



Review

Towards a Future Hydrogen Supply Chain: A Review of Technologies and Challenges

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Abstract: The overuse of fossil fuels has caused a serious energy crisis and environmental pollution. Due to these challenges, the search for alternative energy sources that can replace fossil fuels is necessary. Hydrogen is a widely acknowledged future energy carrier because of its nonpolluting properties and high energy density. To realize a hydrogen economy in the future, it is essential to construct a comprehensive hydrogen supply chain that can make hydrogen a key energy carrier. This paper reviews the various technologies involved in the hydrogen supply chain, encompassing hydrogen production, storage, transportation, and utilization technologies. Then, the challenges of constructing a hydrogen supply chain are discussed from techno-economic, social, and policy perspectives, and prospects for the future development of a hydrogen supply chain are presented in light of these challenges.

Keywords: energy carrier; hydrogen economy; hydrogen production; hydrogen storage; hydrogen transportation; hydrogen utilization; supply chain



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1. Introduction

Energy occupies a crucial position among global concerns, representing a pivotal driver of worldwide economic advancement. Energy resources are fundamental to virtually all human activities. However, the escalating energy crisis, mainly due to excessive reliance on fossil fuels, poses a significant global challenge [1]. As is shown in Figure 1, fossil fuels, such as petroleum, natural gas, and coal, constitute over 80% of global energy consumption, posing a critical issue for global warming that requires ongoing attention [2]. Over the past 120 years, human activities have contributed to an approximate 0.8 °C increase in global temperatures [3]. Additionally, existing fossil fuel reserves are approaching depletion. According to current estimations, petroleum reserves can meet human consumption demands for approximately four decades, natural gas for six decades, and coal for one and a half centuries [4]. The looming scarcity of fossil fuels and rising environmental pollution underscore the urgency of an energy transition [5]. This transition demands the exploration of clean and sustainable energy sources as alternatives to fossil fuels. Future sustainable energy solutions must not only establish a new industrial and technological energy base but also significantly reduce carbon dioxide emissions [6].

Hydrogen, known for its high energy density and low carbon footprint, is emerging as a sustainable and promising energy carrier for the future [7,8]. The concept of using hydrogen as an energy carrier dates back two centuries. Despite its low atmospheric concentration, hydrogen, the third most abundant element on Earth, is found in various compounds like petroleum, natural gas, water, and biomass [9]. Water is the most abundant source of hydrogen, making water electrolysis an ideal method for its production. Historically, the high cost of water electrolysis limited its widespread adoption. However, rapid advancements in renewable energy have enabled the possibility of economically viable electrolytic hydrogen production [10]. Hydrogen production from renewable sources yields

zero carbon emissions, and hydrogen, as a fuel, produces no emissions other than water, thus eliminating environmental pollution. Therefore, integrating hydrogen with renewable energy generation enables a zero-carbon-emission energy process. Hydrogen also offers the advantage of high energy density; as is shown in Table 1, hydrogen surpasses most conventional fossil fuels in terms of its higher heating value (HHV) and lower heating value (LHV). Hydrogen finds extensive applications due to these attributes. Hydrogen can be used as a kind of clean fuel for power generation. It can be integrated into power systems for better reliability. Hydrogen can also be used as a fuel for hydrogen fuel cell vehicles [11]. In the chemical industry, hydrogen has been a kind of raw material for producing chemical products such as ammonia and methanol [12]. Due to the versatile applications of hydrogen, it is considered a promising energy carrier for the future [13].

Table 1. Higher and lower heating values of hydrogen and fossil fuels at 25 °C and 1 atm [15].

Fuel	HHV (kJ/g)	LHV (kJ/g)
Hydrogen	141.9	119.9
Methane	55.5	50.0
Gasoline	47.5	44.5
Diesel	44.8	42.5
Methanol	20.0	18.1

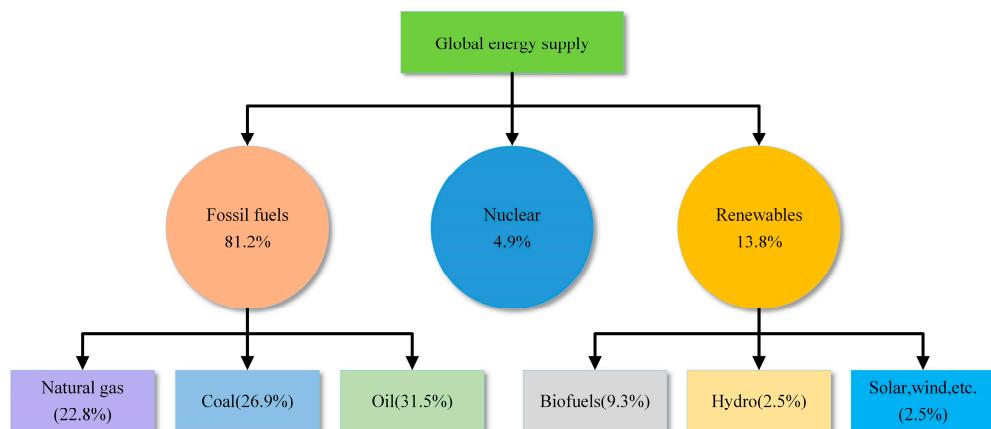


Figure 1. Share of global energy supply in 2018 [14].

The concept of the “hydrogen economy” was proposed by John Bockris in 1970 [16]. In a hydrogen economy, hydrogen serves as the major energy carrier. To achieve a hydrogen economy, hydrogen needs to be integrated into many sectors, such as power systems, transportation, and chemical industries [9]. Establishing a hydrogen supply chain is fundamental for achieving a hydrogen economy [17]. A hydrogen supply chain should encompass hydrogen production, hydrogen storage, hydrogen transportation and delivery, and hydrogen utilization [18,19]. The key components of a hydrogen supply chain are illustrated in Figure 2. Although many studies on hydrogen technologies have been conducted, a comprehensive hydrogen supply chain is still in the early stage of development. This paper reviews the key technologies of hydrogen production, hydrogen storage, hydrogen transportation and delivery, and hydrogen utilization, which are important for the hydrogen supply chain. The challenges of constructing a hydrogen supply chain are also discussed. Then, the prospects of a future hydrogen supply chain are discussed based on the challenges.

The structure of this paper is as follows: Section 2 reviews the methods of hydrogen production, which are divided into producing hydrogen from fossil fuels, biomass, and water. Section 3 discusses the hydrogen storage technologies, which can be categorized as gaseous hydrogen storage, liquid hydrogen storage, and solid hydrogen storage. Methods of transporting hydrogen by compressed gaseous tube trailers, cryogenic liquid tanker

trucks, and pipelines are introduced in Section 4. The employment of hydrogen in power systems, the transportation sector, and the chemical industry is reviewed in Section 5. These sections collectively highlight the key technologies supporting the hydrogen supply chain, addressing all essential components. Section 6 analyzes the challenges and prospects of the hydrogen supply chain, and the paper's conclusions are presented in Section 7.



Figure 2. Key components of hydrogen supply chain.

2. Hydrogen Production

Hydrogen can be generated from many resources, such as fossil fuels, biomass, and water [20]. Table 2 provides a summary of hydrogen production pathways. The technologies for producing hydrogen from fossil fuels, biomass, and water are discussed in the following sections.

2.1. Hydrogen Production from Fossil Fuels

Currently, fossil fuels are still the main resource for hydrogen production. About 96% of hydrogen is produced from fossil fuels. Technologies of hydrogen production from fossil fuels include steam reforming (SR), partial oxidation (POX), and coal gasification [21,22].

2.1.1. Steam Reforming

Steam reforming (SR) is the most mature method for producing hydrogen from fossil fuels. Natural gas is a common hydrogen source for the SR process [23]. The SR process that uses natural gas as the raw material is known as steam methane reforming (SMR). In the SMR process, methane reacts with steam to produce a synthesis gas that is rich in H₂ [24]. Then, the synthesis gas will be sent into the water–gas shift (WGS) reactor. In the WGS reactor, the CO in the synthesis gas will further react with steam and produce more H₂ [25]. The final stage of SMR is separating CO₂ from the synthesis gas for purification. The process of SMR is shown in Figure 3. Catalysts are used in the SMR to accelerate the reaction between methane and steam. High temperatures are required because SMR is an endothermic process. The heat needed in this process is usually supplied by natural gas [26].

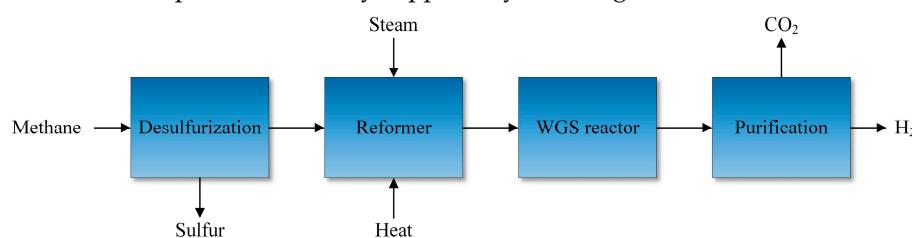


Figure 3. Process of SMR.

Table 2. Hydrogen production pathways.

Processes	Raw Materials	Example of Reactions	Temperature Range (°C)	Refs.
Steam reforming + water–gas shift	Natural gas, hydrocarbons Renewable ethanol	$C_nH_m + nH_2O \xrightarrow{\text{heat}} nCO + (n + 0.5m)H_2$ $CO + H_2O \rightarrow CO_2 + H_2 + \text{heat}$ $C_2H_5OH + H_2O \xrightarrow{\text{heat}} 2CO + 4H_2$ $CO + H_2O \rightarrow CO_2 + H_2 + \text{heat}$	700–1100	[27,28]
Partial oxidation	Natural gas, hydrocarbons Ethanol	$C_nH_m + 0.5nO_2 \rightarrow nCO + 0.5mH_2 + \text{heat}$ $C_2H_5OH + 0.5O_2 \rightarrow 2CO + 3H_2 + \text{heat}$	Thermal: 1300–1500; Catalytic: 700–1000	[29,30]
Gasification	Coal Biomass	$CH_{0.8} + O_2 + H_2O \xrightarrow{\text{heat}} CO + CO_2 + H_2 + \text{byproducts}$ $C_6H_{12}O_6 + O_2 + H_2O \xrightarrow{\text{heat}} CO + CO_2 + H_2 + \text{byproducts}$	700–1400	[31,32]
Pyrolysis	Biomass	Complex reactions	400–1000	[33,34]
Electrolysis	Water	Anode: $H_2O \rightarrow 0.5O_2 + 2e^-$ Cathode: $2H^+ + 2e^- \rightarrow 2H_2$	/	[35]

Catalyst research is a pivotal area in SR, with current studies focusing on both precious and nonprecious metal catalysts [36]. Nickel-based catalysts, such as Ni/Al₂O₃, are notable for their low cost and excellent performance [37]. However, these catalysts can be deactivated by organic sulfur compounds in natural gas. To mitigate this issue, natural gas containing sulfur compounds must be treated in a desulfurization unit before the reforming reaction, with activated carbon commonly employed due to its effective desulfurization properties.

There is growing interest in using solar energy as a heat source for the reforming reaction [38,39]. Compared to traditional heating methods involving natural gas combustion, this approach offers a significant reduction in carbon emissions during the process [40].

In the industrial sector, hydrogen production yield through SR can reach up to 74% [41]. Despite its efficiency, SR is associated with relatively high carbon emissions. Future studies should focus on addressing the carbon emissions caused by the SR process. Researchers are exploring alternative technologies, with membrane reactors gaining attention for their enhanced performance. Membrane reactors, known for their faster reaction rates, are emerging as potential alternatives to traditional steam reforming processes.

2.1.2. Partial Oxidation

Partial oxidation (POX) in hydrogen production involves the reaction of hydrocarbons like methane or heavy oil with steam and oxygen. This reaction results in the partial oxidation of hydrocarbons and the generation of synthesis gas enriched with hydrogen [42]. Notably, heavy oil has a higher carbon-to-hydrogen ratio compared to methane, leading to 69% of the hydrogen production stemming from steam in the POX process. This process also produces more carbon monoxide than the SMR process [43]. Consequently, the synthesis gas from POX requires additional hydrogen enhancement via the WGS reaction. The process of POX is shown in Figure 4. POX necessitates pure oxygen for the oxidation of hydrocarbons due to the challenge of nitrogen separation. Depending on whether a catalyst is used, POX can be classified as thermal partial oxidation (TPOX) or catalytic partial oxidation (CPOX).

