IV 70MPa plastic inner liner fiber-wound hydrogen storage tanks (Figure 6) to commercial fuel cell vehicles [65], and improve the pressure resistance of the metal inner liner using methods such as metal-based composite materials, high-entropy alloys, alloying, etc. [66].

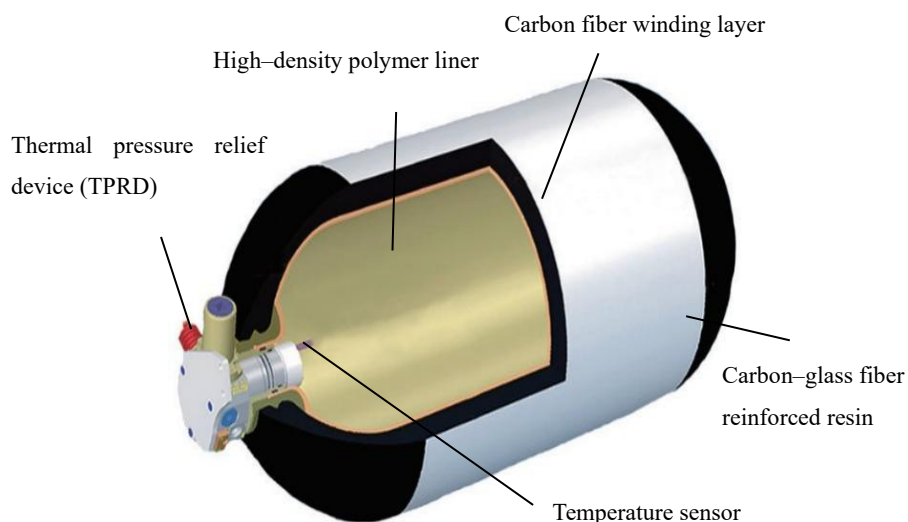


Figure 6. Structure diagram of type IV light high-pressure gaseous hydrogen storage tank [65].

4.2. Liquid hydrogen storage and transportation

The liquid hydrogen storage and transportation includes two categories: cryogenic liquid hydrogen storage and transportation technology and liquid organic hydrogen carrier (LOHC) technology.

4.2.1. Cryogenic liquid hydrogen storage and transportation

The liquid hydrogen storage technology compresses hydrogen and cools it below 20 K, then stores the liquefied hydrogen in an adiabatic container. Compared with gaseous hydrogen storage, the density of liquid storage is greatly increased. However, due to the large temperature difference between liquid hydrogen and the ambient temperature, on the one hand, liquefying hydrogen requires huge energy consumption, and the low-temperature resistance and adiabatic performance requirements for hydrogen storage containers are very strict, which increases the cost of hydrogen storage tanks and leads to a significant increase in hydrogen storage cost; on the other hand, there are risks in evaporation leakage, low-temperature embrittlement of hydrogen storage tanks, and heat insulation failure and operation, and safety issues are very challenging. Moreover, reducing the liquefaction energy consumption, improving the adiabaticity, and low-temperature resistance of the hydrogen storage tank are the key research directions of liquid hydrogen storage. In the design of the storage tank structure, the variable-density multi-layer vacuum adiabatic technology and the active adiabatic refrigerator equipment achieve high adiabaticity and low loss [61]. Commonly used materials for cryogenic hydrogen storage tanks include stainless steel, aluminum alloy, titanium alloy, and cryogenic composite materials. The National Aeronautics and Space Administration of the United States developed the CYCOM 5320-1/IM7 composite material for liquid hydrogen storage tanks, reducing the weight of the hydrogen storage tank by 30% and the cost by 20% [67].

4.2.2. Liquid organic hydrogen carrier (LOHC)

LOHC technology uses the reversible hydrogenation and dehydrogenation reactions between unsaturated liquid organic carriers and hydrogen to achieve the storage and release of hydrogen [65].

