

Prospects of Hydrogen Energy: A Comprehensive Review on Future Sustainable Energy Solutions

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Abstract

With the growing global demand for clean energy, hydrogen energy, as a sustainable, efficient, and environmentally friendly energy carrier, is gradually becoming the focus of energy research and application fields. This paper comprehensively elaborates on the characteristics of hydrogen energy, hydrogen production technologies, storage and transportation methods, as well as its applications in multiple fields, and analyzes in detail the challenges and opportunities faced by the current development of the hydrogen energy industry. Through in-depth discussion of various hydrogen production technologies, such as fossil fuel reforming, water electrolysis, and biological hydrogen production, the advantages, disadvantages, and development trends of different technologies are revealed. Meanwhile, in response to the difficulties in hydrogen storage and transportation, various solutions such as high-pressure gaseous hydrogen storage, low-temperature liquid hydrogen storage, and solid-state hydrogen storage, along with their technological progress, are introduced. In terms of applications, it covers multiple scenarios including transportation, distributed power generation, and industrial fields, demonstrating the broad application prospects of hydrogen energy. Although the current hydrogen energy industry faces challenges in terms of cost and infrastructure construction, with the strengthening of technological innovation and policy support, hydrogen energy is expected to occupy an important position in the future energy structure and become a key force promoting global energy transformation.

Keywords

Hydrogen Energy, Hydrogen Production Technology, Hydrogen Storage, Application, Energy Transformation

1. Introduction

With the acceleration of global industrialization and urbanization, energy demand continues to grow, and the massive use of traditional fossil energy has brought serious environmental pollution and climate change problems. In this context, the development of clean and sustainable energy has become an urgent task. As an ideal energy carrier, hydrogen energy has significant advantages such as high combustion calorific value, zero carbon emissions, and wide sources, and is regarded as an important part of the future energy system.

From a historical perspective, the research and application of hydrogen energy have a long history. As early as the 18th century, scientists began to explore the properties of hydrogen. In the 19th century, the emergence of water electrolysis for hydrogen production provided the possibility for large-scale hydrogen production. Since the 20th century, with the development of high-tech fields such as aerospace, hydrogen energy has been further applied and researched due to its high energy density. In recent years, with the increasing global attention to sustainable development, the hydrogen energy industry has ushered in opportunities for rapid development. Governments around the world have introduced relevant policies, increased support for hydrogen energy technology research and industrial development, promoted hydrogen energy from the laboratory to practical applications, and gradually built a complete hydrogen energy industry chain.

2. Characteristics of Hydrogen Energy

2.1 Physicochemical Properties

Hydrogen (H_2) is the lightest gas in nature, with a density of only 0.0899g/L under standard conditions. It has a high combustion calorific value, and each kilogram of hydrogen can release about 142MJ of energy when burned, which is about 2.8 times that of gasoline, making hydrogen an energy carrier with extremely high energy density. The ignition point of hydrogen is relatively high, at 574°C, but when mixed with air, its explosive limit range is wide, between 4.0%-75.6% (volume fraction). Therefore, special attention must be paid to safety during storage and use. In terms of chemical properties, hydrogen has strong reducibility and can react with many substances, which makes it widely used in chemical, metallurgical and other fields.

2.2 Environmental Friendliness

One of the greatest advantages of hydrogen energy is its environmental friendliness. The only product of hydrogen combustion is water, which does not produce pollutants such as carbon dioxide, nitrogen oxides, and particulate matter,

and is of great significance for mitigating global climate change and improving air quality. Compared with traditional fossil energy, hydrogen energy has significantly lower carbon emissions throughout its life cycle. Even in the hydrogen production process, if low-carbon or zero-carbon technologies such as renewable energy-powered water electrolysis are adopted, its carbon emissions can be almost negligible. For example, hydrogen production by water electrolysis using renewable energy sources such as solar and wind energy can achieve near-zero emissions throughout the entire process from energy production to final use, providing strong technical support for achieving global carbon neutrality goals.

3. Hydrogen Production Technologies

3.1 Fossil Fuel Reforming for Hydrogen Production

3.1.1 Technical Principles and Processes

Fossil fuel reforming for hydrogen production is one of the most widely used hydrogen production methods, among which natural gas reforming is the most common. Its principle is that hydrocarbons in fossil fuels react with water vapor under high temperature and catalyst to generate hydrogen and carbon monoxide. Taking natural gas (mainly composed of methane, CH_4) as an example, the reforming reaction equation is: $\text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3\text{H}_2$. The reaction is usually carried out in a tubular reformer, and the temperature is generally controlled at 700-900°C. The generated carbon monoxide can be further converted into hydrogen through the water-gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$) to increase hydrogen production. The mixed gas after the reaction is purified to remove impurities such as carbon dioxide and hydrogen sulfide, and finally high-purity hydrogen is obtained [1].

3.1.2 Advantages and Disadvantages Analysis

In terms of advantages, fossil fuel reforming for hydrogen production has mature technology and relatively low production costs. At present, this technology has achieved large-scale industrial production with high production efficiency and stability. For example, natural gas reforming for hydrogen production can have a cost as low as 1.5-2.5 US dollars per kilogram in regions rich in natural gas resources. In addition, this technology can make full use of existing fossil fuel infrastructure, facilitating rapid promotion and application [2].

