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Review

Hydrogen Energy in Electrical Power Systems: A Review and Future Outlook

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Abstract: Hydrogen energy, as a zero-carbon emission type of energy, is playing a significant role in the development of future electricity power systems. Coordinated operation of hydrogen and electricity will change the direction and shape of energy utilization in the power grid. To address the evolving power system and promote sustainable hydrogen energy development, this paper initially examines hydrogen preparation and storage techniques, summarizes current research and development challenges, and introduces several key technologies for hydrogen energy application in power systems. These include hydrogen electrification technology, hydrogen-based medium- and long-term energy storage, and hydrogen auxiliary services. This paper also analyzes several typical modes of hydrogen–electricity coupling. Finally, the future development direction of hydrogen energy in power systems is discussed, focusing on key issues such as cost, storage, and optimization.

Keywords: hydrogen energy; electric–hydrogen coupling; electrolytic hydrogen production; fuel cells; future power systems

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1. Introduction

The continued growth of the world's population and urbanization rate has significantly increased energy demand and carbon emissions [1]. To reduce carbon emissions and preserve energy supply, countries worldwide are actively investigating ways to decrease fossil energy consumption and increase the use of renewable energy sources in the energy system [2]. In China, carbon emissions from the power sector account for nearly 40% of the total carbon dioxide emissions of the whole of society [3]. Integrating renewable energy sources is critical to achieving low-carbon operation of the power system and mitigating man-made climate change.

Natural factors can lead to intermittency and uncertainty in renewable energy generation. Some large megacities, such as Guangzhou, Shanghai, Tokyo, and New York, face challenges in managing a diverse range of new energy sources and addressing uneven load distribution. During low-demand periods when many renewable energy sources are connected to the grid, there is a problem of excess power, which can severely affect the safe and reliable operation of the power system [4]. The use of storage batteries to store excess renewable energies will effectively avoid the high penetration rate of renewable energy access to the grid caused by the grid pressure [5]. However, traditional energy storage, mainly lithium compounds and lead-acid batteries, generally have limited by cycle life, unsatisfactory charging and discharging efficiency, and self-discharge problems [6].

Through continuous exploration by researchers, hydrogen has emerged as an energy carrier with great potential. Hydrogen-powered electricity generation has zero carbon emissions and only water as a byproduct, thus not contributing to air pollution [7]. One of the key benefits of hydrogen is its high energy density. For the same mass, hydrogen

can provide three times more energy than gasoline when burned [8], and it can be derived from a variety of sources, including water, oil, natural gas, biofuels, and even sewage sludge [9,10]. A detailed comparison table is included below as Table 1. The table provides a comprehensive overview of how hydrogen fares against traditional fuels, highlighting its potential as a viable alternative for a low-carbon future.

Table 1. Comparison of energy content and energy density of hydrogen with other fossil fuels [3–10].

Fuel	Ratio of Energy and Mass (MJ/kg)	
	Higher Heating Value	Lower Heating Value
Hydrogen	142	120
Methane	55.5	50
Liquefied Petroleum Gas	50.0	46.1
Gasoline	46.4	44
Natural Gas	55	50
Coal (anthracite)	24	35
Ethanol	29.7	26.8

By producing hydrogen through electrolysis for power storage, renewable energy sources can be used more flexibly and their negative impact on the power grid can be reduced. The introduction of electrolyzed hydrogen into fuel cells will enable the development of distributed power sources, stand-alone power generation, and co-generation facilities. In addition, hydrogen electrification based on fuel cells will allow electricity to be produced, when and where it is needed, greatly increasing the flexibility of power generation and reducing losses. Therefore, research on key technologies for hydrogen energy production and storage, electrification, and hydrogen–electricity coupling will be an important part of building a new low-carbon power system.

This paper initially examines the current state of research on hydrogen preparation and storage technologies. It subsequently categorizes the essential technologies for hydrogen electrification and outlines typical approaches to hydrogen–electricity integration. Finally, it explores future directions for applying hydrogen energy, offering insights for future research in electricity power systems.

2. Current Status of Hydrogen Production and Storage

This section will review hydrogen electrolytic preparation and storage technologies, including the principles of electrolytic hydrogen production, preparation methods, electrolyzer technology, and several major types of hydrogen storage.

2.1. Review of Production of Hydrogen from Electrolytic Water

Industrial hydrogen production requires stable gas output, cost control, and simple preparation technology. The main industrial hydrogen production methods include hydrogen from fossil fuels, hydrogen from coke oven gas, hydrogen from methanol, etc. [11,12].

The process of utilizing natural gas, carbon dioxide and methane cracking to produce hydrogen has a long history. Under high-temperature and pressured environments with catalysts, by reacting with water vapour, these gases produce a variety of gases including hydrogen; coke oven gas is a by-product of the coke-making process, mainly including hydrogen and methane [13]. Hydrogen purification involves separating various gases from coke oven gas using solid adsorbents. Methanol reacts with water vapour at specific temperatures and pressures to yield hydrogen and carbon dioxide, which are subsequently separated via pressure swing adsorption to achieve increased hydrogen purity [14].

Although the above methods are relatively mature, they consume high energy in the preparation process and rely on fossil fuels, which will produce carbon-containing waste gas, and this is not conducive to reducing carbon emissions.

By running a direct current through a tank containing electrolytes, water can be broken down to produce oxygen and hydrogen. This process is known in the industry as electrolytic hydrogen production. The significant advantages of this method are that the raw materials are easy to obtain, the process is relatively simple, and no carbon emissions are generated during the preparation process, which reflects the environmental friendliness. However, it is worth noting that the electrolytic water process requires a large amount of electrical energy consumption, which is a major challenge of the method [15].

Alternative methods for hydrogen production, such as ethanol and saccharide reforming, bio-photolysis of water, photochemical water splitting, and high-temperature water splitting, are currently in the developmental phase and exhibit limited technological maturity [16]. Nowadays, as new energy technologies are increasingly deployed on a broad scale, the cost of electricity from photovoltaics, wind turbines, and similar sources continues to decline. This trend has sparked growing interest in the electrolytic production of hydrogen from water. The following section will introduce the principle of electrolysis of water and the development of electrolysis technology in detail.

(a) Technology for electrolyzing water

In an electrolytic water system, two electrodes are immersed in an electrolyte solution and linked to a power supply to enable current flow [17]. When a sufficient DC voltage is applied across the electrodes, water molecules undergo decomposition, yielding hydrogen at the cathode and oxygen at the anode. The electrolyte, introduced into the solution, enhances water conductivity and supports uninterrupted electron movement. Typically, the electrolyte is selected from acidic or alkaline substances and utilizes various ions as charge carriers, such as H^+, OH^-, O^{2-}, etc. [18].