LOHC has attracted much attention due to its characteristics such as high hydrogen storage density, good safety, and recyclable medium [64]. Commonly used LOHC materials mainly include olefins, alkynes, and aromatics [61]. Moreover, the main problems of LOHC are high dehydrogenation temperature, large energy consumption, and low efficiency, which have not met the application requirements [64]. The key to this technology is to improve the dehydrogenation rate of the LOHC medium and the reaction performance of the catalyst [65]. Pez et al. [68] doped nitrogen atoms in the aromatic ring, significantly reducing the dehydrogenation reaction enthalpy; Zhu et al. [69] introduced electron-donating or conjugated substituents on the piperidine ring, reducing the dehydrogenation enthalpy of the hydrogen storage medium; and Wang et al. [70] prepared a bimetallic Pd-Cu alloy catalyst supported on reduced graphene oxide (rGO), making the dehydrogenation product selectivity of dodecahydro-N-ethylcarbazole reach 100%.

4.3. Solid-state hydrogen storage and transportation

Solid-state hydrogen storage utilizes solid materials to adsorb and desorb hydrogen for hydrogen storage and release. Because solid hydrogen storage has a high hydrogen storage density and high safety, it is regarded as one of the most promising hydrogen storage methods and has attracted much attention from scholars at home and abroad [64]. According to different adsorption properties, it can be divided into physical adsorption hydrogen storage and chemical adsorption hydrogen storage.

4.3.1. Physical adsorption hydrogen storage

Physical adsorption hydrogen storage refers to the process where solid materials fix hydrogen molecules on the surface of the adsorbent through physical adsorption. The solid adsorbent and hydrogen molecules are combined by van der Waals forces without involving the formation of chemical bonds. Porous materials such as porous carbon materials, metal-organic framework (MOF) materials, and covalent organic framework (COF) materials are the research hotspots of physical adsorption hydrogen storage materials [71].

Carbon materials generally have characteristics such as a high specific surface area, rich pore structure, low density, and strong chemical stability, becoming a research hotspot in the hydrogen storage field. The main hydrogen storage materials of carbon materials include activated carbon, carbon nanotubes, carbon nanofibers, graphene, mesoporous carbon, and carbon aerogels [72]. However, since carbon materials and hydrogen are combined by van der Waals forces, the interaction force is relatively weak, and the hydrogen storage density at room temperature is relatively low. A large amount of adsorption can be achieved only under relatively high pressure conditions and very low temperatures. Increasing the specific surface area and improving the hydrogen surface adsorption ability are the key factors to improve the hydrogen storage performance of carbon materials [73]. Liang et al. [74] significantly improved the hydrogen storage performance by regulating the distribution of active sites in carbon nanotubes. Brahmananda et al. [75] achieved a mass hydrogen storage density of 13.1% after doping Ti atoms in ψ -graphene. Ma et al. [76] pointed out that the presence of oxygen-containing functional groups ($-\text{COOH}$, $\text{C}-\text{OH}$, and $\text{C}-\text{O}$) contributes greatly to improving the hydrogen adsorption ability.

MOF and COF are three-dimensional porous framework materials that have rapidly emerged. They have an extremely high specific surface area and porosity, and the pore size and functional groups can be precisely regulated, becoming an important research direction in the field of solid hydrogen

storage [73]. MOF and COF are also combined with hydrogen by van der Waals forces, and the interaction force is weak. Generally, they can exhibit only good hydrogen storage performance at extremely low temperatures and have poor hydrogen storage performance at room temperature [77]. Wang [78] investigated the hydrogen storage performance and influencing factors of Zr-based MOFs materials. The research demonstrated that the introduction of $-\text{CN}$, $-\text{Br}$ functional groups, and metal Li ions could significantly enhance the adsorption capacity. Yu [79] synthesized several excellent 3D COF materials and studied their hydrogen storage performance. Vasanthakannan et al. [80] explored the hydrogen storage mechanism, capacity, and kinetic characteristics of scandium atom-modified azatriphenylene-based COF.