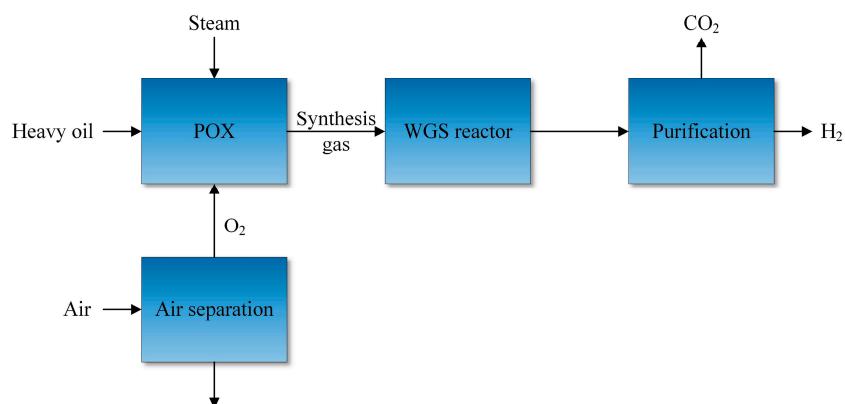


Figure 4. Process of POX of heavy oil.

The TPOX process involves the partial oxidation of hydrocarbons with pure oxygen. Hydrogen-rich synthesis gas is produced at high temperatures (1300–1500 °C) and pressures (3–8 MPa) [29]. The high reaction temperatures in the TPOX process highlight the significance of flammability limits to hydrogen production. In the context of TPOX, superadiabatic combustion (SAC) represents a viable option where the combustion of the reactant mixture occurs above the adiabatic temperature [44].

In contrast, CPOX operates at lower temperatures (700–1000 °C) due to the presence of catalysts. Ni-based catalysts, such as Ni/CeO₂, are considered to offer a balance between low cost and high reaction activity, resulting in their widespread use [45]. The catalyst in CPOX substantially reduces external heat needs, leading to faster reaction rates compared to TPOX [46]. Furthermore, the hydrogen production rate in CPOX depends on the catalyst type [47]. CPOX offers advantages such as high reaction rates, energy efficiency, and selectivity in one reactor, leading to reduced costs in hydrogen production from methane or heavy oil.

Compared to the SR process, POX requires an air separation unit for pure oxygen extraction, resulting in higher costs for these facilities [22]. This requirement limits the broader commercial application of the POX process.

2.1.3. Gasification

Gasification is a complex chemical process in which high-density fuels such as coal react with oxygen and steam at high temperatures and pressures [48,49]. The gasification process can convert coal into synthesis gas with a high proportion of H₂. The synthesis gas needs to be purified before it is sent into the WGS reactor, and the CO in the synthesis gas will further react with steam to produce more H₂. However, the gasification process also produces CO₂. Due to coal's high content of carbon and impurities, coal gasification significantly contributes to carbon dioxide and pollutant emissions, leading to substantial environmental pollution [50]. The process of coal gasification is shown in Figure 5.

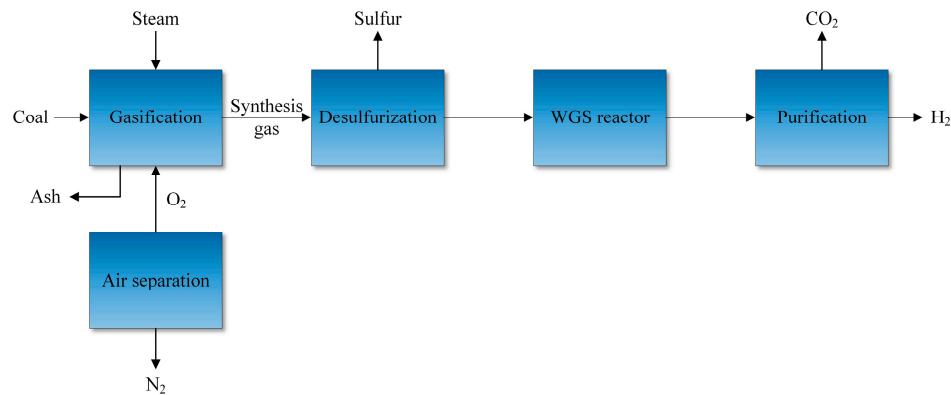


Figure 5. Process of coal gasification.

To address these environmental issues, current research is centered on integrating pollution control devices and carbon capture and utilization (CCU) units into the gasification process. This integration aims to reduce the adverse environmental impacts of coal gasification for hydrogen production [51]. However, incorporating these technologies tends to increase the overall cost of hydrogen production.

Economically, coal gasification is generally less competitive for hydrogen production compared to SR. However, it is cost-effective when integrated with combined heat and power (CHP) generation [49]. This suggests that while coal gasification faces environmental and cost challenges, optimizing the process for specific applications like CHP can improve its viability.

2.2. Hydrogen Production from Biomass

Biomass is recognized as a kind of renewable energy source. Common biomass includes agricultural waste, domestic waste, and plant residues [52]. With the global development of renewable energy, there is increasing attention on using biomass for hydrogen production. Although using biomass for hydrogen production can lead to carbon emissions, the formation of biomass can absorb CO₂. Consequently, biomass is considered a more friendly energy source for the environment than fossil fuels. Presently, prevalent techniques for hydrogen production from biomass involve biomass gasification and biomass pyrolysis [21]. Figure 6 is a diagrammatic sketch of hydrogen production from biomass.

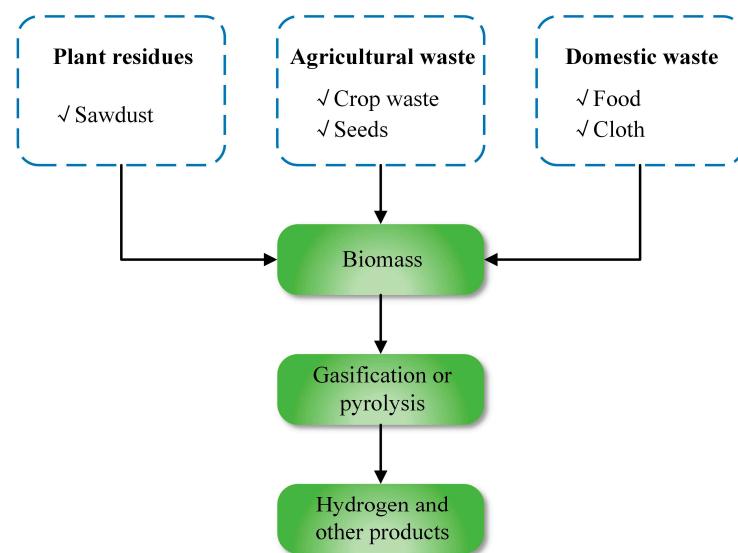


Figure 6. Diagrammatic sketch of hydrogen production from biomass.

2.2.1. Biomass Gasification

Biomass gasification is the most widely used method for producing hydrogen from biomass. This process takes place in a gasifier with high temperature. The main product of the gasification process is synthesis gas that is rich in CO and H₂. However, there are also some byproducts such as tar and char forming during this process [53]. Fixed beds, fluidized beds, and entrained flow gasifiers are commonly used gasifiers for biomass gasification. Removing tar generated during gasification is a critical aspect of this process.

To optimize hydrogen yield, the syngas typically undergoes a WGS reaction within the gasifier, converting CO into additional hydrogen. Currently, studies mainly focus on increasing hydrogen production from biomass gasification while reducing tar and char formation [54]. Zhang et al. [55] reported that using potassium salts like KCL as catalysts can decrease tar and char production and boost hydrogen generation. Ahmed and Gupta [56] investigated how temperature affects gas composition and hydrogen efficiency in biomass gasification. Their study indicated that higher temperatures are conducive to increased hydrogen production, enhancing the hydrogen content in synthesis gas. Florin and Harris [57] suggested using CaO to capture CO₂ in synthesis gas, effectively increasing the hydrogen proportion from 40–50% to 40–80%.

Despite advancements, biomass gasification for hydrogen production faces challenges, primarily due to the complexity and cost associated with the tar removal process. Future research should focus on developing low-cost methods for tar removal, which is essential for the further advancement of biomass gasification.

2.2.2. Biomass Pyrolysis

Biomass pyrolysis, a process with significant potential for hydrogen production, heats biomass at pressures of 0.1–0.5 MPa and temperatures of 500–900 °C. The process of biomass pyrolysis generates gaseous products such as CO and H₂, liquid products including tar and bio-oil, and solid residues like char [58]. The gaseous fraction, containing H₂, CO, CO₂, CH₄, and other components, can be further processed in a WGS reactor to increase its hydrogen content. Pyrolysis at high temperatures typically yields a liquid output rich in viscous tar, and the solid byproduct is primarily char.

Contemporary research in this field primarily concentrates on the optimization of catalysts and pyrolysis temperatures [59,60]. Valle et al. [61] suggested Ni/La₂O₃-Al₂O₃ as a catalyst to convert bio-oil into a hydrogen-rich gas via a dual thermal and catalytic reaction. At 700 °C, this process yielded a gas mixture with up to 93% hydrogen. Hao et al. [62] noted that introducing NiMo catalysts in catalytic pyrolysis increased the hydrogen yield from 13.8 g to 33.6 g per kilogram of biomass. Luo et al. [63] found that utilizing industrial silicate slag as a catalyst in biomass reactions at 1000 °C maximized hydrogen production during pyrolysis.

Biomass pyrolysis for hydrogen production offers advantages such as relatively simple reaction processes and lower carbon emissions. With the selection of effective catalysts and appropriate temperature control, this method represents a viable hydrogen production technique. However, overcoming the challenges in managing resultant tar and char is crucial for further advancement in biomass pyrolysis for hydrogen production.

2.3. Hydrogen Production from Water

Carbon emissions are unavoidable when producing hydrogen from fossil fuels and biomass. In contrast, the products of hydrogen production from water are merely H₂ and O₂, which makes it an ideal method for hydrogen production. Figure 7 illustrates the operation principle of water electrolysis. The development of water electrolysis has made some achievements. For example, water electrolysis comprises about 3% of the total national hydrogen production in China [64]. Currently, alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEME), and solid oxide electrolysis (SOE) are the commonly used technologies for water electrolysis. Table 3 offers a comparison of these technologies. Photocatalytic water splitting is another promising method for hydrogen

production. These technologies can produce hydrogen with no carbon emissions, which can contribute to the global trend towards sustainable energy.

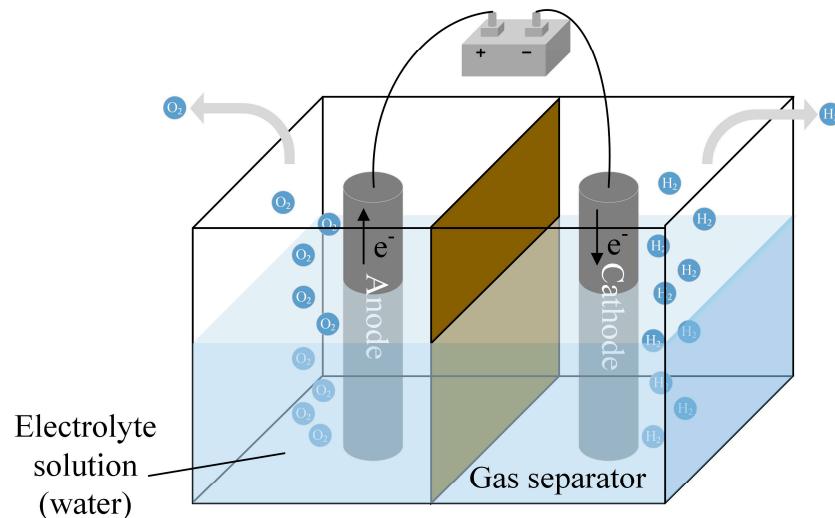


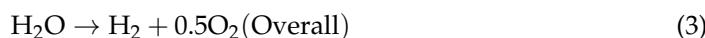
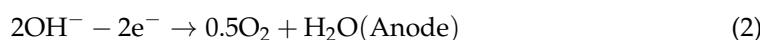
Figure 7. Operation principle of water electrolysis.