To keep the electrolysis reaction controllable, most commercial electrolyzers use current control; the hydrogen production rate in this case can be fixed at a set current value [19].

The efficiency of a hydrogen electrolysis system relates to the voltage efficiency of the cell bank of the electrolysis unit and the efficiency of the associated auxiliary equipment when it is in operation [20]. The efficiency of an electrolytic water system can be quantified by the ratio of the fuel's high heating value (HHV) to the electrical energy input, expressed as Equation (1) [21]. In addition to the commonly used high calorific value efficiency, voltage efficiency is also one of the important indicators to evaluate the performance of water electrolysis systems [22]. The calculation formula of voltage efficiency is shown in Equation (2), and its level directly affects the energy consumption and cost of the electrolytic process. In addition, there are Faraday efficiency, thermal efficiency, and overall system efficiency, which provide an important perspective for a comprehensive understanding of the efficiency of hydrogen electrolysis systems [23–25]. The calculation of the Faraday efficiency is based on the comparison of the actual amount of hydrogen generated with the theoretical amount of hydrogen generated and is crucial for evaluating the chemical selectivity of the electrolysis process [24]. Thermal efficiency is concerned with the thermodynamic efficiency of energy conversion during electrolysis [25]. The calculation of thermal efficiency usually involves a comparison between the input electrical energy and all the thermal energy losses involved in the electrolysis process (such as electrolyte preheating, electrolytic cell heat dissipation, etc.), which is of great significance for optimizing the energy balance of the system [26]. Overall system efficiency is a comprehensive evaluation index that takes into account the efficiency of the electrolysis unit and its auxiliary equipment. It not only includes the voltage efficiency and Faraday efficiency of the electrolyzer itself, but also involves the efficiency of the power supply system (such as photovoltaic panels, wind turbines, and other renewable energy equipment), losses in the transmission and distribution of electrical energy, and the storage and transportation efficiency after electrolytic water hydrogen production. The calculation of the overall energy efficiency of the system is complex and requires consideration of multiple variables, but it provides a

comprehensive perspective for assessing the economic and environmental sustainability of the entire hydrogen electrolysis system.

$$\eta_{EL} = \frac{\mathrm{HHV}\left(\frac{\mathrm{kWh}}{\mathrm{kg}}\right) \times \text{Hydrogen production (kg)}}{\left[\frac{\text{Battery power input (kWh)}}{\text{Energy supply efficiency}}\right] + \text{Energy ancillary loss (kWh)}} \quad (1)$$

$$Voltage\ Efficiency = \frac{Theoretical\ resolution\ voltage}{Cell\ Voltage} \cdot 100\% \quad (2)$$

(b) Electrolyzer technology

Currently, common types of water electrolysis plants used for hydrogen production include alkaline water electrolyzers (AWEs), polymer electrolyte membrane electrolyzers (PEMEs), and solid oxide electrolyzers (SOEs) [26]. Among them, AWEs have a longer history of development and mature technology and dominate the electrolyzer market, while SOEs have a higher operating temperature, lower power consumption, and higher efficiency during electrolysis [27,28]. PEMEs have been developing rapidly in recent years and use proton exchange membranes instead of diaphragms and electrolytes in traditional electrolyzers. The three main types of electrolyzers and their characteristics are summarized in Table 2.

Table 2. Three main parameters of electrolytic cell technology [26–31].

Parameters	AWEs	PEMEs	SOEs
Technology maturity	Widespread commercialization	commercialization	R&D phase
Temperature/°C	60–80	50–80	600–1000
Pressure/bar	10–30	20–50	1–15
Current density/A·cm^{-2}	<0.45	1.0–2.0	0.3–1.0
Individual electric power/MW	6	2	0.15
Electrical efficiency/%	62–82	67–82	81–86
System energy consumption/kWh·m^{-1}	4.2–4.8	4.4–5.0	2.5–3.5
Area of electric stack/m^2	3–3.6	<0.13	<0.06
Hydrogen production rate/m^3·h^{-1}	1400	400	<10
Reactor life/kh	55–120	60–100	8–20
System life/a	20–30	10–20	-
Hydrogen production purity %	>99.8	99.999	-
Cold start time/min	60–120	5–10	>60
Hot start time/s	60–300	<10	900
Investment cost/USD·kW^{-1}	800–1500	400–2100	>2000

Electrolyzers are usually composed of multiple cell banks connected in series. This configuration allows for the cumulative voltage to increase significantly, even though each cell operates at a relatively low voltage of approximately 2 volts. Moreover, at high current densities, electrolyzers with parallel-connected banks of cells can be scaled to achieve megawatt outputs at relatively low voltages (up to a few kVs) [28]. For smooth operation of the system, a power supply unit and other energy supply auxiliaries are also required, as shown in Figure 1: Water is pumped into the electrolytic cell and heated by a heat exchanger to reach the operating temperature [29]. The power supply unit incorporates a transformer and rectifier to supply direct power to the electrolyzer. Following electrolysis, gases generated from water enter a gas separator for initial separation from water, followed by purification and drying processes [30].

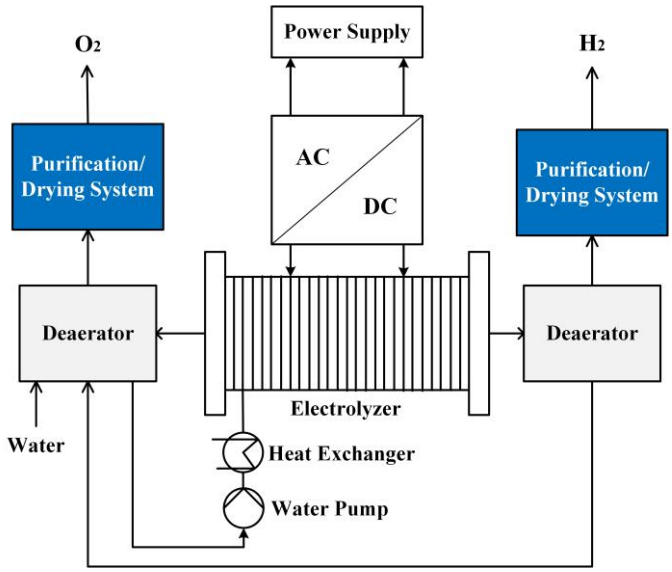


Figure 1. Electrolyzer structure.