However, this technology also has obvious disadvantages. Firstly, the process of fossil fuel reforming for hydrogen production will produce a large amount of carbon dioxide emissions. Approximately 9-12 kilograms of carbon dioxide are emitted for every 1 kilogram of hydrogen produced, which is contrary to the global goal of addressing climate change and achieving carbon neutrality. Secondly, fossil fuels are non-renewable resources, and with the gradual depletion of resources, the stability of supply and price volatility will have an adverse impact on the hydrogen production industry. In addition, the reforming process requires high-temperature conditions, resulting in high energy consumption, and harsh requirements for equipment, increasing equipment investment and maintenance costs [3].

3.2 Water Electrolysis for Hydrogen Production

3.2.1 Alkaline Water Electrolysis Technology

Alkaline water electrolysis technology is a relatively mature method for hydrogen production by water electrolysis. Its principle is that in an alkaline electrolyte (usually potassium hydroxide solution), water decomposes at the anode and cathode under the action of direct current. Oxidation reaction occurs at the anode, where water loses electrons to generate oxygen and hydrogen ions ($4\text{OH}^- - 4\text{e}^- \rightarrow 2\text{H}_2\text{O} + \text{O}_2\uparrow$); reduction reaction occurs at the cathode, where hydrogen ions gain electrons to generate hydrogen ($2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2\uparrow + 2\text{OH}^-$). Alkaline water electrolysis equipment mainly consists of electrolytic cells, power supplies, electrolyte circulation systems, etc. The advantages of this technology are simple equipment structure, convenient operation, relatively low requirements for electrolyte purity, and relatively low cost. However, its disadvantages are also obvious, such as relatively low electrolysis efficiency, generally between 60%-80%, and high energy consumption, usually requiring 4-5 kWh of electricity to produce 1 kilogram of hydrogen. In addition, the electrode materials used in alkaline water electrolysis technology are mostly non-precious metal materials such as nickel-based ones, but their catalytic activity is limited, affecting the further improvement of electrolysis efficiency [4].

3.2.2 Proton Exchange Membrane Water Electrolysis Technology

Proton exchange membrane (PEM) water electrolysis technology is a rapidly developing hydrogen production technology by water electrolysis in recent years. It uses a proton exchange membrane as the electrolyte instead of the traditional alkaline electrolyte. In the PEM water electrolysis system, water on the anode side decomposes into oxygen, hydrogen ions, and electrons under the action of a catalyst ($2\text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}^+ + 4\text{e}^-$). Hydrogen ions migrate to the cathode through the proton exchange membrane, and electrons flow to the cathode through an external circuit. On the cathode side, hydrogen ions combine with electrons to generate hydrogen ($4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2$). This technology has many advantages. Firstly, its electrolysis efficiency is high, reaching 80%-90%, which can effectively reduce energy consumption. The power consumption for producing 1 kilogram of hydrogen can be as low as 3.8-4.5 kWh. Secondly, PEM water electrolysis technology has a fast response speed and can quickly follow the fluctuations of renewable energy power generation for hydrogen production, which is very suitable for coupling with unstable renewable energy power generation systems such as wind power and photovoltaics. In addition, the proton exchange membrane used in this technology can effectively prevent gas cross-permeation, improving the safety and stability of the system. However,

PEM water electrolysis technology also faces some challenges, such as the high cost of proton exchange membranes and catalysts. Currently, proton exchange membranes mainly rely on imports and are expensive, and catalysts are mostly precious metals such as platinum, which to a certain extent limits the large-scale commercial application of this technology [5].

3.2.3 Solid Oxide Water Electrolysis Technology

Solid oxide electrolysis cell (SOEC) technology is an emerging high-temperature water electrolysis technology for hydrogen production. Its working principle is based on the characteristic that solid oxide electrolytes can conduct oxygen ions at high temperatures. Under high-temperature conditions (usually 700-1000°C), water vapor gains electrons at the cathode and is reduced to hydrogen and oxygen ions ($\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + \text{O}^{2-}$). Oxygen ions migrate to the anode through the solid oxide electrolyte and lose electrons at the anode to generate oxygen ($2\text{O}^{2-} \rightarrow \text{O}_2 + 4\text{e}^-$). The advantages of SOEC technology are that the thermodynamic performance of the electrolysis reaction is improved under high-temperature environment, the electrolysis efficiency can be as high as over 90%, and it can utilize low-grade heat sources such as waste heat to realize cascade utilization of energy, further improving energy utilization efficiency. In addition, this technology has relatively low requirements for catalysts at high temperatures, and some cheap metal oxides can be used as catalysts. However, SOEC technology also has some problems. For example, high-temperature operation has extremely high requirements for equipment materials, requiring special materials that are resistant to high temperatures and corrosion, which increases equipment costs and manufacturing difficulties. At the same time, the start-up and shutdown processes of equipment in high-temperature environments are relatively complex, posing severe challenges to the stability and reliability of the system [6].

3.3 Biological Hydrogen Production

3.3.1 Photofermentation Biological Hydrogen Production

Photofermentation biological hydrogen production is a process in which photosynthetic bacteria convert organic matter into hydrogen under light conditions. Photosynthetic bacteria have a unique photosynthetic system that can absorb light energy and convert it into chemical energy to drive hydrogen production. In the photofermentation process, photosynthetic bacteria use organic acids (such as acetic acid, butyric acid, etc.) as carbon sources and electron donors. Under the action of photosynthetic pigments and related enzymes, they convert light energy into chemical energy, decomposing organic acids into hydrogen and carbon dioxide. The reaction process can be simply expressed as: organic acids + light + photosynthetic bacteria $\rightarrow \text{H}_2 + \text{CO}_2$. The advantages of photofermentation biological hydrogen production are mild reaction conditions, usually carried out at room temperature and pressure, and low energy consumption. At the same time, this process uses organic waste as raw materials, realizing the resource utilization of waste and reducing environmental pollution. However, photofermentation biological hydrogen production also faces some limitations. For example, photosynthetic bacteria have strict requirements on light conditions, requiring specific wavelengths and intensities of light for efficient hydrogen production, which limits their large-scale application. In addition, the hydrogen production rate of photofermentation biological hydrogen production is relatively low, and the hydrogen output is limited, which is currently difficult to meet the needs of industrial production [7].