Table 3. Comparison of different electrolysis cell technologies.

Electrolysis Technique	Electrolyte	Operating Temperature	Electrolytic Efficiency	Advantage	Disadvantage	Maturity
AWE	Alkaline aqueous solution	70~90 °C	60~75%	Mature technology, low cost	Corrosion pollution problem, high maintenance cost, long response time	Commercial maturity
PEME	Proton exchange membrane	50~80 °C	70~90%	Safe and pollution-free, high flexibility, adapt to fluctuating power supply	Immature technology, high cost	Preliminary commercialization
SOE	Solid oxide	500~1000 °C	85~100%	Safe and pollution-free, high efficiency	High working temperature, immature technology	Research and development

2.3.1. Alkaline Water Electrolysis

Alkaline water electrolysis (AWE) is the most widely used electrolysis technology for hydrogen production, with significant use since the 20th century. The fundamental principle of AWE for hydrogen production is the electrochemical decomposition of water into O₂ and H₂, powered by an electric current. In AWE, hydrogen gas is generated at the cathode of the alkaline electrolysis cell (AEC) [65]. Water's limited intrinsic electrolytic capability necessitates the addition of alkaline electrolytes like KOH or NaOH, which enhance its electrical conductivity and thereby increase the efficiency of hydrogen production [66]. Traditionally, asbestos materials have been used as separators between the anode and cathode in AWE. The electrolytic reactions in AWE are represented by the following equations [35]:



AWE can use various transition and noble metals as electrodes, with the choice significantly affecting electrolytic performance [65,67]. A key challenge in AWE efficiency is the degradation of the oxygen electrode, often caused by the clogging of electrode material

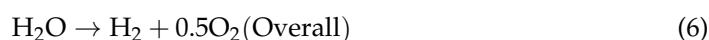
pores due to oxygen bubble generation. Considering the high cost of noble metals, alternative materials such as Ni, Co, Cu, and Fe are commonly used, offering a compromise between cost and reaction activity [68]. In industrial applications, alloys such as Ni-Co are preferred for electrodes in AWE due to their higher reaction activity than pure metals [69].

The structural design of AECs significantly impacts their electrolysis performance. In AECs, two prevalent design approaches are parallel and series connections of multiple individual cells. The parallel connection design, characterized by its relatively simple structure, offers significant manufacturing advantages. However, it is prone to higher ohmic losses within the circuit, which can reduce efficiency. Conversely, the series connection of individual cells, while providing performance benefits, is associated with increased complexity in both design and manufacturing [70].

AWE is currently recognized as the most cost-effective and mature technology for hydrogen production via water electrolysis. Despite its advantages, the choice of electrolyte and membrane materials in AWE poses environmental concerns. Asbestos, which was traditionally used in membranes, is known for its environmental and health hazards. To address these issues, ongoing research is exploring the use of anion exchange membranes (AEMs) as substitutes for asbestos in AWE. This shift aims to reduce the environmental impact and increase the operational flexibility of AWE, making it a more sustainable option for hydrogen production [71,72].

2.3.2. Proton Exchange Membrane Electrolysis

The core component of a proton exchange membrane electrolysis cell (PEMEC) is its proton exchange membrane, which is notably thin [73]. This membrane is sandwiched between anode and cathode catalytic layers that are closely adhered to its sides. In the electrolysis process, H_2O at the anode dissociates into O_2 and H^+ ions. The primary role of the proton exchange membrane is to facilitate the movement of H^+ ions to the cathode. At the cathode, these ions acquire electrons and combine to form H_2 . The overall electrolysis reaction in a PEMEC can be summarized as follows [74]:



The efficiency of PEME largely depends on the materials used for the electrodes. To ensure electrode reactivity, electrodes are typically made from noble metals or their oxides. Different materials show varying catalytic activities at the anode and cathode. Commonly, Pt-based catalysts are used at the cathode, and Ir- or Ru-based catalysts at the anode [75].

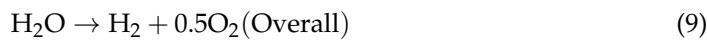
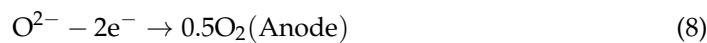
Due to the high cost of noble metals used in PEMEC electrodes, a significant research focus is on cost reduction. This involves doping the electrode materials with less expensive, non-noble metals without substantially reducing electrolysis performance. Wang et al. [76] proposed the use of nitrogen-deficient graphitic carbon nitride (N-CN) to enhance the catalytic activity of IrO_2 nanoparticles in PEME hydrogen production. $\text{IrO}_2/\text{N-CN}$ is an outstanding electrode material for PEM applications with excellent stability and catalytic activity. It has a mass activity that is 7.85 times higher than that of IrO_2 . Marshall et al. [77] prepared various oxide powders doped with combinations of Ir, Ru, and Ta, used as anodes in water electrolysis. Their study found that 7 out of 16 different oxide compositions showed good performance. Alia et al. [78] synthesized Ir-Ni and Ir-Co nanomaterials doped with Ni and Co. These materials performed comparably to commercial Ir and Ir oxide, offering potential cost-effective alternatives.

PEMECs are characterized by a more compact structural design compared to AECs. A significant advantage of PEMECs is their fast proton transport within the membrane, which allows for a rapid response to power fluctuations, a common characteristic of renewable energy sources [79]. This feature makes integrating renewable energy with proton exchange membrane electrolysis promising for future hydrogen production.

However, the commercial production of proton exchange membranes faces significant challenges, primarily due to their complex manufacturing processes, which lead to high production costs. Consequently, the adoption of PEME technology is still in its nascent stages. To advance the large-scale commercialization of PEME, research needs to focus on reducing costs while maintaining efficient proton transport and electrode material activity [80]. These are critical prerequisites for expanding the use of PEME systems in hydrogen production. Addressing these challenges is key to fully realizing the potential of PEMECs, particularly in the context of harnessing renewable energy for sustainable hydrogen production.

2.3.3. Solid Oxide Electrolysis

SOE is a critical technology used for high-temperature steam electrolysis, crucial for hydrogen production. Operating at temperatures between 500 and 1000 °C, solid oxide electrolysis cells (SOECs) consist of vital components like the electrolyte, cathode, and anode. Within this high-temperature environment, steam undergoes electrochemical reactions at the cathode and anode, leading to the production of H₂ and O₂. The primary electrochemical reactions in an SOEC are as follows:



The electrolyte is a crucial component of SOECs, significantly impacting cell performance and the selection of electrode materials and manufacturing methods. Its primary function is to facilitate ion transport during electrolysis. Additionally, the electrolyte material must maintain exceptional mechanical stability across various temperature ranges to ensure the SOEC's overall durability. Common electrolyte materials for SOECs include variants based on zirconia (ZrO₂), ceria (CeO₂), and bismuth oxide (Bi₂O₃) [81]. ZrO₂ is recognized for its high ionic conductivity and mechanical stability, making it the most commonly used electrolyte in SOECs. CeO₂ has a higher ionic conductivity, but its mechanical stability is worse compared to ZrO₂ [82]. Bi₂O₃, although exhibiting the highest oxygen ion conductivity, faces challenges with mechanical performance at lower temperatures.

A significant focus in SOE research is on electrolyte layers, as the electrolyte's electrical resistance is generally higher than that of the electrodes. Reducing the thickness of the electrolyte layer aims to decrease the ohmic resistance within the SOEC, thereby enhancing its overall performance. The pursuit of thinner electrolyte layers remains a primary area of research in the advancement of SOE technology.

The selection of electrode materials significantly influences the performance of SOECs. The anode, responsible for oxygen generation, must possess strong catalytic activity for the oxygen evolution reaction and maintain excellent electrical conductivity, especially at high temperatures [83]. The anode material needs to have a porous structure to allow the free diffusion of generated oxygen, thus preventing irreversible damage. Mixed ionic-electronic conductors (MIECs) are commonly used in oxygen electrode functions, with three main types: perovskites (e.g., La_{0.8}Sr_{0.2}CoO₃), ABO₃ perovskites with cation exchange (e.g., Pr₂NiO_{4+δ}), and double perovskites (e.g., PrBaCo₂O_{5+δ}) [84]. Conversely, the cathode, where water splitting and hydrogen evolution occur, requires materials with excellent electrical conductivity, strong catalytic activity for the hydrogen evolution reaction, and a porous structure. Ni is highly effective for the hydrogen evolution reaction and is a cost-efficient choice. Among the cathode materials used in SOECs, Ni-dispersed yttria-stabilized zirconia (YSZ) is the most common choice for the hydrogen electrode [85].

SOECs demonstrate a higher current density than both AECs and PEMECs at the same electrode potential, giving them a competitive advantage in hydrogen production rates. Studies on operational dynamics under varying power output conditions reveal that SOECs can rapidly transition from a 0% to 80% load in milliseconds while maintaining

performance integrity. However, the main challenges hindering the large-scale deployment of SOECs are cost-related issues and reliability concerns with supporting components [86]. Due to their superior hydrogen production rate and electrolysis efficiency, SOECs offer a promising option for integration with renewable energy sources, suggesting significant potential for future large-scale industrialization.

2.3.4. Photocatalytic Water Splitting

Photocatalytic water splitting is a promising method for using solar energy for hydrogen production [87]. Photocatalysts play an important role in this process. During photocatalytic hydrogen production, photocatalysts absorb photons from a light source, generating electron-hole pairs. Subsequently, photogenerated carriers migrate and separate within the catalyst. Most carriers are annihilated internally through Coulombic forces, while the remaining ones participate in redox reactions on the catalyst's surface, producing H₂ and O₂ [88]. The performance of a photocatalyst is closely related to its band gap. Photocatalysts with an appropriate band gap can generate more photogenerated carriers while reducing carrier recombination. This increases the number of carriers that can participate in redox reactions, thus improving hydrogen production efficiency. Additionally, the number of reaction sites and the specific surface area (SSA) are the key factors that influence the performance of photocatalysts [89].

Currently, there are many kinds of catalysts employed for photocatalytic water splitting, including metal oxides, metal sulfides, and carbon materials. TiO₂ is widely used in photocatalytic hydrogen production due to its excellent electron transfer capabilities and photostability. ZnO is another typical metal oxide photocatalyst because it has a suitable band position for hydrogen production. Metal sulfides like ZnS and CdS exhibit good catalytic activity because of their suitable band gaps. Due to their large SSA, excellent electron transfer capabilities, and controllable morphology, carbon materials such as graphene and graphitic carbon nitride (g-C₃N₄) have gained much attention in recent years. However, most photogenerated carriers recombine rapidly in catalysts, thus limiting the evolution rate of photocatalytic hydrogen production. Techniques such as doping, forming heterostructures, and the use of cocatalysts have been explored in order to improve the performance of photocatalysts [90].

The photocatalytic activity of materials can be improved when doping with heteroatoms in crystal lattices. Dopants can facilitate the separation and transfer of photogenerated carriers and provide additional reaction sites that promote redox reactions, thereby increasing the efficiency of H₂ production. Zhang et al. [91] reported a method using W single atom-modified g-C₃N₄ porous ultrathin nanosheets (W_{SA}-CN-PUNS) as a photocatalyst for hydrogen production. Their experimental results indicated that the incorporation of tungsten atoms can reduce the band gap of the material and inhibit carrier recombination. The catalytic activity of W_{SA}-CN-PUNS was found to be 4.1 times higher than that of undoped CN-PUNS and 9.7 times higher than that of pristine g-C₃N₄. Zhan [92] and coworkers developed a thermal treatment method to dope g-C₃N₄ with phosphorus and oxygen-containing groups. The introduction of P dopants and oxygen-containing groups can lead to a thinner layered structure of g-C₃N₄ and a higher separation rate of photogenerated carriers. This enables the carriers to reach the catalyst surface for redox reactions more easily. The optimal hydrogen evolution rate of the PO-CN can reach up to 11.2 times that of the original CN.