2.2. Developments in Hydrogen Storage Technologies

For the past several years, there has been rapid growth in renewable energy generation. However, these energy sources are usually highly unstable and time- and seasonally dependent, severely affecting power system tides. To better consume renewable energy sources, reliable energy storage methods need to be developed to deal with the volatility and stochasticity of renewable energy sources. Common energy storage methods include pumped storage, compressed air, and chemical batteries [31–35]. Compared with them, based on the function that can smooth out the volatility and uncertainty of new energy sources, hydrogen has the advantages of a strong energy storage capacity, long storage time, and high flexibility, which can be used to realize the following functions [36,37].

Consumption time shift: When supply exceeds demand, hydrogen balances demand and supply by storing excess energy generated by renewable energy sources When demand increases, hydrogen can be used to generate electricity directly or inject electricity into the grid via fuel cells. Especially during times of reduced demand and lower electricity rates, energy can be stored directly in hydrogen to minimize energy expenses; during peak demand periods and when electricity prices are elevated, hydrogen is used to generate electricity to maximize returns. In addition, hydrogen has a much longer effective storage time of weeks or even months compared to batteries, which have an effective storage time of only a few hours or weeks [38].

Seasonal change response: Due to seasonal differences in new energy production, hydrogen can be used to transfer renewable energy sources across seasons. In addition, due to its high energy density, hydrogen can reach MWh or even TWh of storage capacity compared to the kWh to MWh storage capacity of chemical batteries [39,40].

Hydrogen storage and electrochemical energy storage, represented by lithium compound batteries, are two principal energy storage technologies. In terms of energy density, gaseous hydrogen has an energy density of approximately 33.6 kWh/kg, while compressed gaseous hydrogen at 700 bar has a volumetric energy density of about 1.7 kWh/L [41]. Lithium compound batteries have a maximum energy density of up to 0.3 kWh/kg, with a volumetric energy density of approximately 0.75 kWh/L [42]. Regarding cycle life, hydrogen fuel cells typically have a maximum cycle life of no more than 10,000 h, whereas lithium compound batteries generally offer around 2000 charge–discharge cycles, with each cycle experiencing a capacity loss of about 10–20%. In terms of cost, fuel cell power generation based on low-cost grey hydrogen is approximately USD 0.1–$0.2 per kWh, while the cost of green hydrogen produced from renewable energy ranges from USD 0.2 to USD 0.5 per kWh [43]. The generation cost for lithium compound batteries is around USD 0.1–USD

0.2 per kWh, with the potential to decrease to USD 0.05–USD 0.1 per kWh in large-scale grid storage projects due to economies of scale and technological advancements [44,45]. Additionally, hydrogen fuel cells generally have a start-up time on the order of minutes, contrasting with the second-scale response of lithium batteries. In terms of volume, lithium compound batteries are several cubic metres depending on requirements, while fuel cells typically have a volume of no less than several cubic metres [46,47].

From the above comparison, it is evident that hydrogen storage has significant advantages in energy density and service life, while lithium batteries excel in rapid start-up and device volume. Consequently, hydrogen storage is more suitable for seasonal and large-scale energy storage applications, such as addressing grid balancing and the intermittency of renewable energy sources, as well as applications requiring long endurance and high energy density, such as heavy-duty trucks, long-haul shipping, and aviation. On the other hand, electrochemical energy storage represented by lithium compound batteries is well suited for rapid-response applications, such as electric vehicles, grid frequency regulation, and home energy storage systems, as well as for power supply in portable devices such as mobile phones and laptops.

As mentioned above, the development of hydrogen storage technology is an essential prerequisite for the construction of hydrogen-containing power systems. Conventional solutions usually involve storing hydrogen in the form of compressed gases and cryogenic liquids; for extensive applications, underground hydrogen storage has been demonstrated to be an advantageous approach. In recent years, solid-state hydrogen storage has developed rapidly and is considered to be the safest mode of hydrogen storage [48].

To further understand the feasibility and practicality of various hydrogen storage and transportation methods, a comprehensive evaluation of their pros, cons, costs, and overall evaluations is essential. Table 3 summarizes the key aspects of several forms of hydrogen storage and transportation, based on the criteria mentioned.

Table 3. The advantages, disadvantages and cost evaluation of different hydrogen storage and transportation methods [41–48].

Category	Pros	Cons	Cost	Comment
Compressed Gaseous Hydrogen	Mature, suitable for short-distance transportation and distribution	The storage density is relatively low, requiring high-pressure containers, which limits the transportation volume	Short-distance transportation (within 200 km): USD 0.30 to USD 0.50 per kg of H_2. Long-distance transportation: USD 1.00 to USD 3.00 per kg of H_2	Suitable for localized or short-distance applications, but the costs for long-distance transportation are higher.
Liquid Hydrogen	High storage density, suitable for large-scale, long-distance transportation	The liquefaction process has high energy consumption, strict low-temperature storage with transportation requirements, and may have evaporation loss	Medium distances (around 500 km): USD 1.00–USD 2.00/kg H_2	Liquid hydrogen is suitable for long-distance transportation, but the high cost of the liquefaction process and cryogenic storage equipment has a significant impact on the overall cost. High storage density makes it suitable for long-distance transportation but requires considering the energy consumption during the liquefaction process.

Table 3. *Cont.*

Category	Pros	Cons	Cost	Comment
Chemical Hydrogen Carriers	Easy to store and transport at room temperature and pressure, with large transportation volume and high safety	Requires additional hydrogen extraction processes, affecting the overall efficiency	Depending on the chemical carrier used, the cost is between USD 1.00 and USD 5.00/kg H_2. e.g., the transport cost of using ammonia as a carrier is about USD 1.50–USD 3.00/kg H_2, and the additional cost of hydrogen extraction from the carrier should be considered.	Suitable for long-distance or cross-border transportation, safer at normal temperature and pressure, but the overall efficiency is low.
Metal Hydrides	High hydrogen storage density, stable storage, suitable for small-scale or portable applications	The hydrogen storage/release process is slow, and the cost of metal hydride material is high	USD 5.00–USD 10.00/kg H_2, mainly due to high material cost and low efficiency of hydrogen storage/release process.	High storage density, but the process of releasing hydrogen is complex and usually used for special applications rather than large-scale transportation.
Solid Hydrogen	Storage density is extremely high, theoretically	The preparation and processing techniques are complex with high cost, and mainly in the lab stage	At present, it is mainly in the research stage, and the economy has not been fully evaluated. If the practical application is considered, the cost may be extremely high, far more than other forms.	Suitable for experiments and specific applications; commercial and large-scale applications are not yet available.