3.3.2 Dark Fermentation Biological Hydrogen Production

Dark fermentation biological hydrogen production is a process in which anaerobic microorganisms ferment and decompose organic substances to produce hydrogen under anaerobic and dark conditions. Microorganisms involved in dark fermentation mainly include *Clostridium*, *Enterobacter*, etc. These microorganisms decompose complex organic substances (such as carbohydrates, starch, cellulose, etc.) into pyruvate through glycolysis, and pyruvate then undergoes a series of metabolic reactions to generate hydrogen, carbon dioxide, organic acids and other products. For example, the fermentation reaction equation of glucose under the action of anaerobic microorganisms is: $\text{C}_6\text{H}_{12}\text{O}_6 + 2\text{H}_2\text{O} \rightarrow 4\text{H}_2 + 2\text{CO}_2 + 2\text{CH}_3\text{COOH}$. The advantages of dark fermentation biological hydrogen production are wide sources of raw materials, as almost all organic wastes can be used as raw materials, and the reaction does not require light and can be carried out in relatively simple reactors. Compared with photofermentation, the hydrogen production rate of dark fermentation biological hydrogen production is relatively higher. However, this technology also has some problems, such as low hydrogen production efficiency, low purity of hydrogen in the products, which usually contains impurities such as carbon dioxide and methane, requiring subsequent separation and purification. In addition, the organic acid and other by-products produced in the dark fermentation process will inhibit the growth and hydrogen production activity of microorganisms, affecting the stability and sustainability of hydrogen production [8].

3.3.3 Dark-Photo Coupled Biological Hydrogen Production

Dark-photo coupled biological hydrogen production technology combines the advantages of dark fermentation and photofermentation, aiming to improve the efficiency and yield of biological hydrogen production. In this technology, dark fermentation microorganisms are first used to preliminarily decompose organic substances to produce intermediate products such as hydrogen, carbon dioxide, and organic acids. Then, the organic acids produced by dark fermentation are used as carbon sources for photofermentation photosynthetic bacteria, which are further converted into hydrogen under light conditions. Through this coupling method, the metabolic characteristics of different microorganisms are fully utilized, realizing the cascade utilization of organic substances, and improving the overall hydrogen yield and

energy conversion efficiency. For example, the pilot-scale agricultural waste dark-photo coupled biological hydrogen production system designed and constructed by the team of Professor Zhang Quanguo from Henan Agricultural University has achieved continuous and stable operation. The advantage of this technology is that it can more efficiently utilize organic waste, improving hydrogen production efficiency and hydrogen purity. However, the dark-photo coupled biological hydrogen production process is a complex temperature-sensitive biochemical reaction, and its photothermal mass transfer theory and regulation mechanism need to be further clarified. At present, due to the lack of pilot-scale experimental operation data and sustainability analysis, the commercial promotion and application of this technology are restricted to a certain extent [9].

3.4 Other Hydrogen Production Technologies

3.4.1 Photolysis of Water for Hydrogen Production

Photolysis of water for hydrogen production is a process that simulates plant photosynthesis and uses solar energy to decompose water into hydrogen and oxygen. Its basic principle is that photocatalysts absorb light energy to generate electron-hole pairs. Electrons and holes migrate to the surface of the catalyst respectively, and undergo redox reactions with water to generate hydrogen and oxygen. In recent years, progress has been made in water photolysis for hydrogen production technology. For example, on January 4, 2024, a team led by Edman Tsang from the University of Oxford in the UK and a team led by Wu Xinping from East China University of Science and Technology collaborated to construct facet-engineered nitrogen-doped titanium dioxide nanoparticles (N-TiO₂) as catalysts, which were applied to high-temperature photolysis of seawater for hydrogen production, achieving an energy conversion efficiency of up to 15.9%, exceeding the similar systems reported so far. This technology has the advantages of being clean and sustainable, and if large-scale application can be realized, it will provide an inexhaustible source of energy for hydrogen production. However, at present, water photolysis for hydrogen production still faces many challenges, such as low light absorption efficiency of photocatalysts and high recombination rate of photogenerated carriers, resulting in difficulty in further improving energy conversion efficiency, and there is still a large gap from practical industrial application [10].

3.4.2 Thermochemical Cycle Hydrogen Production

Thermochemical cycle hydrogen production is a process that decomposes water into hydrogen and oxygen through a series of thermochemical reactions and cyclic reactions of intermediate compounds. This process usually requires a high-temperature heat source (generally 800-1200°C) and involves multiple chemical reaction steps. For example, iodine-sulfur (I-S) cycle hydrogen production is a typical thermochemical cycle hydrogen production method, whose main reactions include: $\text{SO}_2 + \text{I}_2 + 2\text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4 + 2\text{HI}$ (low-temperature reaction), $2\text{H}_2\text{SO}_4 \rightarrow 2\text{SO}_2 + \text{O}_2 + 2\text{H}_2\text{O}$ (high-temperature reaction), $2\text{HI} \rightarrow \text{H}_2 + \text{I}_2$ (medium-temperature reaction). The advantage of thermochemical cycle hydrogen production is that it can theoretically achieve high hydrogen production efficiency and does not require the use of precious metal catalysts. However, this technology also faces many challenges, such as complex reaction processes involving multiple chemical reactions and separation steps, extremely high requirements for equipment's high-temperature resistance and corrosion resistance, resulting in high equipment costs. At the same time, the synergy and stability between the reaction steps are difficult to ensure, and it is still in the stage of laboratory research and small-scale testing [11].