4.3.2. Chemical adsorption hydrogen storage

Chemical adsorption hydrogen storage is a technology that utilizes the reversible chemical reaction between hydrogen and carrier materials to achieve hydrogen storage. Hydrogen molecules dissociate into hydrogen atoms at the active sites on the surface of the carrier material. The hydrogen atoms diffuse into the interior of the material lattice and chemically react with the carrier to form hydrides bonded by chemical bonds, achieving hydrogen storage; when hydrogen is needed, by heating the hydride, the chemical bond between the hydrogen atoms and the carrier material is broken, releasing hydrogen [66]. It has significant advantages in terms of volumetric hydrogen storage density and room temperature stability and is one of the key technical paths to solve the safe and efficient storage and transportation of hydrogen energy [81]. Moreover, the chemical adsorption hydrogen storage materials studied more include metal hydrides and coordination hydrides.

Metal hydride hydrogen storage is the process where metals and hydrogen react chemically under certain conditions to form metal hydrides for hydrogen storage, mainly including rare earth-based alloys, magnesium-based alloys, titanium-based alloys, vanadium-based alloys, and zirconium-based alloys [61]. Metal hydride hydrogen storage has characteristics such as a high volumetric hydrogen storage density, high storage and transportation safety, good reversibility, and high purity, and has attracted much attention from scientific researchers. However, metal hydrides have high stability, and a large amount of thermal energy needs to be absorbed for dehydrogenation to occur, resulting in a high dehydrogenation temperature [82]. Moreover, in improving the hydrogen storage performance of metal hydrides, the commonly used methods are nanosizing, alloying, and adding catalysts. Ismail [83] studied the influence of different contents of HfCl_4 catalysts on the hydrogen storage performance of MgH_2 . Yu et al. [84] prepared a $\text{Mg}_{80}\text{Ni}_{15}\text{Y}_5$ ternary alloy by vacuum induction melting and studied the influence of Ni and Y doping on the hydrogen storage performance of magnesium-based alloys. Zhang et al. [85] prepared 3–5 nm unrestricted ultrafine MgH_2 nanocrystals by low-temperature plasma-assisted ball milling and achieved reversible hydrogen storage of 6.7 wt% at room temperature. Shahreaz et al. [86] examined the hydrogen storage properties of the rare-earth-based perovskite hydrides XLiH_3 ($\text{X} = \text{Tm}, \text{Yb}$) by first-principles density functional theory (DFT). Thermodynamic stability is evidenced by the negative formation energies of -0.489 and -0.456 eV/atom for TmLiH_3 and YbLiH_3 , respectively. The evaluation of hydrogen storage reveals gravimetric capacities of 1.69 wt.% for TmLiH_3 and 1.65 wt.% for YbLiH_3 , with substantial volumetric capacities of 107 and 107.1 g H_2/L and suitable desorption temperatures of 381.36 and 336.69 K. Wang et al. [87] fabricated a hydrogen-storage composite material in which Co-MOF-74 was used as the carrier, with finely-distributed MgH_2 nanoparticles anchored on its exterior. Within 30 min, the hydrogen absorption capacities of the composite reached 6.6 and 5.2 wt% at 350 °C and 250 °C, respectively, while the corresponding

hydrogen desorption capacities were 6 and 4.4 wt%, respectively. Furthermore, the MgH_2 -Co-MOF-74 composite exhibited outstanding cycling stability. Cao et al. [88] fabricated a multiphase Ti-Fe composite catalyst with multiple Ti/Fe valence states via tube-furnace sintering and investigated its catalytic performance and underlying mechanism toward MgH_2 . After doping with 15 wt% Ti-Fe catalyst, the initial dehydrogenation temperature of MgH_2 was reduced from 309 °C to 199 °C, and the dehydrogenation activation energy decreased from $142.41 \text{ kJ}\cdot\text{mol}^{-1}$ to $120 \text{ kJ}\cdot\text{mol}^{-1}$. Moreover, its hydrogen-storage capacity was maintained above 5.0 wt%. The results demonstrate that the multiphase Ti-Fe catalyst can significantly optimize the hydrogen-storage performance of MgH_2 .