(a) Compressed Gaseous Hydrogen

Compressed gaseous hydrogen is a common method for hydrogen storage and transportation. By compressing hydrogen gas to high pressures, its volume is significantly reduced, making storage and transportation more economical and efficient. Containers for storing compressed hydrogen are typically made from high-strength materials, such as carbon fibre composites, to withstand pressures exceeding 700 bar [49]. Compressed hydrogen can be transported via specially designed high-pressure hydrogen transport vehicles, pressurized pipeline systems, or dedicated trains. As a key form of hydrogen storage technology, compressed gaseous hydrogen benefits from a high gravimetric energy density (approximately 33.6 kWh/kg) and mature technology, making it widely applicable in fields such as transportation and energy storage [50].

However, there are several challenges associated with compressed gaseous hydrogen. Firstly, high-pressure storage requires robust containers, such as high-pressure cylinders, which significantly increase equipment and maintenance costs [51]. Secondly, the compression process is energy-intensive, potentially reducing overall energy efficiency. Additionally, while hydrogen has a high gravimetric energy density, its volumetric energy density is relatively low, which can be a limiting factor in applications requiring high volumetric energy density. The flammability and explosiveness of hydrogen also necessitate stringent safety measures, adding complexity to storage and transportation [52,53].

Future development directions for compressed gaseous hydrogen technology include enhancing compression efficiency and reducing storage costs. This involves developing new, efficient compression technologies and materials to lower the overall economic burden,

as well as integrating with renewable energy sources (such as wind and solar power) to reduce carbon emissions [54].

(b) Liquid Hydrogen

Hydrogen can be liquefied by cooling it to extremely low temperatures, approximately −253 °C (20.28 K). Liquid hydrogen, stored in insulated tanks, can be transported overland [54]. As an efficient method for hydrogen storage and transportation, liquid hydrogen presents significant advantages in current technology and applications [55]. However, several challenges constrain its development, like energy efficiency (liquefying hydrogen requires approximately 30–40% of the hydrogen's energy to operate the refrigeration equipment, which severely impacts economic viability) [56]; boil-off losses (even with high-efficiency insulation materials, liquid hydrogen will evaporate at a rate of 0.1–0.3% per day during storage and transportation [57]. This gradual evaporation means that long-term storage can result in significant hydrogen losses, particularly during long-distance transport, which affects overall economics); cost problems (the costs of cryogenic storage tanks, liquefaction equipment, and transportation infrastructure are high [58]. These costs can substantially increase the unit cost of liquid hydrogen, especially in small-scale applications); and safety concerns (the extremely low temperature of liquid hydrogen poses risks of personal injury to operators, and the highly flammable nature of hydrogen increases the risk of fire or explosion. Furthermore, the ageing of insulation materials can exacerbate boil-off losses and safety risks) [59].

Future research on liquid hydrogen will focus on developing more efficient liquefaction technologies to reduce energy consumption [60]. For instance, employing advanced heat exchange technologies and more efficient compressors or utilizing renewable energy sources to drive the liquefaction process could significantly lower production costs. The development of new and high-efficiency insulation materials, such as those based on nanotechnology, could further reduce evaporative losses during storage. These materials would more effectively block heat transfer, enhancing the thermal efficiency of storage tanks [61]. Expanding hydrogen infrastructure to facilitate the large-scale application of liquid hydrogen will also contribute to reducing its cost.

(c) Chemical Hydrogen Carriers

Hydrogen can be stored and transported in the form of chemical compounds through chemical reactions. Compounds that can react with hydrogen include ammonia (NH_3), methanol (CH_3OH), and liquid organic hydrogen carriers (LOHCs) such as N-ethyl carbazole and dimethyl toluene [62]. Compared to compressed hydrogen gas, chemical hydrogen carriers can store hydrogen at a higher volumetric energy density under ambient temperature and pressure. This form of hydrogen has a higher energy density and lower storage pressure requirements, which helps to reduce storage and transportation costs. Many chemical hydrogen carriers have a long history of commercial use, such as ammonia in the fertilizer industry, indicating relatively mature technologies [63,64].

There are several challenges associated with chemical hydrogen carriers. Firstly, hydrogenation and dehydrogenation processes for chemical carriers like ammonia often involve complex and energy-intensive procedures, requiring sophisticated equipment [65]. The processing of chemical hydrogen carriers may produce by-products or waste, necessitating extra treatment steps and potentially increasing overall costs [66]. Handling ammonia and certain hydrogen compounds can also involve environmental and safety concerns, such as the toxicity of ammonia and the high-temperature stability issues of hydrogen compounds [67]. Moreover, the efficiency and economic viability of hydrogen recovery and reuse remain critical issues that need continuous optimization of related technologies and processes.

Research on chemical hydrogen carriers will focus on several key areas [68–70]: firstly, improving the efficiency of hydrogen dehydrogenation and hydrogenation processes and developing low-energy, cost-effective chemical hydrogen carrier technologies to reduce costs; secondly, enhancing the safety of chemical hydrogen carriers to minimize envi-

ronmental and health impacts; and finally, investigating and developing new chemical carriers to improve their advantages in terms of energy density, storage conditions, and processing costs.

(d) Metal Hydrides

Under specific conditions, hydrogen can react with certain metals or metal alloys to form hydrides, which can release hydrogen gas under certain conditions. Magnesium hydride (MgH_2) and sodium borohydride ($NaBH_4$) are notable for their high hydrogen storage density [71]. Metal hydrides are significant in hydrogen storage and transportation due to their high hydrogen storage density and relatively low safety risks. Their high gravimetric energy density and lower storage pressure requirements enable hydrogen to be stored in solid form at ambient or moderate temperatures, thereby reducing the safety risks associated with high-pressure storage [72,73]. The reactions involved in storing and releasing hydrogen with metal hydrides are reversible, allowing for efficient recovery and reuse of hydrogen.

There are still some mountains researchers need to conquer associated with metal hydrides. Firstly, the hydrogen release process typically requires high temperatures, which can lead to higher energy consumption [74]. Secondly, the hydrogen storage capacity of certain metal hydrides may be limited by material stability and cycle life in practical applications, potentially causing performance degradation over time [75]. Furthermore, the production and handling costs of metal hydrides are relatively high, requiring precise control and advanced technology during preparation, which can increase the overall economic burden [76].

As a result, researchers are focusing on several key areas: optimizing the synthesis and processing of hydrides to improve hydrogen adsorption and release efficiency, reduce energy consumption, and lower production costs; developing new metal hydride materials to enhance hydrogen storage capacity and cycle stability; and investigating and optimizing the operational temperature ranges of hydrides to reduce energy consumption and improve the economic viability of practical applications.

(e) Solid Hydrides

Under extremely low temperatures and high pressures, hydrogen can crystallize to form solid hydrogen, which can be stored in specialized materials [77]. Solid hydrogen materials allow for storage at lower pressures, reducing the need for high-pressure tanks, and they typically offer higher hydrogen density, thereby enhancing the energy density of hydrogen storage [78]. Solid hydrogen storage systems generally exhibit good long-term stability and lower leakage risks, making them safer compared to liquid hydrogen and high-pressure gaseous hydrogen.