4. Hydrogen Storage and Transportation

4.1 High-Pressure Gaseous Hydrogen Storage

4.1.1 Technical Characteristics and Equipment

High-pressure gaseous hydrogen storage is one of the most widely used hydrogen storage methods at present. Its principle is to compress hydrogen to a high-pressure state and store it in specially made high-pressure gas cylinders. Commonly used high-pressure gas cylinder materials include carbon steel, aluminum alloy, and carbon fiber composite materials. With the development of technology, carbon fiber composite cylinders have gradually become the mainstream choice for high-pressure gaseous hydrogen storage due to their advantages of light weight, high strength, and relatively high hydrogen storage density. Currently, the working pressure of on-board high-pressure gaseous hydrogen storage systems can reach 35MPa or even 70MPa. At 70MPa pressure, the hydrogen storage density (mass fraction) of carbon fiber composite cylinders can reach about 5%-6%. High-pressure gaseous hydrogen storage equipment mainly includes hydrogen compressors, high-pressure cylinder groups, pressure reducing devices, etc. Hydrogen compressors are used to compress low-pressure hydrogen to a set high-pressure state, high-pressure cylinder groups are used to store compressed hydrogen, and pressure reducing devices reduce high-pressure hydrogen to an appropriate pressure for users during use [12].

4.1.2 Application Status and Challenges

High-pressure gaseous hydrogen storage technology is mature and relatively low in cost, and has been widely used in current hydrogen fuel cell vehicles, hydrogen refueling stations and other fields. For example, many commercial hydrogen fuel cell vehicles adopt high-pressure gaseous hydrogen storage systems. However, this technology also has some obvious challenges. Firstly, the hydrogen storage density of high-pressure gaseous hydrogen storage is relatively low. Even at a high pressure of 70MPa, its volumetric hydrogen storage density is much lower than that of liquid

hydrogen and some solid-state hydrogen storage materials. This means that to store a sufficient amount of hydrogen, a large space is required, which is a limitation for application scenarios with limited space (such as on-board hydrogen storage). Secondly, high-pressure storage of hydrogen has certain safety risks, requiring strict safety measures and equipment to ensure the safety of storage and use processes. In addition, the compression process of hydrogen consumes a large amount of energy, generally requiring 0.5-1.0 kWh to compress 1 kilogram of hydrogen, which increases the cost of hydrogen storage [13].

4.2 Low-Temperature Liquid Hydrogen Storage

4.2.1 Liquefaction Principles and Processes

Low-temperature liquid hydrogen storage is a method of storing hydrogen by cooling it below its boiling point (-253°C) to convert it into a liquid state. The liquefaction process of hydrogen requires a series of complex refrigeration cycles. Firstly, hydrogen is compressed by a compressor to increase its pressure while releasing compression heat. Then, the compressed hydrogen is initially cooled using a cooling medium (such as liquid nitrogen). Next, refrigeration technologies such as throttling expansion and Brayton cycle are used to further reduce the temperature of hydrogen to meet the liquefaction conditions. Finally, the liquefied hydrogen is stored in a specially made low-temperature insulated storage tank. Low-temperature insulated storage tanks usually adopt a double-layer vacuum structure and are filled with insulation materials to reduce heat input and maintain the low-temperature state of liquid hydrogen [14].

4.2.2 Advantages and Limitations

The greatest advantage of low-temperature liquid hydrogen storage is its high hydrogen storage density. The density of liquid hydrogen is about 70.8kg/m³, which is several times the volumetric hydrogen storage density of high-pressure gaseous hydrogen storage at 70MPa. This enables more hydrogen to be stored in the same storage space, making it very suitable for large-scale, long-distance hydrogen transportation and storage. For example, in the aerospace field, due to the high requirement for fuel energy density, low-temperature liquid hydrogen storage is currently the main hydrogen storage method. However, low-temperature liquid hydrogen storage technology also has many limitations. Firstly, the liquefaction process of hydrogen consumes huge energy, with approximately 10-15 kWh required to liquefy 1 kilogram of hydrogen, which greatly increases the cost of hydrogen storage. Secondly, the investment cost of low-temperature liquid hydrogen storage equipment is high, requiring special low-temperature refrigeration equipment, insulated storage tanks, etc., and the maintenance and operation of the equipment have strict requirements. In addition, liquid hydrogen has evaporation loss during storage. Even with high-performance insulated storage tanks, a certain proportion of liquid hydrogen evaporates every day, which not only causes waste of hydrogen but also may bring safety hazards [15].

4.3 Solid-State Hydrogen Storage

4.3.1 Metal Hydride Hydrogen Storage

Metal hydride hydrogen storage is a method of storing hydrogen by reacting metals or alloys with hydrogen to form metal hydrides. Its principle is that under certain temperature and pressure conditions, metal (or alloy) M reacts with hydrogen to form metal hydride MH_n, and the reaction equation is: $M + n/2H_2 \rightleftharpoons MH_n + \text{heat}$. When hydrogen needs to be released, the metal hydride is decomposed by heating or reducing pressure to release hydrogen. Commonly used hydrogen storage metals or alloys include magnesium-based alloys, titanium-based alloys, rare earth-based alloys, etc. The advantages of metal hydride hydrogen storage are high hydrogen storage density (mass fraction up to 1%-5%, volumetric hydrogen storage density up to 100-150kg/m³), good safety, and high purity of hydrogen (the released hydrogen purity can reach more than 99.999%). However, its disadvantages are also obvious. For example, the hydrogen storage and release processes require certain temperature and pressure conditions, the response speed is relatively slow, and the cost of some hydrogen storage alloys is high, and the cycle life needs to be further improved [16].