Coordination hydrides are ionic compounds composed of metal cations (Li^+ , Na^+ , Mg^{2+}) and hydrogen-containing composite anions (such as BH_4^- , AlH_4^- , NH_2^-), and hydrogen storage is achieved through the covalent bond between hydrogen and the central atom (B, Al, N) of the anion. It has an extremely high theoretical hydrogen storage capacity and is regarded as one of the most promising solid-state hydrogen storage materials. However, coordination hydrides have problems such as high dehydrogenation temperature, poor kinetic performance, and poor reversibility, which hinder their practical applications [64]. In recent years, scientific researchers have made significant progress in improving the hydrogen storage performance of coordination hydrides through strategies such as catalytic doping, nanosizing, and composite system construction. Chen et al. [89] designed and synthesized a three-dimensional nested CNT@TiO_2 composite material and explored its influence as a catalyst on the hydrogen storage performance of NaAlH_4 . Wan et al. [90] prepared LiBH_4 nanosized powders with a particle size of 20–50 nm and studied the dehydrogenation thermodynamics and kinetics of LiBH_4 at the nanoscale.

5. Applications

Hydrogen energy has high calorific value, low-carbon emissions, and excellent energy carrier characteristics, and its applications have been widely penetrated into many key fields such as transportation, industry, and power generation. With the continuous progress in green hydrogen production technology, hydrogen storage solutions, and fuel cells, the application of hydrogen energy is rapidly expanding from traditional industrial scenarios to more diverse and cutting-edge directions.

5.1. Transportation field

Transportation contributes a significant amount of carbon emissions globally, so it has become increasingly important to find effective solutions to reduce carbon emissions from transportation. Against the background that all countries are actively promoting the implementation of climate goals and accelerating the transition to clean energy, hydrogen energy, as a low-emission technical solution for decarbonization in the transportation sector, has attracted extensive attention. Moreover, the application of hydrogen energy transportation in the world has formed a diversified layout, covering hydrogen energy buses, heavy trucks, logistics trucks, ships, unmanned aerial vehicles, and other categories. By the end of 2025, there are nearly 1,300 operational hydrogen refueling stations around the world, the number of hydrogen fuel cell vehicles in stock is about 120,000, and the annual sales volume is about 28,000, with a year-on-year increase of about 48% [91]. In April 2025, Hyundai Motor of South Korea launched the second-generation NEXO hydrogen fuel cell SUV. The total power of its fuel cell stack has been increased to 110 kW, and hydrogen refueling can be completed in 5 minutes [92]. BMW, Mercedes Benz, Mazda, and Honda also developed vehicles that can be run with hydrogen. In

maritime industry, China, Japan, France, Norway, and the United Kingdom have developed hydrogen-powered cruise ships. Hydrogen energy is progressively utilized in ferries, service vessels, and coastal ships. In aviation, Boeing and Airbus have developed small-scale aircrafts for demonstration and testing purposes, aiming to assess the feasibility of hydrogen utilization within their respective fleets [93]. However, the aviation sector faces unique infrastructure challenges. Substantial investment and stringent safety control measures are required for hydrogen storage, transportation, and management at airports. Germany has led the implementation of several hydrogen units for passenger service. California's hydrogen commuter trains commenced operations in 2024 [94].

The application research of hydrogen energy in the transportation field mainly focuses on hydrogen fuel cells, which are electrochemical devices that convert the chemical energy of hydrogen into electrical energy. Proton exchange membrane fuel cells (PEMFCs) represent the core technology for hydrogen energy applications in the transportation sector, and they constitute a key focus of global research, development, and industrialization.

The working principle of a PEMFC is shown in Figure 7. Hydrogen undergoes an oxidation reaction at the anode under the action of a catalyst, forming H^+ and e^- . H^+ moves directionally through the proton exchange membrane toward the cathode under the drive of the concentration gradient; e^- cannot pass through the proton exchange membrane and flows through the external circuit to the cathode to form an electric current; H^+ , e^- , and oxygen at the cathode undergo a reduction reaction under the action of a catalyst to form water [95]. The proton exchange membrane and catalyst are the two key materials that determine the core performance of the fuel cell and are also the core research and development directions currently [96].