However, solid hydrogen also presents several challenges. The cost of storage materials is relatively high, particularly for rare metal hydrides [79]. Moreover, the processes of hydrogen release and adsorption often require higher temperatures and pressures, which can increase the system's energy consumption and complexity. The reaction rates and hydrogen release rates of solid hydrogen storage materials may also limit their efficiency and practicality in certain applications [80]. The material's cycle life and hydrogen recovery efficiency are important factors that need to be addressed.

Researchers are focused on developing new types of solid hydrogen materials, seeking more cost-effective solutions, and optimizing the processes of hydrogen adsorption and release [81].

2.3. Application of Integration of Hydrogen Storage with Renewable Energy Sources

The integration of hydrogen storage with renewable energy sources is a crucial pathway to achieving sustainable energy systems. Hydrogen storage technologies enable the conversion of intermittent renewable energy production, such as wind and solar power, into reliable and adjustable hydrogen energy storage. Hydrogen energy and renewable energy have been applied in various industrial scenarios [82–86]. The American company

SunHydrogen has developed a photocatalytic technology that utilizes semiconducting materials with high photocatalytic performance to enhance hydrogen production efficiency, aligning hydrogen production closely with solar energy generation to achieve a sustainable hydrogen supplement [82]. The Norwegian Hywind project employs floating wind turbines to enable hydrogen production and storage under variable wind conditions [83]. In Southern Australia, the Hydrogen Park project utilizes electricity generated from hydropower stations for hydrogen production and storage, demonstrating the practical integration of hydropower with hydrogen energy [84]. In addition, Europe has achieved the integration of hydrogen energy with biomass energy. These application cases illustrate various models of hydrogen storage technology within renewable energy systems, advancing technological development and providing valuable practical experience and demonstration effects for future energy systems [85,86].

3. Key Technologies for Hydrogen Electrification

Hydrogen energy is usually connected to the power system through an electrification process as an energy carrier; the electrification of hydrogen is usually realized in the form of gas-to-electricity conversion to release energy. In this section, hydrogen electrification technologies based on fuel cells will be introduced, and medium- and long-term storage methods and ancillary services based on hydrogen energy will also be summarized.

3.1. Hydrogen Electrification Technology

Fuel cells can maximize the energy contained in hydrogen and can convert the chemical energy of hydrogen directly into electricity with an efficiency of 60–80% and only water as a by-product of the reaction [87].

(a) Principle of operation

As shown in Figure 2, a hydrogen fuel cell delivers hydrogen to the anode, initiating ionization to release electrons and H^+ ions, while air is supplied to the cathode to generate negative oxygen ions [88]. Like an electrolyzer, various fuel cell types vary in their charge transfer direction and electrolyte charge carriers, potentially producing the water on either side. Typically employing platinum-coated carbon materials as catalysts, different fuel cell types interact with diverse electrolytes. Table 4 provides an overview of these electrolytes' characteristics. Later, an example of a polymer electrolyte membrane fuel cell (PEMFC) will be discussed.

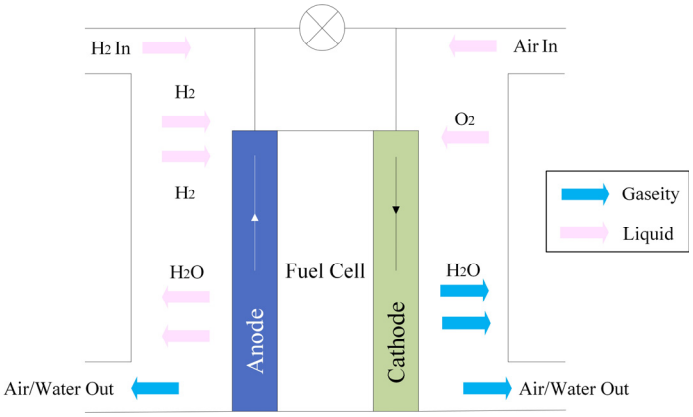


Figure 2. Fuel cell working principles.

Table 4. Operating temperature, cell voltage efficiency and advantages and disadvantages of different types of fuel cells [89–94].

Typology	Operating Temperature	Battery Pack Voltage Efficiency	Advantage	Drawbacks
Proton Exchange Membrane Fuel Cell (PEMFC)	80 °C–100 °C (low temperature) or 200 °C (high temperature)	50–60%	Fast start-up and versatility	Catalysts are expensive
Solid Oxide Fuel Cells (SOFCs)	800 °C–1000 °C	60–80%	With solid electrolytes, the reaction heat is reusable and less costly.	Presence of metal corrosion problems
Alkaline fuel cell (AFC)	Approx 70 °C	About 60%	Good current response	Limited application scenarios
Molten Carbonate Fuel Cell (MCFC)	Approx 650 °C	60–80%	Good conductivity and high current density	Slow start, only for large-scale use.
Phosphoric acid fuel cell (PAFC)	Approx 180 °C	More than 80%	High efficiency	Low current density and high catalyst cost

(b) Structure of Fuel Cell Systems

A typical fuel cell system consists of a battery pack and its auxiliary equipment, including hydrogen tanks, pumps, air compressors, power electronics, thermal management systems, etc., as shown in Figure 3. A single fuel cell can produce a rated voltage of 0.6 V to 0.8 V at rated loads [95], and the voltage of the battery pack can be boosted by increasing the number of cells. Similar to the electrolyzer, paralleling fuel cell packs can increase the current and thus the output capacity. In addition, the current can be increased by increasing the effective area of the cells. Typically, fuel cell systems are also equipped with a number of auxiliary devices, wherein a compressor is used to feed air into the reaction tank, and a hydrogen storage tank can output hydrogen to the reaction tank at a controlled flow rate and pressure. In addition, the fuel cell system typically includes a condenser to cool the incoming compressed air, alongside a humidification device that prevents the proton exchange membrane in the reactor tank from drying out [96]. Typically, an inverter is also installed to convert the generated DC power to AC power.