4.3.2 Chemical Hydride Hydrogen Storage

Chemical hydride hydrogen storage is a method of storing hydrogen by using chemical hydrides to react with water or other substances to produce hydrogen. Commonly used chemical hydrides include sodium borohydride (NaBH₄), ammonia borane (NH₃BH₃), lithium aluminum hydride (LiAlH₄), etc. Taking sodium borohydride as an example, its reaction equation with water is: $NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2\uparrow$. This reaction can proceed rapidly under the action of a catalyst, producing a large amount of hydrogen. The advantages of chemical hydride hydrogen storage are extremely high hydrogen storage density. For example, the theoretical hydrogen storage mass fraction of ammonia borane can reach 19.6%, which is much higher than other hydrogen storage methods. At the same time, chemical hydrides are usually solid or liquid, which are convenient for storage and transportation and have high safety. However, this technology also has some problems. For example, the preparation cost of chemical hydrides is high, and the recovery and regeneration of by-products after the reaction are difficult. Currently, no economically efficient regeneration method has been found, which limits its large-scale application [17].

4.3.3 MOFs and COFs for Hydrogen Storage

Metal-organic frameworks (MOFs) and covalent organic frameworks (COFs) are a class of new porous crystalline materials with large specific surface areas and adjustable pore structures, showing good application prospects in the

field of hydrogen storage. Their hydrogen storage principle is to adsorb hydrogen molecules in the pores of the materials through physical adsorption. The hydrogen storage performance of MOFs and COFs mainly depends on their structural parameters such as specific surface area, pore size, and pore volume. By reasonably designing and regulating the structure of the materials, their adsorption capacity and adsorption/desorption kinetic performance for hydrogen can be improved. At present, researchers have developed a variety of high-performance MOFs and COFs hydrogen storage materials. Under low-temperature and high-pressure conditions, the hydrogen storage mass fraction of some materials can reach more than 5%. However, MOFs and COFs hydrogen storage technologies are still in the laboratory research stage. The main challenge is that the hydrogen storage capacity under normal temperature and pressure is low, which is difficult to meet the needs of practical applications. In addition, the synthesis cost of materials is high, and large-scale preparation is difficult [18].

4.4 Hydrogen Transportation

4.4.1 High-Pressure Gaseous Transportation

High-pressure gaseous transportation is one of the most commonly used hydrogen transportation methods at present. It involves compressing hydrogen to high pressure (usually 20-50MPa) and transporting it through high-pressure tube trailers or pipelines. High-pressure tube trailers consist of multiple high-pressure gas cylinders and are suitable for medium-short distance, small-batch hydrogen transportation, with advantages such as high flexibility and low initial investment. High-pressure pipeline transportation is suitable for large-scale, long-distance hydrogen transportation, with advantages such as high transportation efficiency and low cost. Currently, a certain scale of hydrogen pipeline networks has been built globally, mainly distributed in industrially developed regions. However, high-pressure gaseous transportation also has some problems. For example, the transportation efficiency of high-pressure tube trailers is low, and the energy consumption and cost per unit transportation volume are relatively high; high-pressure pipeline transportation has large initial investment, long construction period, and needs to consider issues such as hydrogen corrosion and sealing [19].

4.4.2 Low-Temperature Liquid Transportation

Low-temperature liquid transportation is a method of transporting hydrogen after liquefaction through low-temperature tank trucks or ships. Low-temperature tank trucks are suitable for medium-short distance transportation of liquid hydrogen, while ships are suitable for long-distance, large-scale liquid hydrogen transportation across oceans. Compared with high-pressure gaseous transportation, low-temperature liquid transportation has a larger unit volume transportation capacity and higher transportation efficiency, especially for long-distance, large-scale hydrogen transportation, its cost advantage is more obvious. For example, the transportation capacity of a large liquid hydrogen transport ship can reach thousands of tons, which is much higher than that of high-pressure tube trailers. However, low-temperature liquid transportation also has some disadvantages. For example, the liquefaction process of hydrogen consumes high energy, increasing transportation costs; the manufacturing and maintenance costs of low-temperature tank trucks and ships are high, and there is a certain amount of evaporation loss during transportation [20].

4.4.3 Solid-State Transportation

Solid-state transportation is a method of transporting hydrogen using solid substances formed after hydrogen storage materials (such as metal hydrides, chemical hydrides, etc.) absorb hydrogen. Its advantages are high safety. Hydrogen is stored in solid substances, which is not easy to leak or explode; no high-pressure or low-temperature equipment is needed during transportation, and the operation is relatively simple. In addition, the volumetric hydrogen storage density of solid-state transportation is relatively high, which is beneficial to improving transportation efficiency. However, solid-state transportation also faces some challenges. For example, the cost of hydrogen storage materials is high, the hydrogen storage and release processes need to consume a certain amount of energy, and the cycle life of some hydrogen storage materials is short, which limits their large-scale application (Chen Changpin et al., 2020)[21].