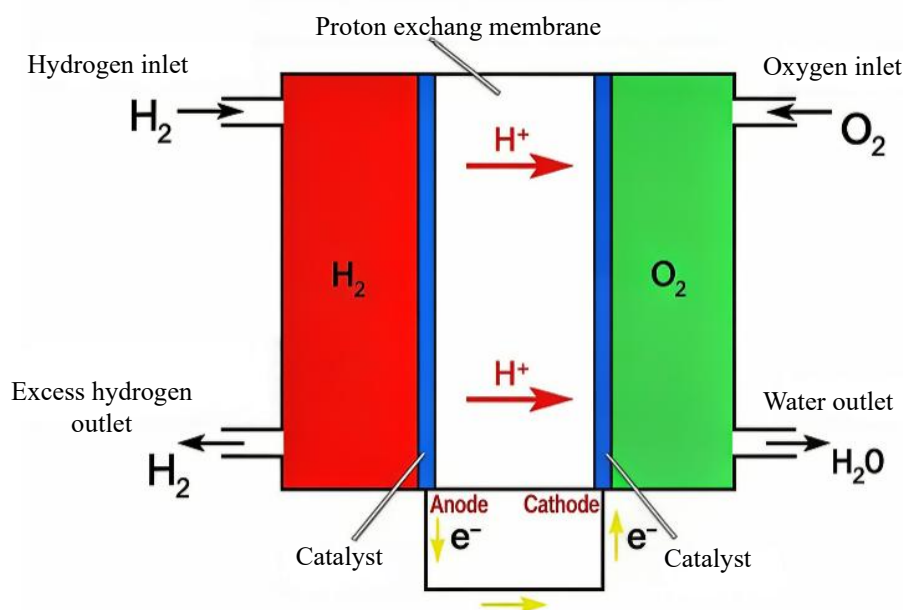


Figure 7. The working principle of a PEMFC.

5.2. Industrial field

More than 90% of hydrogen consumption is concentrated in the industrial field. The industrial field is not only the largest current consumer market for hydrogen energy but also the link with

the most urgent need for “green hydrogen” substitution and the greatest emission reduction potential in the future. Moreover, gray hydrogen is the absolute dominant source, and low-emission hydrogen accounts for less than 1% of global hydrogen energy production. The International Energy Agency (IEA) predicts that by 2030, low-emission hydrogen will account for about 4% of global total hydrogen energy consumption; in 2050, the proportion of green hydrogen in industrial hydrogen consumption is expected to reach 40% to 60% [97].

Hydrogen is recognized as a versatile energy carrier and reducing agent in industrial applications. In the chemical industry, more than 50% of the hydrogen globally is used for ammonia synthesis. In petroleum refining, hydrogen is used for desulfurization and denitrification (hydrotreating), which are key steps in converting heavy oil into light fuels (hydrocracking); hydrogen is an important basic raw material for methanol production. In the metallurgical industry, hydrogen can replace coke or carbon monoxide as a reducing agent and react with iron ore to produce iron and water, achieving nearly zero carbon emissions. Japan’s COURSE50 project, through the injection of coke oven gas and hydrogen into the blast furnace tuyeres, has achieved approximately a 16% carbon emission reduction in its experimental blast furnace [98]. As an industrial fuel, it replaces natural gas, petroleum, and coal in industries such as glass manufacturing, ceramic sintering, and non-ferrous metal processing.

5.3. Power generation field

Hydrogen energy storage power generation is another important field of hydrogen energy application. This technology uses hydrogen as an energy storage medium. During the stage of surplus grid power, surplus electric energy is used for electrolytic hydrogen production and hydrogen storage; when the grid power is short, the stored hydrogen is directly used for power generation through a fuel cell or converted into methane to supply energy to traditional gas turbines, achieving flexible power supply. This technology is regarded as a potentially effective solution to balance the power supply and demand of a power grid with a high proportion of renewable energy grid-connected [99]. Grove Company launched a new 640 kW hydrogen energy power generation device, which is not only the largest hydrogen energy power generation equipment globally but also marks a major breakthrough in the Chinese hydrogen energy industry [100]. In December 2025, MingYang Smart Energy Group’s first 30 MW pure hydrogen gas turbine was put into operation, supporting 500MW of wind power + 5 MW of photovoltaic power, producing 48,000 standard cubic meters of hydrogen per hour, achieving a full-chain closed-loop of “electricity-hydrogen-electricity” [101].