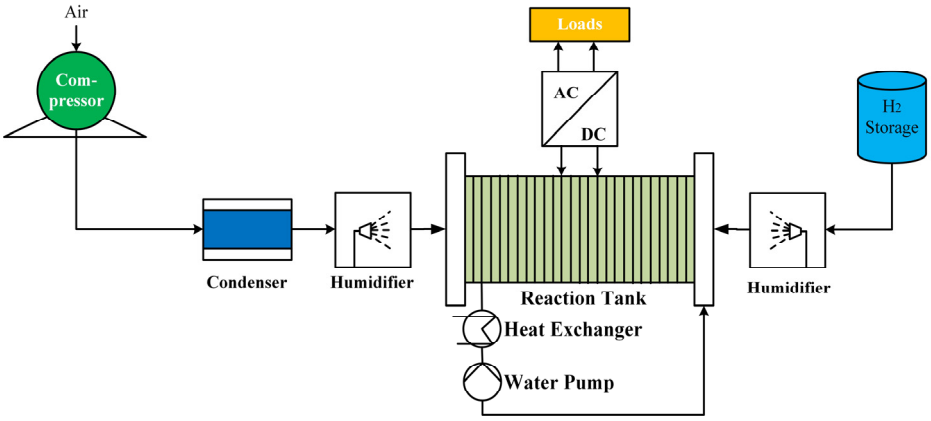


Figure 3. Fuel cell system structure.

Typically, the highest efficiency of a fuel cell is attained when supplying power to the load. Lowering the current density below its peak power density can mitigate cell voltage losses, thereby enhancing cell efficiency [97]. Systematically, fuel cells can be

engineered to operate within the optimal efficiency range through strategic system control and design [98,99].

3.2. Hydrogen Ancillary Service Technologies

Hydrogen energy systems, comprising both fuel cells and electrolyzers, offer versatile ancillary services to the grid. These include peak load management, frequency regulation, mitigation of negative electricity pricing occurrences, voltage stabilization, and emergency power restoration efforts [100].

Similar to other forms of energy storage, hydrogen can initially address issues related to power supply constraints in transmission and distribution lines caused by inadequate capacity [101]. The cost of scheduling to address the "congestion" of power flow can be significantly higher. To solve the "congestion" problem of tidal currents, the dispatch costs increase considerably. Flexible application of the electrolysis–electrification process of hydrogen will allow efficient and low-cost regulation of grid currents.

Frequency regulation aims to uphold grid stability by closely aligning grid frequency and amplitude with their respective reference values. This is achieved through coordinated injection or absorption of power, ensuring equilibrium between electricity supply and demand. In current power systems, frequency regulation typically operates with two tiers. The initial tier involves primary frequency control, which ensures ongoing management during brief deviations from the nominal frequency [102]. For frequency deviations of more than 30 s, a second level, frequency restoration control, is required. This level of control has a greater capacity to provide frequency regulation over longer time scales. Fuel cells and electrolyzers can implement these two levels of frequency control, which can increase or decrease the reference value of power output based on a frequency signal [102]. During instances of frequency reduction, the fuel cell can ramp up power generation, while the electrolyzer can adjust electrolysis rates downward. This capability makes it a cost-effective device enabling efficient demand response.

Helping to reduce the negative prices that occur in the electricity market is a major advantage of electrified hydrogen equipment. Negative electricity prices occur primarily due to a lack of flexibility on the generation side. In electricity markets with high hydrogen penetration, a similar but more flexible regulation of the spot price of electricity can be achieved by increasing or decreasing the rate of hydrogen production in the electrolyzer, or by adjusting the output power of the fuel cell, similar to that of a generator.

Hydrogen devices offer an additional capability known as voltage support [103]. These devices, linked to the grid through power electronic converters, can regulate the power factor of both the fuel cell and electrolyzer. This regulation involves adjusting their power outputs to meet the voltage requirements at the grid connection point. In the event of a power outage, the fuel cell allows for a noiseless and fast black start compared to a conventional generator [104].

3.3. Hydrogen–Electric Power Systems

Like gasoline engines, certain internal combustion engines or turbines can operate directly using hydrogen, generating power as a result. However, owing to hydrogen's comparatively lower volumetric energy density, the thermodynamic efficiency of hydrogen internal combustion engines typically ranges from 20% to 25%, which is less than that of gasoline internal combustion engines [105]. In addition, although no carbon dioxide is released, the combustion of hydrogen produces nitrogen dioxide as an air pollutant [106]. The use of fuel cells as a power source in a hydrogen–electric power system will be effective in avoiding air pollution.

Vehicles equipped with fuel cells will differ from conventional new energy vehicles in that the driving distance is limited due to insufficient battery capacity; the former will have a longer driving distance. It is expected that 3% of cars sold globally in 2030 will be fueled by hydrogen, and by 2050, the percentage could reach 36% [107]. Numerous companies are actively advancing fuel cell powertrain technology, focusing on enhancing both reliability

and safety. Toyota's Mirai fuel cell vehicle, for instance, utilizes a commercially available PEMFC with a volumetric power density of 3.1 km/L and a peak power output of 144 kW. Future advancements aim to enhance the safety and compactness of hydrogen storage in vehicles. Presently, the majority of commercial hydrogen fuel cell vehicles utilize high-pressure compressed hydrogen fuel tanks for storage.

In recent years, there has been notable progress in the development of fuel-cell ships alongside fuel-cell vehicles. Ship emissions during navigation contribute approximately 2.5% to global greenhouse gas emissions. Fuel cells offer sufficient power for ships travelling long distances and can fulfil the auxiliary energy requirements of large vessels, contrasting with battery-powered ships. This trend is also observed in fuel cell trains, with hydrogen-powered regional trains already operational in Europe and projected to capture over 30% of the market in the future [108,109].

4. Key Technologies for Hydrogen–Electric Coupling

Electric–hydrogen coupling systems have been studied by scholars, and it has been demonstrated that considering generation and transmission planning within the framework of electric–hydrogen integration will reduce the total system cost [110]. In general, electric–hydrogen coupling can be categorized according to the location of implementation, including load-side and power-side electric–hydrogen coupling.

4.1. Load-Side Electric–Hydrogen Coupling

The load-side electricity–hydrogen coupling model is shown in Figure 4 [111]. Taking China as the example, electricity from large-scale centralized renewable energy power plant stations in the northwestern part of China can be transported to the load-intensive central and eastern parts of China through extra-high-voltage transmission lines, and then hydrogen can be produced through electrolysis on the load side to achieve voltage support or capacity reserve for the power grid through hydrogen fuel cells or hydrogen gas turbines.