5. Applications of Hydrogen Energy

5.1 Transportation Field

5.1.1 Hydrogen Fuel Cell Vehicles

Hydrogen fuel cell vehicles are an important application form of hydrogen energy in the transportation field. They directly convert the chemical energy of hydrogen and oxygen into electrical energy through hydrogen fuel cells to drive electric motors and provide power for the vehicles. Compared with traditional fuel vehicles, hydrogen fuel cell vehicles have advantages such as zero emissions (only emitting water), long driving range (up to 500-1000 kilometers), and short refueling time (3-5 minutes). Currently, automobile manufacturers such as Toyota, Honda, and Hyundai have launched a number of commercial hydrogen fuel cell vehicles, which have been put into small-scale commercial operation in some regions around the world. However, the development of hydrogen fuel cell vehicles still faces some challenges, such as high cost of fuel cells, lagging construction of hydrogen refueling infrastructure, and high price of hydrogen, which restrict the speed of market promotion [22].

5.1.2 Hydrogen-Powered Forklifts

Hydrogen-powered forklifts are typical applications of hydrogen energy in short-distance transportation and material handling fields. Compared with traditional lead-acid battery forklifts, hydrogen-powered forklifts have advantages such as short refueling time (1-3 minutes), strong endurance, zero emissions, and low maintenance costs, and are particularly suitable for places with high requirements for operating efficiency and environmental protection, such as logistics warehouses, ports, and factories. Currently, hydrogen-powered forklifts have been widely used in developed countries such as Europe and America, and the market scale is constantly expanding. China is also actively promoting the demonstration application of hydrogen-powered forklifts, and some logistics enterprises and ports have begun to trial use them. With the development of the hydrogen energy industry and cost reduction, hydrogen-powered forklifts are expected to replace some traditional forklifts in the future and become an important force in the material handling field [23].

5.1.3 Hydrogen Energy Rail Transit

Hydrogen energy rail transit includes hydrogen trains, hydrogen trams, etc., and is a new application of hydrogen energy in the public transportation field. Hydrogen trains are powered by hydrogen fuel cells and have advantages such as zero emissions and low noise compared with traditional diesel locomotives, making them suitable for regional railways and branch railways with high environmental requirements. In 2018, the world's first hydrogen train was put into trial operation in Germany, demonstrating the feasibility of hydrogen energy in the rail transit field. Hydrogen trams combine the advantages of trams and hydrogen fuel cell technology, do not require overhead contact lines, have relatively low construction costs, and have good environmental performance. Currently, China has carried out demonstration operation projects of hydrogen trams in many cities, achieving good results. The development of hydrogen energy rail transit is of great significance for promoting the green transformation of urban public transportation [24].

5.2 Distributed Power Generation Field

5.2.1 Household and Commercial Fuel Cell Power Generation Systems

Household and commercial fuel cell power generation systems (also known as fuel cell cogeneration systems) are distributed energy systems that integrate power generation and heat supply. They use hydrogen as fuel to generate electricity through fuel cells, and at the same time use the waste heat generated during power generation to provide hot water or heating. The power generation efficiency of the system can reach 40%-50%, and if waste heat utilization is included, the comprehensive energy utilization efficiency can be as high as over 80%, which is much higher than that of traditional thermal power generation. Household and commercial fuel cell power generation systems have advantages such as high energy utilization efficiency, low environmental pollution, and stable and reliable power supply, and are particularly suitable as distributed power sources for homes, office buildings, hotels, and other places. Currently, Japan is at the forefront of the world in promoting the application of household fuel cell power generation systems, with hundreds of thousands of systems put into use. China is also actively carrying out relevant demonstration projects to promote the commercial application of this technology [3].

5.2.2 Off-Grid Hydrogen Energy Power Generation Systems

Off-grid hydrogen energy power generation systems are mainly used in remote areas, islands, communication base stations and other places not covered by the power grid to provide stable power supply. The system usually consists of renewable energy power generation equipment (such as solar panels, wind turbines), water electrolysis hydrogen production equipment, hydrogen storage equipment, and fuel cell power generation equipment. Its working principle is: when renewable energy power generation is sufficient, the excess electricity drives the water electrolysis hydrogen production equipment to produce hydrogen, which is stored; when renewable energy power generation is insufficient or there is no power generation, the stored hydrogen is used to generate electricity through fuel cells to meet the electricity demand. Off-grid hydrogen energy power generation systems realize the stable utilization of renewable energy, solve the electricity problem in remote areas, and have advantages such as zero emissions and sustainability. However, the initial investment cost of the system is high, and the integration and optimization technology of the system needs to be further improved [25].

5.3 Industrial Field

5.3.1 Iron and Steel Metallurgy

Iron and steel metallurgy is a major energy consumer and carbon emitter. The traditional steel production process uses coke as a reducing agent and energy source, producing a large amount of carbon dioxide emissions. The application of hydrogen energy in the iron and steel metallurgy field provides the possibility for realizing the green transformation of the steel industry. Hydrogen-based steelmaking technology uses hydrogen instead of coke as a reducing agent to reduce iron ore to iron. The reaction equation is: $\text{Fe}_2\text{O}_3 + 3\text{H}_2 \rightarrow 2\text{Fe} + 3\text{H}_2\text{O}$, and the reaction product is water, avoiding carbon dioxide emissions. Currently, hydrogen-based steelmaking technology is still in the testing and demonstration stage, and a number of international steel enterprises have carried out relevant pilot projects. The main challenges faced by hydrogen-based steelmaking are the high cost of hydrogen, the need for major adjustments to the steelmaking process, and the difficulty in researching and manufacturing related equipment. However, with the development of the

hydrogen energy industry and technological progress, hydrogen-based steelmaking is expected to become an important development direction of the steel industry in the future [26].