Seasonal hydrogen storage is regarded as a promising long-duration energy storage solution to address the seasonal mismatch between renewable power generation and electricity demand, supporting grid balancing at multi-month time scales. Hydrogen storage can convert surplus wind and solar power into hydrogen during high-generation seasons and regenerate electricity to the grid during low-renewable seasons.

6. Cross-cutting bottlenecks

Against the dual backdrop of intensifying global environmental challenges and the structural transformation of the energy system, hydrogen has emerged as a central pillar of national energy strategies worldwide, owing to its distinctive energy attributes and broad application potential. However, hydrogen is a typical secondary energy carrier spanning multiple industrial chains; its commercialization requires the coordinated integration of renewable energy generation, equipment

manufacturing, pipeline infrastructure, safety management, and standardization systems. The scale-up and commercialization of hydrogen therefore face a series of critical bottlenecks across the value chain, encompassing production, storage, transportation, and end-use, manifested as multidimensional shortcomings in technological economics, infrastructure, standards and regulation, market mechanisms, and safety systems. Together, these constraints severely impede the industry's transition from pilot demonstration to large-scale deployment.

Hydrogen production. Green hydrogen produced via water electrolysis coupled with wind and solar power represents the ultimate development pathway for the hydrogen industry. It is, however, hampered by high capital costs of core equipment and low overall energy conversion efficiency. Key components and materials, including electrolyzers, PEMs, and catalysts, suffer from elevated costs and limited operational lifetimes, substantially inflating the levelized cost of green hydrogen production. Moreover, the intermittency, volatility, and stochasticity of renewable power generation, compounded by the geographical mismatch between resource-rich regions and hydrogen demand centers, compromise the stability of green hydrogen output and result in low utilization rates of electrolyzers powered by otherwise curtailed wind and solar electricity [15]. Consequently, a continuous, stable, and large-scale low-carbon hydrogen supply remains unattainable, falling short of the volumetric demand from the industrial, energy, and transportation sectors.

Hydrogen storage and transportation. Storage and transportation constitute the critical link connecting production with consumption and represent the principal bottleneck constraining the scale-up of the hydrogen industry. The dominant technology, compressed gaseous hydrogen storage, suffers from low gravimetric and volumetric storage density, limited pressure-bearing capacity, and high storage and delivery costs. Moreover, liquid hydrogen storage is not commercially viable at scale, given its substantial cryogenic energy consumption, expensive equipment, and stringent operational requirements. Emerging storage technologies, such as solid-state hydrogen storage and LOHCs, remain at the laboratory research and small-scale demonstration stage, hindered by poor cyclic stability, insufficient volumetric storage density, and formidable challenges in mass production. With regard to transmission infrastructure, high-pressure pure-hydrogen pipelines and hydrogen-blended gas networks remain sparsely deployed; retrofitting technologies and technical standards for adapting natural-gas pipelines are underdeveloped, and a long-distance, high-capacity, low-cost hydrogen transmission network has yet to take shape. Hydrogen delivery relies heavily on tube trailers and cryogenic liquid tankers, which are constrained by limited transport radius, low delivery efficiency, and high overall costs. As a result, green hydrogen resources in remote regions cannot be efficiently allocated to end-use markets, giving rise to the industry-wide predicament of “producible but not storable, storable but not transportable”.

Hydrogen applications. Hydrogen end-use applications are dominated by demonstration operations of fuel cell vehicles, whereas penetration into core energy-intensive sectors, such as hydrogen-based steelmaking, chemical reduction, energy storage and peak shaving, distributed power generation, and maritime shipping, remains minimal. A diversified, large-scale application market has yet to be cultivated. Moreover, the industry lacks a well-established market-based pricing mechanism, carbon accounting framework, and price pass-through mechanism, rendering the low-carbon value of green hydrogen difficult to quantify, transfer, and monetize. From a value-chain perspective, coordination among upstream and downstream stakeholders is weak: Loose coupling among hydrogen producers, equipment manufacturers, and end-use enterprises has precluded the formation of agglomerated, integrated industrial clusters. The resulting fragmentation of the value chain impedes cost reductions through economies of scale, confining most hydrogen projects to demonstration status rather than sustainable commercial profitability.