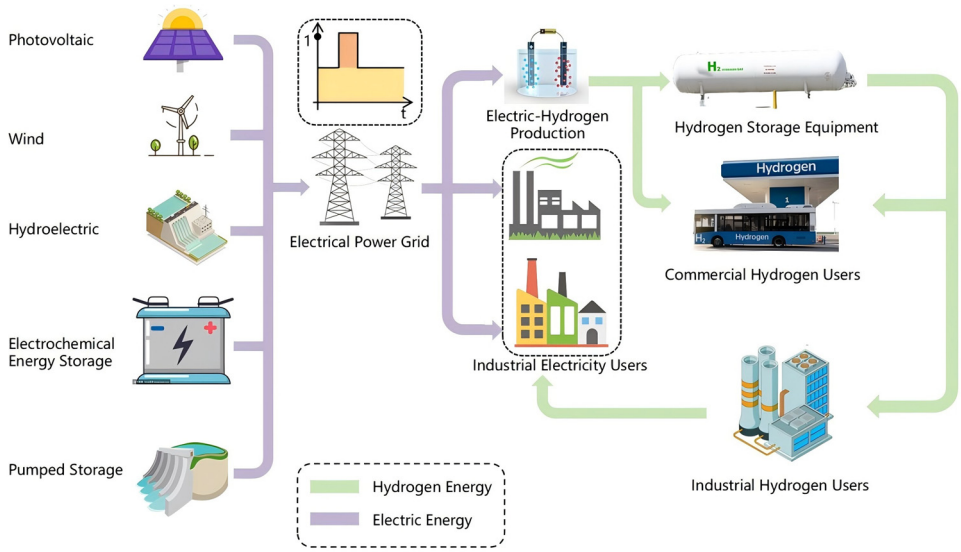


Figure 4. Schematic diagram of load-side electric–hydrogen coupling mode.

The load-side electricity–hydrogen coupling model has several advantages. First, hydrogen production plants can be flexibly located. Given that the electricity powering the electrolyzer originates from the grid, hydrogen plants can be strategically located near regions with significant hydrogen demand. This approach reduces expenses associated with hydrogen conversion, storage, and transporting over long distances, thereby mitigating potential safety hazards linked to extensive, long-range hydrogen logistics.

Secondly, UHV (ultra-high-voltage) transmission lines can be fully utilized for optimal allocation of large-scale renewable energy. As indicated by the research findings,

the expense of hydrogen pipeline transport rises from USD 4.5/kg to USD 10/kg with a distance increase from 400 km to 1000 km [112,113]. Conversely, for the identical distance, the expense of electricity transmission via UHV lines escalates from USD 0.05/kWh to USD 0.09/kWh. In terms of energy equivalence, the unit cost for transmitting electricity is approximately one-fourth to one-fifth of that for hydrogen conveyance. Therefore, concerning energy distribution, UHV lines present a more favourable economic competitiveness compared to hydrogen pipelines.

Finally, there are large differences in peak and valley electricity prices near load centres. This can provide a degree of financial compensation for losses in the electricity–hydrogen–electricity energy conversion process.

Nevertheless, this approach carries certain drawbacks. Primarily, the initial lower capital outlay for UHV lines does not invariably translate into reduced overall energy transmission expenses. Given the intermittent nature of renewable energy sources, they must be complemented with coal, hydroelectricity, electrochemical storage, and pumped storage to achieve a more consistent power output for UHV lines. This integration necessitates additional investments in flexible power sources and storage systems, potentially driving up the overall system costs.

The operational flexibility of electrolyzers might not be fully utilized, as the variability of renewable energy has already been mitigated through adaptable power sources and storage batteries. The relative stability of power transmitted to the load side limits the performance of electrolyzers in providing grid balancing services and absorbing renewable energy fluctuations on the power side [114].

4.2. Power-Side Electric–Hydrogen Coupling

Electricity–hydrogen coupling modes on the power supply side include three categories: transmission mode, hydrogen transmission mode, and local balancing mode [115].

(a) Electricity-transmission method

Figure 5 illustrates this conceptual framework [116]. Within this setup, electrolyzers, hydrogen storage facilities, and hydrogen gas turbines are strategically positioned on the power side to mitigate losses associated with renewable energy sources. The electrolysis tanks exhibit robust responsiveness, effectively harnessing power derived from renewable sources; the resultant hydrogen serves dual purposes, catering to local consumption or facilitating re-electrification.

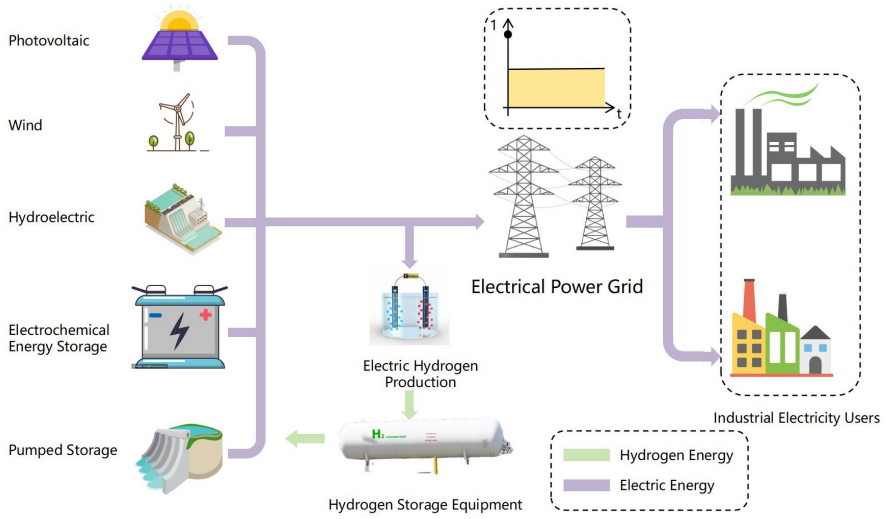


Figure 5. Schematic diagram of power-side electric–hydrogen coupling—transmission mode.

This model offers significant benefits by optimizing both renewable energy integration and transmission line efficiency. As the number of coal and natural gas power plants

gradually decreases, electrolyzers, hydrogen storage systems, and hydrogen gas turbines play a crucial role in peak shaving and grid balancing services. During periods of high renewable energy output, electrolysis tanks operate at maximum capacity, storing hydrogen in dedicated tanks. Conversely, when renewable energy production dips, hydrogen gas turbines engage to stabilize transmission lines, maximizing renewable energy utilization while ensuring high operational efficiency.

Similar to the load-side electric–hydrogen coupling model, this model has an inefficient electric–hydrogen–electric conversion process with high energy losses.

(b) Hydrogen-delivery mode

Figure 6 illustrates the schematic representation of the model [117]. Renewable energy-derived hydrogen generated at the power generation site is transported via pipelines to the central load centre located at a considerable distance.