Constructing heterostructures can enhance photocatalyst performance by increasing the number of reaction sites and improving the separation capability of photogenerated carriers. Jiang et al. [93] developed an isotype step-scheme (S-scheme) heterojunction using g-C₃N₄ and liquid sulfur. This catalyst has a favorable layered structure with a large SSA. The optimized S-g-C₃N₄-E photocatalyst exhibited an optimal hydrogen evolution rate that is approximately 49 times higher than that of exfoliated g-C₃N₄. Wang et al. [94] proposed a 0D/1D Co₃O₄/TiO₂ p-n heterojunction based on n-type TiO₂ and p-type Co₃O₄. The hydrogen evolution activity of TiO₂ and Co₃O₄ is very low. However, the Co₃O₄/TiO₂ p-n

heterojunction can greatly enhance the photocatalytic hydrogen evolution rate, which can reach up to $3.46 \text{ mmol g}^{-1}\text{h}^{-1}$.

Cocatalysts can inhibit photogenerated carrier recombination, provide additional reaction sites, and reduce the overpotential of redox reactions, thus improving the hydrogen evolution activity of photocatalysts. Noble metals like Pt, Rh, and Au are common types of cocatalysts. However, it is unfeasible to use these expensive materials for large-scale commercial photocatalytic hydrogen production. Consequently, finding cheap cocatalysts with high catalytic activity has become a research focus in recent years. Xue et al. [95] used 1T'-MoS₂ as a cocatalyst for g-C₃N₄ nanocages (NCs), designing a 1T'-MoS₂/g-C₃N₄ NC composite photocatalyst. The presence of 1T'-MoS₂ increased the number of reaction sites on the photocatalyst surface and inhibited photogenerated carrier recombination. The hydrogen evolution rate of the 1T'-MoS₂/g-C₃N₄ NC composite can reach up to 162 times that of pure g-C₃N₄ NC and even 1.2 times that of Pt/g-C₃N₄ NCs. Liang et al. [96] used oxygen incorporating 1T and 2H multiphase MoS₂ (O-1T/2H-MoS₂) as a cocatalyst for two-dimensional (2D) layered porous graphite-like carbon nitride (p-g-C₃N₄). The O-1T/2H-MoS₂ has good performance as a kind of cocatalyst. The hydrogen evolution activity of O-1T/2H-MoS₂/g-C₃N₄ is 11 times that of 1T/2H-MoS₂/p-g-C₃N₄.

Solar energy is the most abundant renewable energy form, making photocatalytic hydrogen production a promising method for future hydrogen production. However, most research in this area does not achieve a 10% solar-to-hydrogen (STH) efficiency. Therefore, further research on improving photocatalyst performance is necessary for the large-scale commercial application of photocatalytic hydrogen production.

3. Hydrogen Storage

Hydrogen storage is recognized as a promising solution for medium- to long-term energy storage. It has a high mass energy density but a significantly lower volumetric energy density compared to conventional fuels (1/3000th that of gasoline). Therefore, a critical requirement in developing hydrogen storage is enhancing the volumetric energy density of hydrogen [97]. As is shown in Figure 8, current hydrogen storage methods are divided into three main types: gaseous, liquid, and solid-state storage. Each of these storage methods offers unique advantages and challenges, and their suitability varies depending on the specific context.

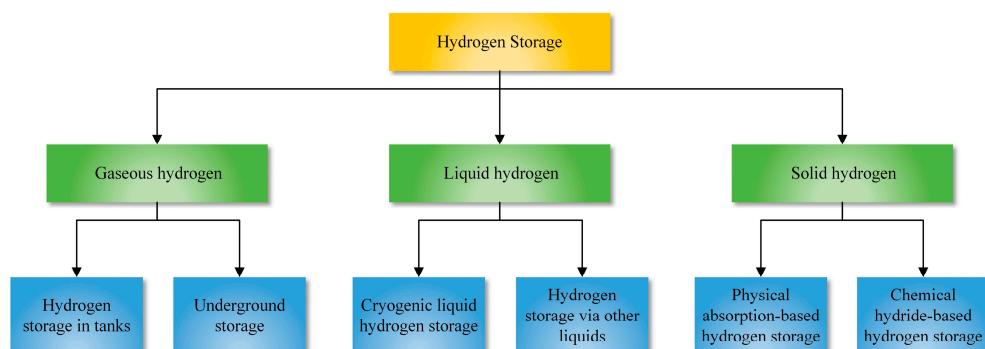


Figure 8. Hydrogen storage technologies.

3.1. Gaseous Hydrogen Storage

Compressing hydrogen gas is an effective and direct method for enhancing hydrogen storage, enabling the containment of larger hydrogen quantities within a constrained volume. Given that hydrogen is the least dense gas found naturally, this process allows for a more practical and space-efficient way to store hydrogen, addressing its low volumetric energy density.

3.1.1. Hydrogen Storage in Tanks

Storing compressed hydrogen in tanks is a widespread practice [98]. Tank storage of hydrogen has the advantage of requiring relatively relaxed operational conditions, as it can be conducted at ambient temperatures. Additionally, hydrogen stored in tanks is easily extractable and can be transported conveniently. Current research in this area primarily focuses on developing hydrogen storage containers. Common types of materials used for hydrogen storage containers include metal, polymers, and carbon fibers [99].

Despite the commercial applications of hydrogen storage in tanks, there are notable limitations to this method. A significant limitation is its storage capacity, which may not suffice for seasonal energy storage needs. Additionally, the operation of hydrogen storage tanks involves handling high gas pressures, presenting potential safety risks in case of accidents. Another challenge is that the storage pressure in tanks often exceeds that required for hydrogen utilization, thus necessitating advanced pressure regulation systems for the practical use of stored hydrogen [100]. Future research should focus on the development of low-cost, high-pressure hydrogen storage tanks, which is essential for further commercial application of gaseous hydrogen storage.

3.1.2. Underground Hydrogen Storage

Underground hydrogen storage offers an advantage of considerable capacity [101]. The utilization of depleted oil and gas reservoirs for underground hydrogen storage is a widely adopted approach in this regard [102]. This method leverages depleted oil and gas reservoirs by injecting hydrogen underground for storage, with the intention of future extraction and use. These depleted reservoirs are particularly advantageous due to their substantial subsurface storage capacity, making them suitable for large-scale hydrogen storage requirements [103]. One of the significant benefits of using depleted oil and gas reservoirs is the existing underground infrastructure. These decommissioned reservoirs have been equipped with the requisite surface and subsurface infrastructure, which can significantly reduce the costs of constructing new storage facilities [104]. Therefore, storing hydrogen in depleted oil and gas wells is currently the most economical method for underground hydrogen storage [105]. Moreover, oil and gas reservoirs provide a relatively stable storage environment, which is crucial for the safety of hydrogen storage systems. Within these reservoirs, hydrogen remains comparatively stable, effectively mitigating the risks of leakage and diffusion. Thus, the use of depleted oil and gas wells for hydrogen storage not only capitalizes on existing infrastructure but also contributes to the safety and cost-effectiveness of the storage system.

Storing hydrogen in salt caverns is emerging as a highly promising underground hydrogen storage approach. The porous and permeable nature of salt formations provides exceptional storage capacity, enabling significant hydrogen containment in relatively small underground spaces. Salt caverns possess considerable sealing properties, effectively preventing hydrogen leakage. This capability aligns well with the needs of large-scale hydrogen storage projects. Compared to hydrogen storage in depleted oil and gas reservoirs, salt cavern storage provides superior structural stability, which permits higher hydrogen pressures and, consequently, improved economic efficiency. Furthermore, this method facilitates rapid hydrogen extraction and injection, making it suitable for managing both seasonal and daily energy demand fluctuations [106]. Despite its excellent performance in hydrogen storage, the unit capital cost for salt cavern hydrogen storage is higher than that for depleted oil reservoir storage due to the higher operation pressure. However, its effectiveness has led to widespread global adoption [107].

As underground hydrogen storage emerges as a potential solution for seasonal energy demand imbalances, it encounters certain problems. Firstly, these storage facilities are usually located in specific geographical regions, potentially limiting the distribution of hydrogen. This limitation requires long-distance hydrogen transportation, leading to increased transportation costs and energy consumption. Additionally, while hydrogen generally remains stable within these reservoirs, there are cases where hydrogen may

undergo reactions with other substances influenced by microorganisms. Such reactions can alter the composition of the stored gas, potentially compromising the purity of the stored hydrogen.

3.2. Liquid Hydrogen Storage

A crucial disadvantage of gaseous hydrogen storage is the low volumetric energy density. In contrast, liquid hydrogen has a much higher energy density than that of gaseous hydrogen. Currently, methods of storing hydrogen in a liquid state include cryogenic liquid hydrogen storage and storing hydrogen via other liquids.

3.2.1. Cryogenic Liquid Hydrogen Storage

Cryogenic liquid hydrogen storage involves cooling hydrogen gas to about -253°C and storing it in specialized low-temperature adiabatic liquid hydrogen tanks. This process attains a remarkable hydrogen storage density of approximately 71 kg/m^3 , exceeding that of solid-state hydrogen storage methods [108]. Notably, the volumetric density of liquid hydrogen is around 845 times higher than that of its gaseous form, enabling the storage of larger hydrogen quantities in relatively compact containers.

To address the growing demands of the future liquid hydrogen industry, it is imperative to explore materials suitable for storage tanks that maintain high performance at low temperatures [109]. Stainless steel, recognized for its excellent low-temperature corrosion resistance and weldability, also notably resists hydrogen embrittlement. Consequently, it is extensively employed in the storage and transportation of cryogenic liquid hydrogen. However, its mechanical properties in specific challenging environments, such as saline atmospheres, require further enhancement. In comparison, aluminum alloys, notably lighter and more corrosion-resistant, also boast excellent processability. The 2219 aluminum alloy, in particular, has been utilized in the fabrication of liquid hydrogen storage tanks for rockets and commercial aircraft. Composite materials, as a promising lightweight alternative for liquid hydrogen storage, have garnered increasing attention in recent years. Despite their potential, research on composite materials remains in a nascent stage. Future advancements could position these composites as viable substitutes for traditional liquid hydrogen storage materials.

Nonetheless, cryogenic liquid hydrogen storage does present several issues. Firstly, it requires substantial initial investment, and the liquefaction process demands considerable energy, leading to high overall energy consumption. Additionally, there are issues of evaporation loss and safety concerns during the storage process [110]. As a result, cryogenic liquid hydrogen storage is currently mostly used in sectors with high hydrogen storage density requirements, such as aerospace and laboratory research. Despite its potential, the integration of liquid hydrogen into broader energy systems remains a relatively underexplored area [10]. Reducing the cost of the hydrogen liquefaction process is a prerequisite for the large-scale utilization of liquid hydrogen in energy systems.

3.2.2. Hydrogen Storage via Other Liquids

Hydrogen storage with organic liquids involves using liquid organic compounds as carriers in reversible catalytic hydrogenation and dehydrogenation reactions. The process begins with the catalytic hydrogenation of liquid organic hydrogen carriers like C_7H_{14} and $\text{C}_{13}\text{H}_{24}$ for safe hydrogen storage [111]. The hydrogenated liquid is then transported to distribution points, where it undergoes catalytic dehydrogenation in a reactor to release the stored hydrogen.

Organic liquid hydrogen storage offers several benefits. It provides high hydrogen storage density and allows for convenient storage under ambient conditions, ensuring safety and facilitating long-term storage across different seasons and regions. This method is particularly suitable for long-distance transportation. Additionally, organic liquid hydrogen storage can be used to supply hydrogen for existing hydrogen energy vehicles [112]. However, there are some problems associated with this technology, including high costs and concerns about the purity of the released hydrogen. Additionally, there are safety

concerns, such as the potential for vigorous reactions with oxidants in substances like C₇H₁₄, which could pose fire hazards.

In contrast, liquid solutions of borohydrides (NaBH₄) are employed for hydrogen storage, offering enhanced safety over organic liquid hydrogen storage [113]. NaBH₄ offers high hydrogen capacity, which can reach up to 10.8 mass%. However, the regeneration of NaBO₂ from the dehydrogenated NaBH₄ requires extreme temperature and pressure conditions, leading to higher costs for the process [114]. Therefore, ongoing research efforts are crucial to develop more cost-effective methods and enable the large-scale application of this hydrogen storage technique.