Standards and safety governance. Given its flammability, high diffusivity, and operation under cryogenic or high-pressure conditions, hydrogen imposes stringent safety requirements across its lifecycle, including production, storage, transportation, refueling, and end-use [102]. However, the standardization system for hydrogen remains incomplete: Unified and authoritative industry codes are lacking in critical areas such as hydrogen purity certification, equipment manufacturing specifications, engineering construction standards, refueling and operational protocols, and emission standards. Furthermore, a comprehensive safety regulatory framework has yet to be established. Dedicated risk assessment models, intelligent monitoring and early-warning systems, emergency response protocols, and normalized safety management systems remain inadequate; industry safety admission thresholds are ill-defined, and the primary responsibility of enterprises for safety production is inadequately enforced. These deficiencies constitute latent safety hazards and constrain the steady and orderly development of the industry.

7. Implications

The coupled bottlenecks along the hydrogen-energy value chain carry meaningful implications for technology R&D, industrial configuration, market construction, and policy-making [8,15].

Technological implications. Differentiated research-and-development strategies are required in accordance with distinct TRLs. For mature routes, such as alkaline water electrolysis and compressed gaseous hydrogen storage, efforts should focus on capital-cost reduction and long-term operational reliability. In contrast, emerging low-TRL technologies, including AEM water electrolysis and solid-state hydrogen storage, demand priority breakthroughs in core materials and kinetic performance. Notably, optimizing a single segment in isolation cannot remove systemic barriers; full-chain coordination among hydrogen production, storage, transportation, and downstream applications must be emphasized to achieve overall system efficiency.

Industrial implications. From an industrial perspective, these inter-linkage constraints expose the drawbacks of fragmented industrial patterns. Collaborative innovation among equipment suppliers, hydrogen producers, and end-users should be encouraged to form integrated industrial clusters and capture economies of scale. Given the spatial mismatch between renewable-energy-rich regions and major hydrogen-consuming hubs, the phased construction of hydrogen delivery infrastructure requires forward-looking planning.

Market and policy implications. For market and policy governance, formal carbon-accounting frameworks and reasonable pricing mechanisms are essential to monetize the low-carbon value of green hydrogen. During the scale-up phase of green-hydrogen capacity, transitional low-carbon hydrogen sources, represented by blue hydrogen and industrial by-product hydrogen, can serve as feasible near-term supplements. Moreover, unified standards and systematic safety-risk evaluation covering the value chain are indispensable prerequisites for mitigating safety hazards and enabling the large-scale commercial deployment of hydrogen energy [12].

8. Limitations

In this review, we aim to provide the technical status and research hotspots in the field of hydrogen energy production, storage, and transportation, and it is necessary to point out the following limitations:

First, despite the systematic search protocol, the review is restricted to English- and Chinese-language publications and to three major databases plus CNKI; studies indexed elsewhere or published in other languages may have been missed, leaving residual selection bias.

Second, no quantitative meta-analysis is conducted, as the original studies exhibit considerable heterogeneity in system boundaries, assumptions, and data sources, rendering statistical synthesis inappropriate.

Third, we do not include full lifecycle assessment or techno-economic modeling (TEM). Therefore, the efficiency, cost, and emission figures cited are reported values from the literature and have not been recalculated under unified functional units or background assumptions; direct cross-comparisons should be interpreted with caution. Fourth, we do not perform region-specific policy evaluations, nor do we quantify the differentiated impacts of national subsidies, carbon pricing, or import tariffs on hydrogen economics. As such, the applicability of the findings should be adjusted according to local policy contexts.

Furthermore, it must be recognized that the capital costs, energy conversion efficiencies, TRLs, and policy incentives associated with hydrogen technologies are evolving rapidly. Emerging developments, such as novel electrolyser materials, advanced hydrogen storage media, and demonstration projects for cross-border hydrogen supply chains, may render some of the data cited in this review outdated shortly after publication. Accordingly, the conclusions presented herein should be regarded as an interim synthesis based on publicly available literature within the retrieval time window. Readers are advised to periodically update the reference information presented in this review in light of real-world project progress and newly released national strategic frameworks.