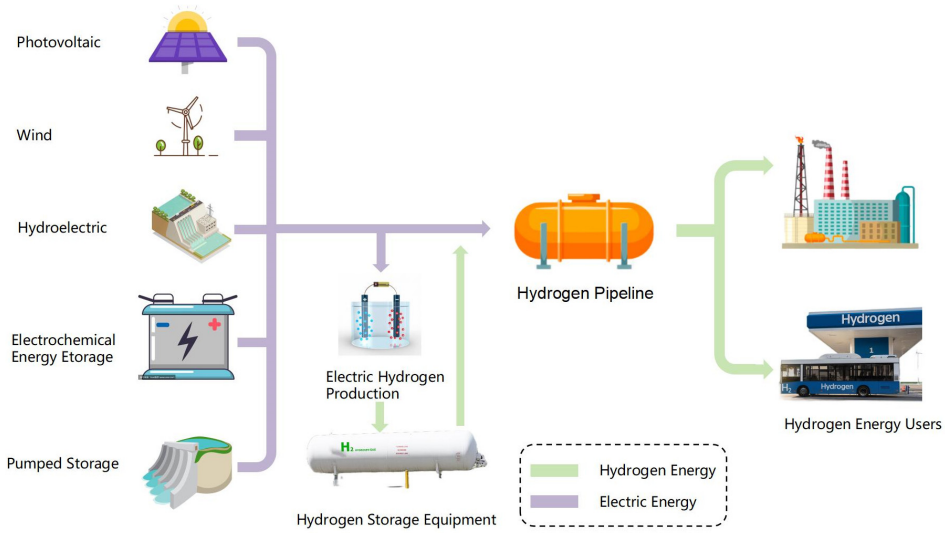


Figure 6. Schematic diagram of remote electric–hydrogen coordinative hydrogen delivery mode.

The advantage of this model is that the transmission of renewable energy over long distances through hydrogen reduces the pressure on the power grid and can effectively support the large-scale development and utilization of renewable energy. Unlike electricity, the supply and demand for hydrogen do not need to be balanced instantaneously and are therefore more tolerant of fluctuations. Also, pipelines can be used as a means of storage.

However, the construction of hydrogen pipelines remains expensive and is in its initial phases, posing constraints on hydrogen transmission. Conventional hydrogen trucking is viable only for limited distances and small-scale operations. Although blending hydrogen into natural gas pipelines can lower costs, the blend ratio should not surpass 10%, thus constraining large-scale hydrogen transport.

(c) Local equilibrium

This model utilizes locally produced hydrogen from renewable energy sources on the power side. Its primary strengths include cost-effectiveness and enhanced efficiency. By avoiding the need for hydrogen electrification, energy losses during conversion processes are minimized. However, the model's effectiveness heavily relies on local hydrogen demand. Insufficient demand necessitates transporting hydrogen generated from renewable sources to other regions. Consequently, industries reliant on hydrogen as raw material or fuel, such as chemical production, steel manufacturing, and fuel-cell vehicles, should strategically locate themselves in regions abundant in renewable energy resources [118].

5. Outlook for the Development of Hydrogen Energy Applications

Given the advancements in hydrogen production, transportation, storage, and integration with electricity, along with supportive policies promoting hydrogen as a pivotal energy source, its research and application are poised for substantial growth. This paper consolidates existing research findings on hydrogen energy, projecting future developments in the power sector to emphasize the following key areas:

5.1. Reducing Electrolysis Costs and Improving Preparation Yields

The primary expense in producing hydrogen via water electrolysis is the electricity cost, directly impacting the overall electrolysis cost. Consequently, optimizing energy consumption stands as the critical factor in reducing the production cost of hydrogen through water electrolysis. There are two main ways to reduce the cost: the first is to further develop the electrolysis membrane technology to reduce the energy consumption in the electrolysis process; the second is to use cheaper renewable electricity.

For electrolytic membrane technology, different technology routes appear to be advancing together; although the AWE is more mature, it also faces the problem of service life. Therefore, research is needed to increase the long-term stability of AWEs by improving the chemical, mechanical, and thermal stability of the membranes, as well as by using highly conductive polymer compositions to increase ionic conductivity.

PEM technology presents distinct advantages compared to alkaline electrolysis, including elevated operational current density, superior gas purity, increased outlet pressure, and reduced spatial requirements. Nonetheless, the primary obstacle facing this technology remains the cost associated with its components. Reducing membrane thickness by enhancing mechanical resistance can improve efficiency and durability, and reducing the loading of noble materials by adjusting the surface properties of the catalyst material (e.g., increasing the surface area) can improve the kinetic properties of the electrode material, which in turn reduces the power consumption of the PEM.

The SOE is an efficient technology that is rapidly evolving. However, its main challenge is durability. Enhancing electrolyte conductivity and refining the chemical and mechanical robustness of the electrolyzer is crucial for enhancing durability. Moreover, adjusting the electrochemical surface characteristics and ensuring compatibility with the electrode materials can extend the lifetime of SOEs.

5.2. Development of New Materials to Enhance Hydrogen Storage Capacity

Currently, high-pressure storage stands out as the most viable and extensively employed hydrogen storage technique in transportation applications. However, it comes with inherent drawbacks. Firstly, due to the high pressures involved, storage tanks necessitate costly and challenging-to-produce high-strength materials. Secondly, compressed hydrogen occupies a considerable volume, restricting storage capacity per unit space. Thirdly, elevated pressures heighten the risk of leaks or ruptures, posing safety concerns. Hence, innovative materials are urgently required to address these challenges associated with high-pressure storage methods.

Liquid hydrogen storage avoids the problems associated with high-pressure hydrogen storage, but liquefied hydrogen requires higher energy, which results in higher costs. Another challenge of liquid hydrogen storage is the fact of hydrogen boiling or evaporation. Research in low-temperature storage of liquid hydrogen is a critical area of study, with current efforts concentrated on enhancing tank designs and materials to overcome the complexities linked to storing hydrogen at such temperatures.

5.3. Optimizing Control Methods to Improve Power Generation Efficiency

The flexible application of hydrogen to power systems through fuel cells will be an important direction of hydrogen electrification. In the research of fuel cells, the technical issues of catalyst degradation need to be more clearly understood in order to increase their power rating, extend their continuous operating time, and reduce production costs. Various

components within hydrogen-based power systems typically interconnect through power electronic converters for hydrogen production and utilization. To ensure optimal system performance, converters require attributes such as adaptable voltage ratios, efficient conversion rates, and minimal current fluctuations. Research in converters for hydrogen fuel cells should prioritize effective control mechanisms to mitigate power output disruptions caused by switching faults. Concurrently, enhancing voltage ratios is essential for system reliability, thereby bolstering fuel cell power generation efficiency.

According to the literature review and research in different periods, it can be seen that the application of hydrogen energy in the power system will mainly focus on the improvement of system efficiency, service life, and durability, as well as the coupling and coordinated control of hydrogen energy and power systems. As the whole of society pays more attention to the research of hydrogen energy, under the guidance and promotion of national and local policies, a power system containing hydrogen energy will be developed in the long run.

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