3.3. Solid Hydrogen Storage

Solid-state hydrogen storage transforms H₂ into a solid solution or hydride through physical or chemical processes. This method surpasses gaseous and liquid hydrogen storage in terms of higher volumetric density, reduced storage pressure, ease of transportation, enhanced safety, and reusability. Therefore, it is especially beneficial for applications requiring strict volumetric specifications for hydrogen storage. The primary classifications of solid-state hydrogen storage technologies are physical adsorption storage and chemical hydride storage.

3.3.1. Physical Adsorption-Based Hydrogen Storage

Hydrogen in its molecular form can be stored on the surfaces of certain porous solids through physical adsorption [115]. This process typically employs materials with large surface areas. Carbon-based materials such as activated carbon, carbon nanotubes, and graphite nanofibers, characterized by their highly porous structure, offer extensive micropores and mesopores for effective hydrogen adsorption and storage. Their significant chemical stability improves their performance in hydrogen adsorption and release. Specifically, graphite nanofibers exhibit remarkable mechanical strength, ensuring stability throughout hydrogen storage cycles [6,116]. Juneja et al. [117] proposed a method for hydrogen storage using a novel graphene–carbon nanotube hybrid material. The results indicate that the material in question has a strong hydrogen storage capacity, reaching up to 5.9 wt%. Furthermore, it allows for hydrogen storage at room temperature, with the process exhibiting good reversibility. Kostoglou et al. [118] investigated the hydrogen adsorption capacity of a nanoporous polymer/polyaniline-derived activated carbon (PDAC) material. The experimental results demonstrated that PDAC possesses an excellent capacity for hydrogen storage, reaching 5.5 wt%. It can achieve reversible hydrogen storage at a low temperature of 77 K and a pressure of 60 bar. Notably, this storage capacity is significantly higher than that of commercial activated carbon.

Zeolites represent another promising material in the realm of hydrogen storage. Zeolites are naturally occurring porous materials primarily composed of silicon, aluminum, and oxygen. Their crystal lattice structures encompass micropores and mesopores, offering numerous adsorption sites, which makes them excellent physical adsorbents. Zeolite-based hydrogen storage, typically performed under moderate temperature and pressure, demonstrates a high adsorption capacity [6], making it suitable for diverse hydrogen energy applications.

The significant advantage of physical adsorption for hydrogen storage lies in its safety. This method, which does not involve chemical reactions, minimizes potential safety hazards linked to chemical processes, thus providing a secure and reliable means of hydrogen storage. However, the current hydrogen charging and discharging process usually requires high pressures. Materials capable of hydrogen absorption and release under more moderate conditions should be explored for the commercialization of physical adsorption-based hydrogen storage.

3.3.2. Chemical Hydride-Based Hydrogen Storage

Chemical hydride storage, a pivotal technology in hydrogen storage, relies on a chemical reaction that combines hydrogen gas with chemical hydrides to form stable hydrides. This technology is primarily divided into two categories: metal hydride storage and complex hydride storage.

Metal hydrides, the most widely used materials in chemical hydride storage, are produced by hydrogen's reaction with metals and alloys. These materials are known for their controlled hydrogen absorption and desorption properties, allowing them to absorb and release hydrogen gas under suitable conditions. This reversible process reaches equilibrium at certain temperatures and pressures, permitting metal hydrides to absorb and release hydrogen as needed, which is crucial for effective hydrogen storage and release. However, the release of hydrogen from metal hydrides typically necessitates high temperatures due to the high enthalpy of their formation [119]. Table 4 provides a summary of the hydrogen storage capacities and release temperatures of some advanced metal hydrides. Metal hydride storage is characterized by high volumetric density and safety, attributed to its slow hydrogen release rate. The stability of these hydrides also renders them suitable for long-term energy storage, potentially addressing imbalances in energy demand over prolonged periods [120].

Table 4. Hydrogen storage capacities and release temperatures of different metal hydrides.

Hydrides	Hydrogen Storage Capacities (wt%)	Temperature (K)	Ref.
MgH ₂ -CPF	5.67	623	[121]
MgH ₂ -Ni/TCN	5.24	423	[122]
Mg ₉₁ Ni ₆ Cu ₃	5.6	448	[123]
TiV _{1.5} ZrCr _{0.5} MnFeNi	1.6	673	[124]
Mg ₁₀ Ti ₃₀ V ₂₅ Zr ₁₀ Nb ₂₅	1.19	418	[125]
(ZrTiVFe) ₉₀ Al ₁₀	1.3	298	[126]
Mg ₃₅ Al ₁₅ Ti ₂₅ V ₁₀ Zn ₁₅	2.5	375	[127]

Ammonia borane (NH₄BH₄), a complex hydride, is recognized for its potential in hydrogen storage. The decomposition of NH₄BH₄ occurs in four distinct steps, contributing to its high hydrogen storage density. However, the dehydrogenation of NH₄BH₄ is irreversible, posing significant challenges for its regeneration. NaAlH₄ is a cost-effective complex hydride. Chen et al. [128] have demonstrated that Co-doped nanoporous carbon scaffolds can enhance the hydrogen storage capabilities of NaAlH₄. LiAlH₄, another complex hydride, has a substantial hydrogen storage capacity of up to 10.5 wt%. Despite this, its dehydrogenation process is very slow under moderate conditions. Current studies are exploring the addition of catalysts such as metal oxide and carbon-based materials to facilitate the dehydrogenation process of LiAlH₄ [129].

Currently, hydride-based hydrogen storage is limited by reaction kinetics, poor reversibility, and high reaction temperatures. Future research needs to focus on developing more efficient hydrides for their application in more fields.

4. Hydrogen Transportation and Delivery

Considering the separate locations of hydrogen production and utilization, the development of secure and cost-effective hydrogen transportation and delivery methods is crucial for its industrial-scale application. Hydrogen transportation is primarily influenced by factors such as capacity, transport distance, and economic considerations. Given the versatility of hydrogen storage options, there are several choices available for its transportation. As seen in Figure 9, the most prevalent methods for hydrogen transportation and delivery encompass compressed gaseous tube trailer transportation, cryogenic liquid tanker truck transportation, and pipeline transportation [130]. Table 5 provides an overview

of hydrogen transportation options. These methods ensure that hydrogen, regardless of its production site, can be effectively and safely delivered to places of utilization, thus supporting the establishment of a hydrogen supply chain.

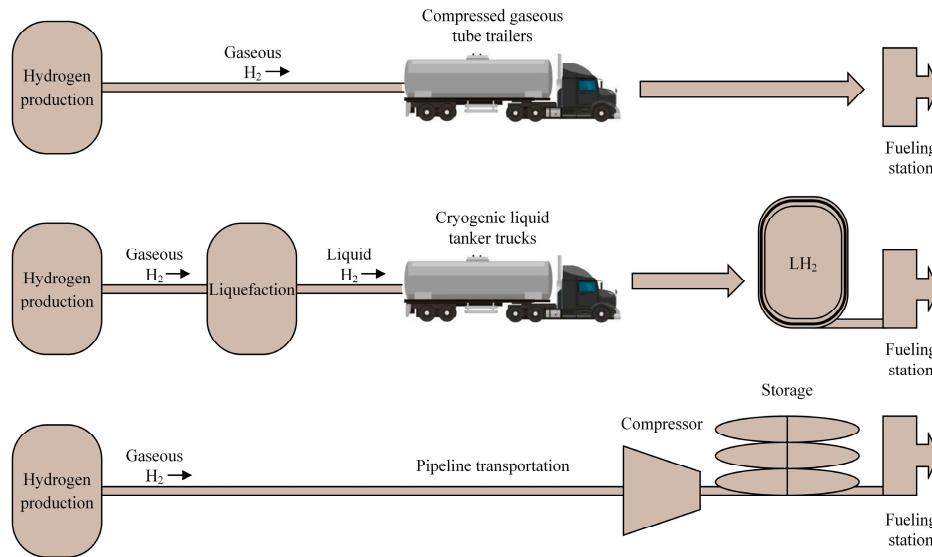


Figure 9. Hydrogen transportation and delivery technologies.

Table 5. Overview of hydrogen transportation options (L: low, M: medium, H: high).

Hydrogen Transportation Option	Capacity	Transport Distance	Energy Loss	Fixed Costs	Variable Costs	Deployment Phase
Hydrogen pipelines	H	H	L	H	L	Medium to long term
Gaseous tube trailers	L	L	L	L	H	Near term
Liquefied tankers	M	H	H	M	M	Medium to long term

4.1. Compressed Gaseous Tube Trailers

Transporting gaseous hydrogen via tube trailers, a traditional method, requires hydrogen to be compressed before loading it onto trucks. The pressure of compressed hydrogen, usually ranging from 200 to 500 bar, depends on cost considerations and hydrogen demand [131]. The energy required for hydrogen compression varies, mainly based on the final pressure level. For instance, compressing hydrogen to 160 bar consumes about 0.5 kWh of electricity per kilogram. If starting at a pressure level of 20 bar, compressing 1 kg of hydrogen to 200 bar requires approximately 0.7 kWh, whereas compression to 250 bar demands around 0.9 kWh of electricity per kilogram.

The transport capacity of a tube trailer is directly related to the pressure level of the hydrogen. For example, a trailer can carry 25,000 L of hydrogen compressed to 200 bar, equivalent to a weight of about 420 kg. This highlights the need for advanced hydrogen storage tanks capable of handling higher pressure levels, thereby enhancing tube trailers' transportation capacity.

Weisberg et al. [132] proposed a hydrogen delivery system based on glass-fiber tube trailers, operating at 200 K and 700 bar. The material properties of the glass-fiber containers and the stored hydrogen exhibit synergistic effects. Their research indicates that this method could reduce the cost of hydrogen transportation to below USD 1 per kilogram. Table 6 details the capacities, pressures, weights, and other parameters of hydrogen storage tanks made from diverse materials [133].

Table 6. Capacity and weights of selected tank types for compressed hydrogen transportation used in the assessment [133].

Tank Type	Volume (L)	Pressure (bar)	H ₂ Capacity (kg)	Tank Tare Weight (kg)
Steel cylinder container (SC)	23,800	200	400	26,298
Steel tubes (STs)	19,292	200	324	27,254
Composite super light container (CC)	45,500	250	957	18,854
Composite trailer (CT)	44,200	250	979	21,810

During the transportation of compressed hydrogen via tube trailers, there is an estimated loss of approximately 4% of hydrogen. Furthermore, not all hydrogen stored in tanks can be utilized; a small amount of hydrogen will remain in the tanks, leading to certain losses. Presently, the overall cost of transporting compressed gaseous hydrogen using tube trailers is around USD 2.86 per kilogram, making it a cost-effective option for hydrogen transportation [134,135].

The cost of transporting gaseous hydrogen via tube trailers is heavily influenced by distance. It is particularly advantageous for short to medium distances, typically less than 200–300 km, especially when the quantities of hydrogen to be transported are relatively small [136]. This method's efficiency and cost-effectiveness decrease over longer distances or for larger hydrogen quantities, suggesting the need for alternate transportation methods under such circumstances.

4.2. Cryogenic Liquid Tanker Trucks

Liquid hydrogen has a much higher energy density than gaseous hydrogen. The capacity of a single cryogenic liquid tanker truck is ten times that of a truck carrying gaseous hydrogen. Therefore, transporting hydrogen by cryogenic liquid tanker trucks can reduce the frequency of transport, leading to lower fuel and operational costs [137]. Although the operational costs of cryogenic liquid tanker trucks are higher than those of gaseous tube trailers, the unit cost of liquid hydrogen transportation still has an advantage. Due to the large capacity and high operational cost of cryogenic liquid tanker trucks, they are suitable for medium- to long-distance hydrogen transportation and delivery [138].