5.3.2 Chemical Industry

Hydrogen energy is widely used in the chemical industry and is an important raw material for the production of many chemical products. For example, in the ammonia synthesis industry, hydrogen reacts with nitrogen under high temperature, high pressure, and catalyst to produce ammonia ($\text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3$); in methanol synthesis, hydrogen reacts with carbon monoxide to produce methanol ($\text{CO} + 2\text{H}_2 \rightleftharpoons \text{CH}_3\text{OH}$). Traditional hydrogen production in the chemical industry mainly relies on fossil fuel reforming, with high carbon emissions. Replacing fossil fuel-based hydrogen production with renewable energy-based hydrogen production can significantly reduce carbon emissions in the chemical industry and promote the development of the chemical industry towards green and low-carbon. In addition, hydrogen energy can also be used in chemical processes such as hydrocracking and hydrofining to improve the quality and output of chemical products. Currently, some chemical enterprises have begun to try to use green hydrogen (hydrogen produced by renewable energy) for production, exploring low-carbon development paths for the chemical industry [2].

5.3.3 Hydrogen Steelmaking

Hydrogen steelmaking is a new type of steelmaking process that uses hydrogen as a reducing agent to replace coke used in traditional steelmaking processes. In the traditional blast furnace steelmaking process, coke is not only a reducing agent but also provides the heat required for the steelmaking process. In contrast, hydrogen steelmaking reduces iron oxide in iron ore to iron through the reaction of hydrogen with it, generating metallic iron and water, thereby avoiding carbon dioxide emissions. This process has significant environmental advantages and is an important way for the steel industry to achieve carbon neutrality.

Currently, hydrogen steelmaking is still in the experimental and demonstration stage. Some major steel enterprises in the world have begun to make relevant attempts and explorations. For example, Sweden's HYBRIT project is the world's first hydrogen steelmaking demonstration project, aiming to create a fossil fuel-free steel production chain. The project plans to achieve commercial production by 2026 by using hydrogen as a reducing agent.

However, hydrogen steelmaking also faces some challenges. Firstly, the cost of hydrogen is a key issue. Currently, the production cost of green hydrogen is relatively high, which affects the economic viability of hydrogen steelmaking. Secondly, the steelmaking process needs to be significantly adjusted. Compared with traditional steelmaking processes, hydrogen steelmaking differs in reaction kinetics, heat and mass transfer, requiring adjustments and improvements to steelmaking equipment and process parameters. In addition, large-scale hydrogen supply is also a problem, requiring the establishment of a complete hydrogen production, storage, and transportation system.

Despite these challenges, with the continuous development of hydrogen energy technology and cost reduction, hydrogen steelmaking is expected to be widely applied in the future, promoting the transformation of the steel industry towards green and low-carbon.

6. Challenges and Opportunities in the Development of the Hydrogen Energy Industry

6.1 Faced Challenges

6.1.1 Technical Bottlenecks

The hydrogen energy industry still faces many technical bottlenecks. In the hydrogen production link, although fossil fuel reforming for hydrogen production has mature technology, it has high carbon emissions; among water electrolysis hydrogen production technologies, PEM electrolysis and SOEC electrolysis have high efficiency but high costs, and key materials (such as proton exchange membranes, catalysts) rely on imports; technologies such as biological hydrogen production and water photolysis for hydrogen production are still in the stage of laboratory research or small-scale testing, and their hydrogen production efficiency and stability need to be improved. In the hydrogen storage and transportation links, high-pressure gaseous hydrogen storage has low density, low-temperature liquid hydrogen storage has high energy consumption, and the performance and cost issues of solid-state hydrogen storage materials have not been effectively solved; the safety and economy of hydrogen transportation also need to be further improved. In the application link, the cost, life, and reliability of fuel cells are still key factors restricting their large-scale application, and the construction of hydrogen energy infrastructure (such as hydrogen refueling stations) is relatively lagging behind [27].

6.1.2 Cost Issues

Excessive cost is an important factor restricting the development of the hydrogen energy industry. In terms of hydrogen production costs, currently, fossil fuel reforming for hydrogen production has relatively low costs, but if carbon capture and storage (CCS) technology is considered, its cost will increase significantly; renewable energy-powered water electrolysis for hydrogen production is limited by the cost of renewable energy power generation and electrolysis equipment, and the current cost is still high, about 30-50 yuan per kilogram, which is much higher than the cost of traditional fossil energy-based hydrogen production. In terms of hydrogen storage and transportation costs, the

compression energy consumption and equipment costs of high-pressure gaseous hydrogen storage, the liquefaction energy consumption and equipment costs of low-temperature liquid hydrogen storage, and the material costs of solid-state hydrogen storage are all high; the unit cost of hydrogen transportation is also much higher than that of traditional fuels. In addition, the cost of hydrogen energy application equipment (such as fuel cell vehicles, fuel cell power generation systems) is also high, making it difficult to compete with traditional energy equipment [28].

6.1.3 Lagging Infrastructure Construction

The lag in infrastructure construction is another important factor restricting the development of the hydrogen energy industry. Hydrogen refueling stations are important infrastructure for the application of hydrogen energy in the transportation field, but the number of hydrogen refueling stations worldwide is relatively small and unevenly distributed. By the end of 2023, about 600 hydrogen refueling stations had been built globally, mainly concentrated in a few countries such as Japan, Germany, and the United States. The number of hydrogen refueling stations in China is about 150, which is far less than the number of new energy vehicle charging piles. Hydrogen pipeline construction is also relatively lagging. The total length of hydrogen pipelines worldwide is about 4000 kilometers, mainly distributed in Europe and the United States, while the total length of hydrogen pipelines in China is less than 1000 kilometers. The lack of infrastructure makes the supply and use of hydrogen inconvenient, limiting the promotion and application of hydrogen energy [29].