9. Future roadmap

The future development of the hydrogen energy industry must be based on breakthroughs in core technologies. Moreover, focus needs to be on research and development in directions such as efficient catalysts, new hydrogen storage materials, and key components of fuel cells. Through means such as material modification, process optimization, and technology integration, solving the core pain points in each link of hydrogen production, storage, transportation, and application is crucial. Furthermore, it is important to promote the collaborative iteration of technologies in all links of the industrial chain to achieve technical matching and maximize efficiency. In addition, relying on renewable energy sources such as wind power and photovoltaic to develop a green hydrogen production system, improve the layout of hydrogen energy storage, transportation infrastructure and application scenarios, and build an integrated hydrogen energy industry ecosystem of “production-storage-transportation-application” is needed. Only through the multiple efforts of technological innovation, industrial collaboration, and ecological construction can we gradually break through the technical and industrial barriers to the large-scale application of hydrogen energy, promote hydrogen energy to become an important part of the diversified and integrated energy system, and contribute to the realization of the global energy transformation and the “dual carbon” goal.

10. Conclusions

Hydrogen, as a secondary clean energy carrier with high energy density and environmental friendliness, is playing an increasingly vital role in the energy system. Focusing on the three core segments of the hydrogen energy industry chain—hydrogen production, hydrogen storage and

transportation, and hydrogen utilization—this paper reviews the research status and technical characteristics of various hydrogen production processes, storage and transportation technologies, and hydrogen applications in transportation, industry, and power generation.

In terms of hydrogen production, fossil fuel-based hydrogen production is technologically mature and cost-effective, but its substantial carbon emissions make it necessary to upgrade toward blue hydrogen through integration with CCUS technology. Water electrolysis is the core pathway for green hydrogen production: AWE has already been commercialized, while PEMWE, SOEC, and AEM electrolysis still require breakthroughs in key challenges such as catalysts and high-temperature-resistant materials. Biomass-based hydrogen production and photocatalytic water splitting remain at the laboratory research stage and are still far from large-scale industrialization. Regarding hydrogen storage and transportation, high-pressure gaseous storage currently has the highest degree of industrialization, but its storage density falls short of the requirements of vehicle-mounted and similar applications. Liquid hydrogen storage, including cryogenic liquid hydrogen and liquid organic hydrogen carriers, is constrained by high liquefaction energy consumption and harsh dehydrogenation conditions, respectively. Solid-state hydrogen storage has become a research hotspot owing to its high storage density and safety, and the development of novel solid-state storage materials represents a key direction for future research. On the application side, proton exchange membrane fuel cells are the core technology for hydrogen utilization in transportation, with the cost of precious-metal catalysts limiting wider adoption. The industrial sector is currently the largest hydrogen consumption market, where green hydrogen substitution will help the chemical and metallurgical industries achieve deep decarbonization. Hydrogen energy storage and power generation can smooth out the intermittency of wind and solar power, serving as an important regulation means for new-type power systems.

Overall, the bottlenecks across the hydrogen energy industry chain are mutually coupled, and technological breakthroughs in a single segment alone cannot drive leapfrog development of the entire industry. Future efforts should focus on new materials research and development, creating low-cost, high-performance catalysts and hydrogen storage materials while continuously optimizing the entire production-storage-transportation-utilization chain. It is also essential to vigorously develop green hydrogen production modes coupled with wind and solar power, improve storage and transportation infrastructure, expand diversified demonstration application scenarios, and promote coordinated technological iteration across all segments. Through technological innovation, policy support, and collaborative development of the industrial ecosystem, the challenges of cost, materials, and engineering scale-up can be gradually overcome, accelerating the transition of hydrogen energy from demonstration projects to large-scale commercialization.

Use of AI tools declaration

In the preparation of this manuscript, AI tools (DeepSeek, Doubao, and Kimi) were employed to assist with literature searching and English grammatical proofreading.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

Author contributions

Xiaowei Chen: Writing-original draft preparation, Investigation. Yichen Yang: Writing-review and editing, Investigation. Baofeng Zhang: Conceptualization, Funding acquisition, writing-review and editing. Zhenhai Qin: Investigation, Visualization, data curation.

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