However, the H₂ liquefaction process is technically challenging. Moreover, H₂ liquefaction requires much more energy than compressing H₂, leading to a higher cost. Hence, it is economically unfeasible for small-scale plants to construct hydrogen liquefaction facilities. Currently, cost advantages in hydrogen liquefaction are only possible in very large-scale plants, combined with liquid hydrogen tanker trucks and related equipment. Additionally, hydrogen loss during liquefaction and transportation is a critical issue [139]. During transportation, due to the propensity of liquid hydrogen to evaporate or boil off, some hydrogen is inevitably lost from storage tanks. This loss is larger when the surface area to volume ratio of the tank is higher. Therefore, larger liquid hydrogen tanks have certain advantages. Maintaining tanks below the boiling point of hydrogen is essential to minimize losses, thus the insulation performance of liquid tankers significantly impacts the operation of the tanks [140].

4.3. Pipelines

Due to the uneven distribution of hydrogen production facilities, long-distance hydrogen transportation and delivery often becomes necessary. Pipeline transportation is considered an ideal method for this purpose. Hydrogen, having only 1/8th the density of natural gas, requires compression to pressures of 10–20 bar for pipeline transportation. In scenarios with large-scale hydrogen production and long transportation distances,

pipeline transportation of hydrogen demonstrates significant economic and environmental benefits [141].

Pipeline hydrogen transportation, while promising, faces significant safety challenges including leakage and hydrogen embrittlement. Due to the small molecular weight of hydrogen, it is more prone to leakage in pipeline transport compared to natural gas. In existing polyethylene natural gas pipelines, the leakage rate of hydrogen is 4–5 times that of methane. The hydrogen permeation rate in pipelines made of carbon steel is also higher than that of natural gas.

Many metal materials are susceptible to hydrogen embrittlement, which leads to reduced material toughness and increased fatigue crack propagation rates, ultimately resulting in material failure. Globally, natural gas pipelines typically employ X70 and X80 steel, whereas hydrogen pipelines use X42 and X52 steel [141]. Different steel grades are affected differently by hydrogen embrittlement, but all experience a decline in performance. The welding joints and small components of pipelines like bolts and rivets are more susceptible to embrittlement [142]. Additionally, during the hydrogen compression process before pipeline transportation, compressor components and other equipment can suffer from hydrogen embrittlement. Given that most existing gas pipelines are designed for natural gas, optimizing pipeline design and material selection is essential for adapting these infrastructures for hydrogen transportation and delivery.

In the early stages of hydrogen development, constructing pipelines specifically for transporting pure hydrogen is costly. Blending hydrogen into natural gas and utilizing the existing natural gas pipeline network for hydrogen transportation is a viable strategy to facilitate the shift towards pure hydrogen [143]. This blending process involves mixing produced hydrogen with natural gas before injection into the pipeline network. Given the extensive natural gas pipeline infrastructure in industrialized countries, even a small percentage of hydrogen in the natural gas blend can contribute significantly to hydrogen transportation, thereby fostering the growth of the hydrogen industry. Furthermore, a hydrogen–methane blend can be directly produced and injected at the start of the natural gas pipeline network, often originating from SMR technology [144].

It is crucial to recognize that blending hydrogen into natural gas pipelines can also lead to hydrogen embrittlement. To maintain the safety of facilities transporting this hydrogen–natural gas blend, many countries control the concentration of hydrogen within a low range. For example, the U.S. Department of Energy posits that current natural gas pipelines in the United States are capable of transporting blends with up to 20% hydrogen concentration. The UK's HyDeploy project demonstrated the successful transportation of a 20% hydrogen blend in natural gas, with minimal impact on the safety of pipeline networks [145]. Additionally, German research indicates that transporting blends with less than 20% hydrogen is feasible without compromising pipeline network safety [146].

In conclusion, existing natural gas pipelines can transport blends with low hydrogen proportions. However, transporting blends with a higher proportion of hydrogen or pure hydrogen would require significant modifications to the existing pipeline infrastructure. Although the capital investment required for building hydrogen pipelines is high, the service life of hydrogen pipelines is believed to be several decades [131]. Moreover, since these pipelines are typically buried underground, hydrogen transportation via pipelines is deemed safer and more environmentally sustainable than alternative methods.

5. Hydrogen Utilization

Hydrogen is not only an ideal form of energy but also a versatile industrial raw material, with diverse applications across different industries. As is shown in Figure 10, it is extensively used in several industrial sectors, such as in power systems, the transportation sector, and the chemical industry.

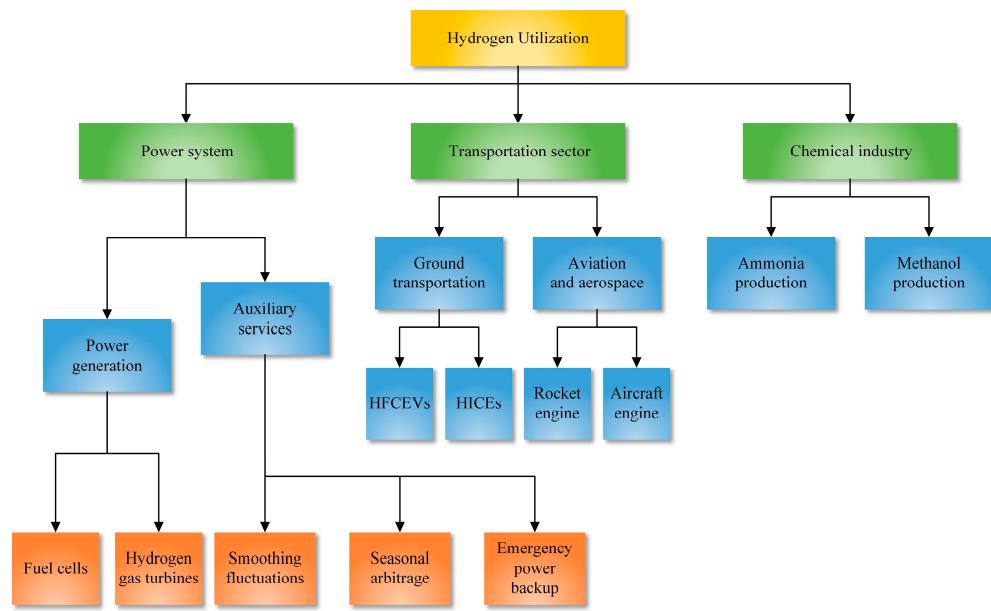


Figure 10. Hydrogen utilization methods.

5.1. Hydrogen Employment in Power Systems

Hydrogen, with its clean and nonpolluting characteristics, is an ideal source of power. In addition, hydrogen can function as a vital long-term energy storage method. The rapid development of renewable energy has made low-cost hydrogen production possible. Hydrogen can be utilized in novel power systems with a significant proportion of renewable energy, functioning both as a means to generate electricity and as energy storage, providing auxiliary services for the power system.

5.1.1. Hydrogen-Based Power Generation

Current power systems predominantly depend on fossil fuels for power generation. However, these nonrenewable fuels significantly contribute to environmental pollution. Therefore, there is an urgent need for a clean and sustainable energy source for power generation in power systems. Hydrogen power generation offers several advantages, including high energy density, zero emissions, and a rich supply of resources. Utilizing hydrogen for power generation can considerably reduce environmental pollution and help mitigate climate change. In future power systems, hydrogen power generation is expected to play a pivotal role. Currently, the main technologies for hydrogen power generation include hydrogen fuel cell power generation and hydrogen gas turbine power generation.

Hydrogen fuel cells, often regarded as the distributed power source of the 21st century, have garnered considerable attention globally. They directly convert the chemical energy of fuels into electricity. The operation principle of hydrogen fuel cells is shown in Figure 11. As a technology with zero emissions, high efficiency, and low noise levels, hydrogen fuel cell technology continues to evolve to meet the growing demand for clean energy solutions [147].

Fuel cells can be categorized based on operating temperatures into low-temperature and high-temperature fuel cells. Low-temperature fuel cells include phosphoric acid fuel cells (PAFCs), alkaline fuel cells (AFCs), and proton exchange membrane fuel cells (PEMFCs). High-temperature fuel cells encompass solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs). Each type of fuel cell exhibits distinct technological characteristics [148] (seen in Table 7).

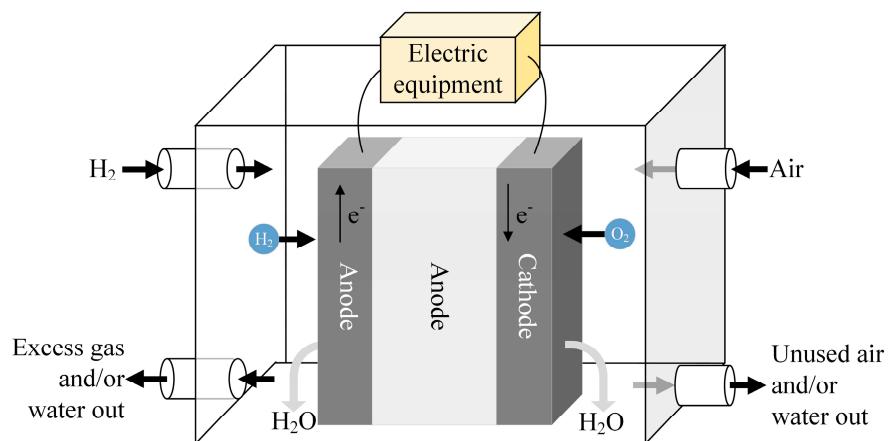


Figure 11. Operation principle of hydrogen fuel cells.

Table 7. Comparison of different fuel cell technologies [149].

Fuel Cell Type	Operating Temperature (°C)	System Output (kW)	Electrical Efficiency (%)	Combined Heat and Power (CHP) Efficiency	Advantages
PAFC	150–200	50–1000	>40	>85	Higher overall efficiency with CHP, increased tolerance to impurities in hydrogen
AFC	90–100	10–100	60	>80	Cathode reaction faster in alkaline electrolyte leads to higher performance, can use a variety of catalysts
PEMFC	50–1000	<1–250	53–58	70–90	Solid electrolyte reduces corrosion and electrolyte management problems, low temperature, quick start-up
SOFC	600–1000	<1–3000	35–43	<90	High efficiency, fuel flexibility, solid electrolyte reduces electrolyte management problems, suitable for CHP
MCFC	600–700	<1–1000	45–47	>80	High efficiency, fuel flexibility, can use a variety of catalysts, suitable for CHP

PAFCs, one of the earliest developed fuel cell technologies, stand out as one of the most mature and commercially viable options in the field. The use of PAFCs in over 200 stationary power stations with capacities above 200 kW and successful megawatt-level pilot projects operating for over 40,000 h demonstrate their economic viability and reliability. Despite these advantages, PAFCs face certain problems. One significant issue is the corrosiveness of the electrolyte used in PAFCs, which can limit their range of applications [149]. Additionally, PAFCs have a limited tolerance to CO in the input gas, necessitating a high level of hydrogen purity for efficient operation. As hydrogen production processes improve, PAFCs are expected to increase their technical and cost advantages, particularly in large-scale power plant applications. However, their efficiency, which does not exceed that of other fuel cell types, may limit their potential for further market expansion [150].

AFCs operate at relatively low temperatures using an aqueous solution of KOH as the electrolyte and Ni as the electrode catalyst. This composition provides AFCs with a cost advantage over other fuel cell types. Known for their simple structure and high electrical efficiency, AFCs are used in specific applications such as powering submarines and spacecraft [151]. Furthermore, the water produced as a byproduct of their operation can be effectively utilized. However, AFCs confront a significant challenge: the aqueous solution

of KOH can easily react with CO₂, forming carbonates. This reaction necessitates periodic replacement of the electrolyte, which can complicate maintenance and operation [152]. Furthermore, the use of asbestos in AFC diaphragms has raised environmental concerns due to its potential for pollution [153].

PEMFCs are a fuel cell technology characterized by their straightforward design, rapid startup, and excellent dynamic response characteristics [154]. PEMFCs utilize solid-state electrolytes, effectively addressing the corrosion issues typically associated with medium- and low-temperature fuel cells. However, they are sensitive to impurities in the fuel, requiring a high degree of fuel purity for optimal performance [155]. A significant limitation of current PEMFC technology is the requirement of noble metals for electrodes, leading to high costs that limit large-scale commercial utilization [156]. Future studies should focus on developing non-noble electrodes. Despite these challenges, the rapid response capabilities of PEMFCs make them promising for potential applications in future advanced power systems.