6.1.4 Safety and Standard Issues

The safety of hydrogen energy and the lack of relevant standards are also factors restricting the development of the industry. Hydrogen is flammable, explosive, and has a fast diffusion speed. Although technically, the use of hydrogen is safe as long as appropriate safety measures are taken, the public still has concerns about the safety of hydrogen energy, which to a certain extent affects its promotion and application. In addition, the hydrogen energy industry involves multiple links such as hydrogen production, storage, transportation, refueling, and application. Currently, the relevant standard system is not perfect, and there are differences in standards between different countries and regions, which brings obstacles to technical exchanges and cooperation in the hydrogen energy industry and large-scale development. It is necessary to establish a unified and complete hydrogen energy safety standards and specifications to improve public awareness and trust in hydrogen energy [30].

6.2 Development Opportunities

6.2.1 Policy Support

Governments around the world are increasing their policy support for the hydrogen energy industry, providing a good policy environment for its development. Many countries have included hydrogen energy in their national energy strategies and introduced a series of policy measures to encourage hydrogen energy technology research and development, industrial development, and infrastructure construction. For example, Japan issued the "Basic Hydrogen Strategy", proposing the goal of achieving a hydrogen society by 2030; Germany introduced the "National Hydrogen Strategy", planning to establish a hydrogen energy infrastructure network by 2030; China also released the "Medium and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021-2035)", clarifying the development goals and key tasks of the hydrogen energy industry. The introduction of these policies provides direction guidance and financial support for the development of the hydrogen energy industry, and will accelerate the innovation of hydrogen energy technologies and the large-scale development of the industry (Global Energy Internet Development and Cooperation Organization, 2021)[31].

6.2.2 Technological Innovation

Technological innovation is the core driving force for the development of the hydrogen energy industry. In recent years, technological innovations in the hydrogen energy field have continued to emerge. In terms of hydrogen production technologies, efficient and low-cost water electrolysis for hydrogen production technologies (such as new PEM electrolyzers, SOEC electrolyzers), low-energy-consuming water photolysis for hydrogen production technologies, and efficient biological hydrogen production technologies have made continuous progress; in terms of hydrogen storage technologies, high-performance hydrogen storage materials (such as new metal hydrides, MOFs materials) and efficient hydrogen storage systems have been continuously developed; in terms of fuel cell technologies, high-power density, long-life, and low-cost fuel cells have emerged. These technological innovations will gradually break through the technical bottlenecks of the hydrogen energy industry, reduce costs, and improve the competitiveness of hydrogen energy [32].

6.2.3 Growing Market Demand

With the increasing global demand for clean energy and low-carbon development, the market demand for hydrogen energy is also expanding. In the transportation field, the market share of hydrogen fuel cell vehicles is gradually increasing, and the demand for hydrogen energy is rising; in the industrial field, the green transformation of industries such as steel and chemicals has an increasingly urgent demand for low-carbon hydrogen energy; in the distributed power generation field, the application scope of hydrogen energy power generation systems is expanding. In addition, with the large-scale development of renewable energy, the demand for hydrogen energy as an energy storage medium

will also increase significantly. The growth of market demand will drive the large-scale development of the hydrogen energy industry and form a benign industrial ecology [33].

7. Conclusions and Prospects

As a clean, efficient, and sustainable energy carrier, hydrogen energy has an important strategic position in the global energy transformation. This paper comprehensively analyzes the characteristics of hydrogen energy, hydrogen production technologies, hydrogen storage and transportation methods, application fields, as well as the challenges and opportunities faced by the industry's development.

From the current development situation, the hydrogen energy industry has made certain progress, with relatively mature technologies in hydrogen production, storage, transportation, and application links, but it also faces challenges such as technical bottlenecks, high costs, lagging infrastructure construction, and safety and standards.

Looking to the future, with continuous technological innovation and breakthroughs, the production cost of hydrogen energy will gradually decrease, hydrogen storage and transportation technologies will become more efficient and safe, and the application scope of hydrogen energy will further expand. The continuous strengthening of policy support and the continuous growth of market demand will promote the large-scale development of the hydrogen energy industry and gradually build a complete hydrogen energy industry chain.

In terms of hydrogen production, renewable energy-powered water electrolysis for hydrogen production will become the mainstream hydrogen production method in the future. With the reduction of renewable energy power generation costs and the progress of electrolysis technology, the cost of green hydrogen will drop significantly, and it is expected to compete with traditional hydrogen production methods. In terms of hydrogen storage and transportation, solid-state hydrogen storage technology is expected to make breakthroughs, realizing efficient and low-cost hydrogen storage and transportation; the hydrogen pipeline network will be continuously improved, improving the efficiency and economy of hydrogen transportation. In terms of application, hydrogen energy will be widely used in transportation, distributed power generation, industry, and other fields, becoming an important part of the energy system.

In conclusion, although the development of the hydrogen energy industry still faces many challenges, it has a broad prospect. Through the joint efforts of governments, enterprises, research institutions, and other parties, hydrogen energy is expected to occupy an important position in the future energy structure and make important contributions to the global achievement of carbon neutrality goals and the promotion of energy transformation.

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