SOFCs and MCFCs both operate at high temperatures and offer distinct advantages. SOFCs are characterized by high current and power densities, which allow for efficient waste heat utilization and integration with gas turbines in CHP generation systems. However, their power output is not effective at moderate to low temperatures [157,158]. On the other hand, MCFCs are known for their reduced pollutant emissions and high electrical efficiency. Both SOFCs and MCFCs, being high-temperature fuel cells, typically have slower startup times and limited dynamic response capabilities compared to lower-temperature fuel cells [150]. Consequently, their primary applications are in stationary power generation and CHP scenarios, where these characteristics are less of a limitation [159].

Hydrogen gas turbines represent a crucial technology for the conversion of hydrogen energy into electricity, aiming to achieve low- or zero-carbon power generation. Leading companies such as Mitsubishi Hitachi Power Systems, General Electric Power, Siemens Energy, and Ansaldo Energia have already developed and manufactured gas turbine units that use hydrogen as their primary fuel source [160]. However, the advancement of hydrogen gas turbine technology encounters various challenges, including issues related to flame stability and NO_x emissions. To realize hydrogen-enriched or pure hydrogen power generation using gas turbines, modifications or even complete redesign of their combustion systems are required. Presently, major gas turbine manufacturers have made significant strides in technology and have initiated demonstration projects. Some turbine models have even entered commercial operation. Nevertheless, the overall development of this field is still in its early stages.

5.1.2. Storing of Energy and Auxiliary Services

Future power systems will integrate more renewable energy sources like wind and solar power. However, the output of wind and photovoltaic (PV) power plants is greatly influenced by weather, which may reduce the stability of the power system [161,162]. It is essential for power systems to involve energy storage systems to maintain their normal operation.

Energy storage can balance the random output of renewable energy sources. Surplus electricity can be used for hydrogen production. This process helps to smooth the output of renewable energy. Hydrogen storage can function as short-term energy storage to interact with the power system. Hydrogen can also function as long-term storage and provide some auxiliary services.

PEMFCs are particularly effective in responding to fluctuations in renewable energy output [163]. They enable hydrogen storage systems to adjust in real time to the varying outputs of wind farms and solar power plants. Hydrogen storage systems can absorb power during peaks in wind and solar output and release power during periods of low output [164,165]. This ability to store and release energy as needed is crucial for maintaining grid stability. Moreover, electrolysis cells and fuel cells can be coordinated with the grid to help adjust the grid frequency by either injecting or consuming energy. When combined

with inverters or rectifier monitoring systems, hydrogen-based equipment can also regulate voltage. This contributes to a more stable joint power curve from wind and solar sources, maintaining grid frequency and voltage at near-normal levels. Such integration enhances the grid-friendliness of renewable energy, making it a more reliable and consistent contributor to the power system. This synergy between renewable energy sources and hydrogen storage systems is key to the future of sustainable and stable power systems.

The disparity in electricity demand across different seasons presents problems, as currently there is not an ideal solution for seasonal energy storage. In this context, hydrogen storage emerges as an option, offering significant advantages such as large storage capacity and extended duration. During periods of surplus renewable energy generation, hydrogen can be produced at a lower cost and then utilized for electricity generation when the demand is high. The ability to be stored for extended periods, ranging from weeks to months, enables hydrogen storage to assist in achieving seasonal energy balance within the power system [166]. Furthermore, in regions where electricity prices fluctuate seasonally, hydrogen energy storage can present arbitrage opportunities. Seasonal price differentials are now in place in some areas due to the wide variation in electricity demand between seasons, with higher electricity prices during winter and summer. As these price differentials continue to expand, the feasibility of using hydrogen storage for seasonal arbitrage becomes increasingly viable.

Hydrogen's potential for long-term storage also positions it as a viable alternative for emergency backup power sources [167]. The mainstream options for such systems currently include diesel generators, lead-acid batteries, and lithium batteries. Diesel generators, while common, are noisy and environmentally polluting. Lead-acid and lithium batteries, though widely used, face challenges such as shorter lifespans, lower energy density, and limited endurance. In contrast, mobile hydrogen fuel cells offer an environmentally friendly, quiet, and long-endurance alternative for emergency power backup.

5.2. Hydrogen Employment in Transportation Sector

The transportation sector plays a vital role in urban infrastructure and significantly impacts the environment. This sector is a major contributor to carbon emissions, which are a key factor in global warming. Therefore, decarbonizing transportation is increasingly important in efforts to combat climate change [168]. Hydrogen, with its high energy density and zero-emission features, is considered a potential alternative fuel for the decarbonization of the transportation sector.

5.2.1. Hydrogen Employment in Ground Transportation

New energy vehicles have been developing rapidly in recent years. Currently, electric vehicles are the major type of new energy vehicles. Moreover, hydrogen-fueled vehicles are considered a promising choice for future new energy vehicles. Hydrogen-fueled vehicles mainly include hydrogen fuel cell electric vehicles (HFCEVs) and hydrogen-based internal combustion engine vehicles [169].

Fuel cells like PEMFCs and SOFCs are suitable for hydrogen-fueled vehicles. Recently, hydrogen fuel cell technologies have made significant advancements, which can improve the efficiency of HFCEVs. Companies such as Toyota, Honda, BMW, and Hyundai are developing HFCEVs. Toyota has developed a PEMFC for their HFCEVs. The power density of this PEMFC is 3.1 km/L and the maximum power output can reach up to 144 kW. BMW has focused on vehicles powered by liquid hydrogen [108].

The cost is a critical factor influencing consumer choices. Currently, hydrogen fuel cell vehicles do not have a cost advantage compared to electric vehicles and rely on policy subsidies for their deployment. According to Wang et al.'s analysis [170], hydrogen fuel cell vehicles demonstrate better economic viability in the field of large transport vehicles. It is predicted that in 2030, large transport vehicles using hydrogen fuel cells will have an advantage in cost. By around 2033, hydrogen fuel cell buses will have an economic advantage over buses powered by other energy forms. Furthermore, the cost of

passenger cars powered by hydrogen is predicted to be competitive before 2035. Although hydrogen fuel cells currently lack a market advantage in terms of lifecycle economics, the long-term outlook is positive. With expected reductions in hydrogen production costs, hydrogen fuel cells are likely to gain a gradual cost advantage, leading to independent market development.

In addition to hydrogen fuel cell vehicles, utilizing internal combustion engines (ICEs) to convert hydrogen into automotive energy represents a viable option. Research indicates that hydrogen-based internal combustion engines (HICEs) might offer cost advantages over hydrogen fuel cells in vehicle applications [171]. The concept of HICE is not new, with research dating back to as early as 1923. However, widespread adoption has been limited due to challenges in hydrogen production technology and associated costs.

Using hydrogen as a fuel for HICEs provides significant environmental advantages compared to gasoline [172]. Additionally, hydrogen gas exhibits favorable combustion characteristics in HICEs compared to fossil fuels. Hydrogen gas can combust across a wide temperature range, and its combustion performance remains robust under various conditions with low requirements for fuel/air ratios [173]. Hydrogen can also be blended with other fuels for combustion in ICEs to provide energy for vehicles. For instance, hydrogen can be mixed with natural gas to enhance adiabatic flame temperature [174], and it can cocombust with diesel, demonstrating excellent combustion performance [175]. This versatility makes hydrogen more accessible for utilization in internal combustion engines. Many automotive companies worldwide have conducted experiments on HICEs across various vehicle types, with promising results observed in the application of these engines in small passenger cars. The application of these engines in ground transportation vehicles holds significant potential for reducing carbon emissions and driving the sector's decarbonization.

However, the costs of compressing or liquefying hydrogen, along with high loss rates throughout its production, storage, and application, currently limit the broader utilization of hydrogen in ground transportation. The sector's shift towards hydrogen as a primary fuel source relies on further reductions in hydrogen costs and improvements in hydrogen production and distribution infrastructure [176].

5.2.2. Hydrogen Employment in Aviation and Aerospace Sectors

In the aerospace industry, the weight of rockets is a critical factor, and the energy density of the fuel used plays a vital role in optimizing this. Hydrogen, with its high energy density, is a preferred choice in rocket propulsion systems. The use of liquid hydrogen combined with liquid oxygen as rocket fuels provides the necessary energy while significantly reducing the overall weight of the rocket. The aerospace sector stands as one of the most extensively utilized domains for liquid hydrogen applications, with hydrogen serving as rocket fuel for over 50 years. The United States has been at the forefront of incorporating liquid hydrogen into space exploration technologies. Notable developments include the M-1 liquid hydrogen rocket engine in the 1960s, followed by the RL10 Centaur and J-2 high-energy rocket engine. More recently, the U.S. has continued to innovate with new hydrogen-fueled rocket engines such as the J-2X and BE-3 [15,177].

In aviation, which is the fastest mode of common transportation, fossil fuels are currently the predominant fuel choice [178]. With the annual growth in air traffic, the carbon emissions from aviation fuels have significantly impacted the environment. Hydrogen, as a clean and pollution-free energy source, offers a promising alternative. Due to its high energy density, aircraft utilizing hydrogen as fuel can achieve lighter weights, thereby increasing the nonstop flying distance [179]. Furthermore, hydrogen exhibits excellent combustion properties in the air, making it suitable for supersonic aircraft. Research on using hydrogen as aviation fuel has a long history. In 1956, Lockheed Aircraft Corporation manufactured the CL-400 aircraft powered by liquid hydrogen. The Soviet Union designed the TU-154 commercial jet in 1988, which included an engine that used liquid hydrogen as fuel. Boeing has shown significant interest in liquid hydrogen-fueled aircraft, evidenced by

the successful testing of the Phantom in 2013, which achieved a continuous nonstop flight of 4.5 h at high altitudes [15,177,180].

Hydrogen-powered aircraft offer advantages such as extended engine lifespan and efficient combustion performance. The adoption of liquid hydrogen as aircraft fuel can contribute significantly to environmental protection and reduce the aviation sector's reliance on fossil fuels. However, challenges such as the cost of liquid hydrogen fuel and safety considerations related to its storage and handling continue to be areas of focus in the development of hydrogen-fueled aviation.

5.3. Hydrogen Employment in Chemical Industry

Hydrogen is indeed a highly versatile and crucial industrial raw material, playing a significant role in chemical industrial processes. Among its most important applications is the production of ammonia and methanol, both of which are fundamental to a wide array of industrial products and processes.

5.3.1. Hydrogen-Based Production of Ammonia

Ammonia (NH_3) serves as a key component in fertilizers, providing essential nitrogen for plant growth. In industry, it serves as a primary refrigerant with favorable thermodynamic properties and acts as a precursor in the synthesis of various nitrogen-containing compounds. Overall, ammonia's multifunctional applications span agriculture, industry, and environmental sectors, making it a compound of great importance.

The production of ammonia is a significant global consumer of hydrogen. The primary method for synthesizing ammonia is the Haber–Bosch process [181], where H_2 reacts with N_2 under high temperatures (300–550 °C) and pressures (150–250 bar) in the presence of a catalyst. The reaction is represented by the following equation:



Nitrogen for this process is typically obtained from the air, while hydrogen is predominantly sourced from SMR. This process involves the reaction between methane and steam in the presence of a catalyst, resulting in the production of a synthesis gas rich in hydrogen. Subsequently, the produced hydrogen reacts with nitrogen to form ammonia in the Haber–Bosch synthesis, which is a critical step in the ammonia manufacturing process. The reaction process is illustrated in Figure 12. SMR for ammonia synthesis is highly favored due to the abundance of methane, the principal component of natural gas. The process's significance lies in its role as the primary method for large-scale ammonia production.

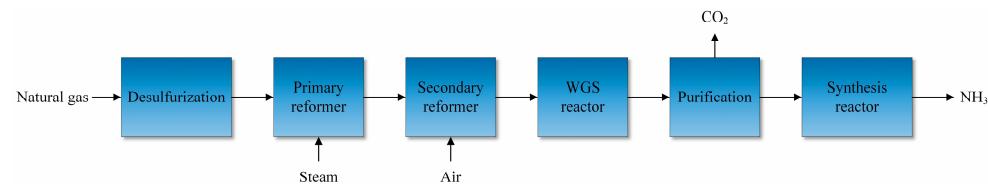


Figure 12. Schematic depiction of ammonia synthesis from natural gas [182].

However, natural gas reforming for hydrogen production relies on fossil fuels and generates a certain amount of carbon emissions. Therefore, utilizing hydrogen produced from water becomes a more environmentally friendly method for ammonia synthesis. The process of ammonia production based on water electrolysis for hydrogen is illustrated in Figure 13. The feasibility of this approach will improve with the development of low-cost renewable energy sources for hydrogen production in ammonia synthesis.

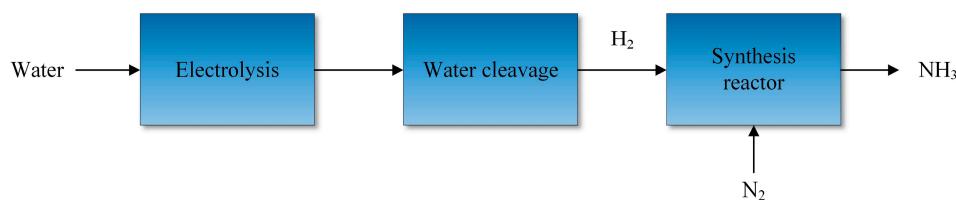


Figure 13. Schematic depiction of ammonia synthesis based on hydrogen produced from water electrolysis [182].

5.3.2. Hydrogen-Based Production of Methanol

Methanol (CH_3OH) is indeed a highly versatile compound with a wide range of applications across different industries. Its primary use as a chemical feedstock is crucial in synthesizing various important chemicals like formaldehyde, acetic acid, and polymers. Beyond its industrial applications, methanol also serves as a clean-burning alternative fuel in transportation and power generation, contributing to reduced emissions [183,184]. Additionally, as an energy carrier, it plays a role in storing renewable energy in processes like power-to-gas.

A significant portion of the world's hydrogen supply is used in the production of methanol. The Lurgi MegaMethanol process, originating from the German engineering company Lurgi [182], is a well-acknowledged technology for large-scale methanol production. The synthesis reaction for methanol is presented as follows:



The Lurgi MegaMethanol process starts with the SMR to generate H_2 and CO . The conversion of synthesis gas to methanol then occurs in a high-pressure reactor, typically using a copper-based catalyst. A key characteristic of the Lurgi MegaMethanol process is its operation at high pressures, enhancing methanol production efficiency. A well-performing catalyst enables the reaction to produce more methanol. The process also includes advanced separation and purification units to refine the methanol product. The Lurgi MegaMethanol process is reliable, energy-efficient, and scalable for large-scale industrial applications.

Due to CO_2 being one of the primary reactants, the synthesis of methanol is considered a method for CO_2 recycling, gaining increasing attention in recent years [185]. Comparatively, the production of renewable methanol using hydrogen combined with CO_2 can offer social benefits over fossil-based methanol and future electrochemical-based methanol [186]. The prospective use of low-cost renewable energy to produce hydrogen, which then reacts with carbon dioxide to generate methanol, represents an alternative approach to carbon capture and utilization (CCU) [187].

6. Challenges and Prospects of Future Hydrogen Supply Chain

Despite extensive research in hydrogen production, storage, transportation, and utilization, the establishment of a hydrogen supply chain still encounters multifaceted challenges, encompassing techno-economic, social, and policy aspects (Seen in Figure 14).

From a techno-economic perspective, the high cost of hydrogen production is the primary challenge. The most promising method for future green hydrogen production is water electrolysis. However, the cost of hydrogen production by water electrolysis ranges from USD 6–12 per kilogram, which is very high. Without the subsidies of governments, it is difficult for water electrolysis to achieve economic viability in the short term. Moreover, hydrogen is usually stored in a compressed gaseous state or a liquid state, and the processes of compression and liquefaction are technically challenging and expensive. The significant loss of hydrogen during the process of hydrogen storage and transportation (especially of liquid hydrogen) is another problem. Additionally, hydrogen embrittlement can add risks to hydrogen storage and transportation. To overcome these challenges, it is important to

utilize local renewable energy sources to provide low-cost electricity for water electrolysis. Noble metals are commonly used for hydrogen production and fuel cells, which contributes significantly to the high cost of hydrogen. Therefore, it is crucial to develop low-cost materials that can replace noble metals. Research on using transition metal oxides as alternative catalysts needs to be conducted to reduce hydrogen utilization costs. Developing materials resistant to hydrogen embrittlement that are also cost-effective will play a crucial role in hydrogen infrastructure development.

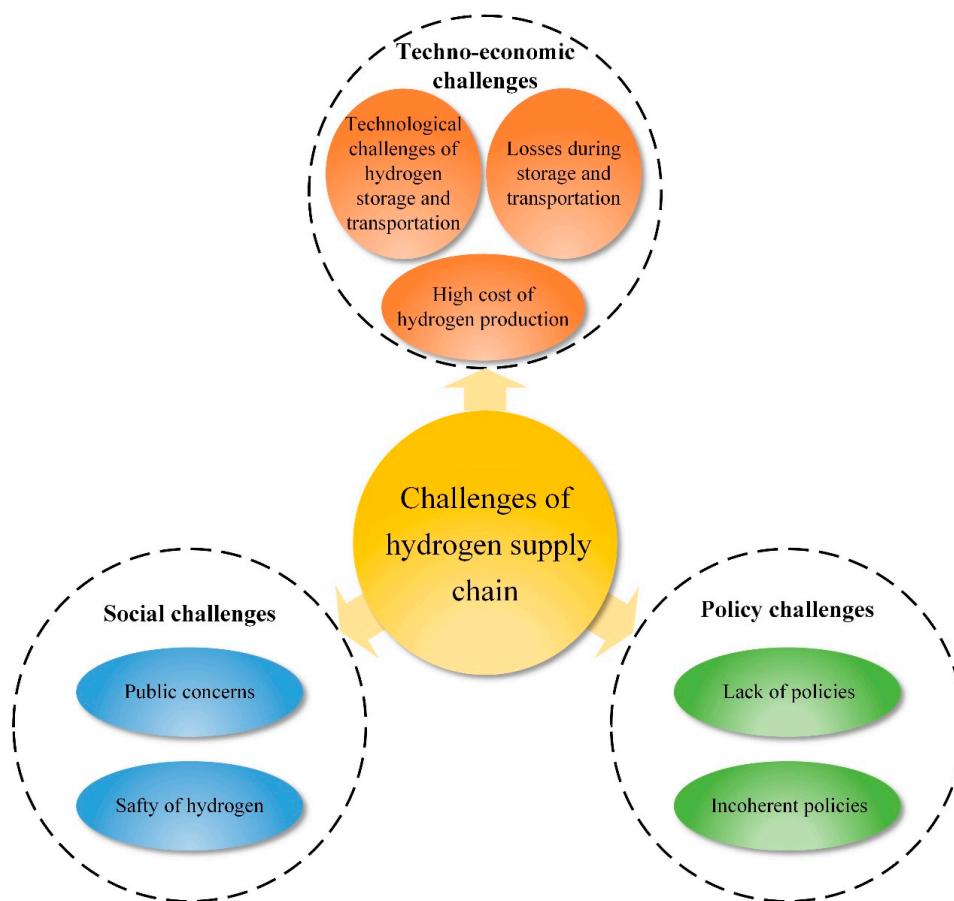


Figure 14. Challenges of hydrogen supply chain.

In terms of social challenges, the safety of hydrogen and the public's concerns about its large-scale application pose significant hurdles to the development of a hydrogen supply chain. Hydrogen, compared to natural gas, exhibits several hazardous properties such as ease of leakage, low ignition energy, a wide flammability range in air, extensive explosion range, and embrittlement effects. Additionally, hydrogen is odorless and burns with a nearly invisible flame, making its detection challenging and posing potential safety risks. However, hydrogen's safety is manageable, as evidenced by its widespread industrial use. Currently, hydrogen utilization is concentrated in large factories, limiting public interaction and familiarity and potentially raising safety concerns and resistance to its large-scale adoption. To mitigate these concerns and safely implement large-scale hydrogen applications, it is essential to train a cohort of operators with specialized knowledge and emergency responders equipped to handle disaster scenarios. Furthermore, public awareness campaigns are needed to secure stable public support. In the early stages of the hydrogen supply chain, information dissemination is a valuable tool. Governments should utilize the media to promote hydrogen energy and organize educational activities to enhance public understanding of hydrogen technology. This will not only increase the public's acceptance of hydrogen energy but also improve safety in its utilization.

Regarding policy challenges, a lack of consistent policy support can be a greater obstacle than technical issues in national hydrogen supply chain development. The U.S.A., a global leader in hydrogen development, suffers from a lack of coherent policy, often influenced by presidential prerogatives rather than national consensus. This inconsistency has impacted the development of hydrogen energy, with successive governments altering or halting ongoing hydrogen programs. In China, while preliminary incentives for hydrogen fueling station construction were introduced, subsequent policies revoked the planned financial support [188]. To foster the hydrogen supply chain, governments need to refine policies supporting hydrogen development, reducing or eliminating fossil fuel subsidies and reallocating those funds to subsidize hydrogen technologies, especially electrolysis. Additionally, building hydrogen infrastructure is a daunting task requiring broad societal support. Governments should actively align stakeholders with the hydrogen industry, promoting the construction of the hydrogen supply chain through collaborations between government, industry, and academia.

7. Conclusions

The construction of a hydrogen supply chain is essential for realizing a hydrogen economy in the future. A comprehensive hydrogen supply chain should include components of hydrogen production, storage, transportation and delivery, and utilization, each of which has a number of technologies with different levels of maturity. Due to the diversity of technologies, the construction of a hydrogen supply chain is complex. This paper reviews the technologies associated with the hydrogen supply chain and discusses the advantages and disadvantages of these technologies, which can help practitioners to select suitable technologies when constructing a hydrogen supply chain. Furthermore, this paper analyzes the challenges of constructing a hydrogen supply chain from techno-economic, social, and policy perspectives, and the prospects of a future hydrogen supply chain are presented. The main conclusions of this paper are summarized as follows:

1. Currently, 96% of hydrogen is produced from fossil fuels, but producing hydrogen from fossil fuels can cause carbon emissions. In contrast, hydrogen production from biomass through gasification and pyrolysis offers lower carbon emissions. Water electrolysis and photocatalytic splitting of water are considered ideal methods for future green hydrogen production because only H₂ and O₂ are produced during the process. AWE is the most mature method for water electrolysis, while PEME and SOE have better efficiency and flexibility.
2. Gaseous hydrogen storage is a low-cost and simple method for hydrogen storage. Due to the large capacity, underground hydrogen storage is an option for seasonal energy storage. Storing hydrogen in a liquid state can offer a high energy density, but the liquefaction process is technically difficult and expensive. An alternative is storing hydrogen in other liquids. Storing hydrogen in a solid state through physical adsorption or chemical reactions can achieve safe hydrogen storage and a high storage density.
3. Regarding hydrogen transportation, compressed gaseous tube trailers, which have lower technical complexity, are suitable for short-distance transport of small quantities. Cryogenic liquid tanker trucks can transport more hydrogen per trip than gaseous tube trailers, making them suitable for medium-distance transportation of larger hydrogen quantities. Pipeline transportation of hydrogen involves higher capital costs but offers a large transportation capacity, making it suitable for long-distance transportation of large volumes of hydrogen.
4. Hydrogen is a fuel and chemical feedstock with a wide range of applications. In the power systems sector, hydrogen can generate electricity through hydrogen fuel cells and hydrogen gas turbines. It can also serve as an energy storage method and provide auxiliary services for power systems, including smoothing fluctuations in renewable energy output, enabling seasonal energy storage arbitrage, and serving as an emergency backup power source. Liquid hydrogen has also been used as rocket

fuel due to its high energy density, and researchers have made significant progress in exploring its potential as a fuel for cars and aircraft. Moreover, hydrogen has been utilized in the large-scale industrial production of ammonia and methanol.

There are both commercially applied technologies and emerging technologies under research in each segment of the hydrogen supply chain. The advancement of these technologies is crucial for the construction of the hydrogen supply chain. The rapid development of renewable energy could facilitate low-cost hydrogen production in the future, which can increase public interest in the hydrogen supply chain. The promotion of hydrogen technology research, development of hydrogen infrastructure, and support of public and national policy is essential for constructing a comprehensive hydrogen supply chain.

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