Development of renewable energy multi-energy complementary hydrogen energy system (A Case Study in China): A review

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Abstract
The hydrogen energy system based on the multi-energy complementary of renewable energy can improve the consumption of renewable energy, reduce the adverse impact on the power grid system, and has the characteristics of green, low carbon, sustainable, etc., which is currently a global research hotspot. Based on the basic principles of hydrogen production technology, this paper introduces the current hydrogen energy system topology, and summarizes the technical advantages of renewable energy complementary hydrogen production and the complementary system energy coordination forms. The problems that have been solved or reached consensus are summarized, and the current status of hydrogen energy system research at home and abroad is introduced in detail. On this basis, the key technologies of multi-energy complementation of hydrogen energy system are elaborated, especially in-depth research and discussion on coordinated control strategies, energy storage and capacity allocation, energy management, and electrolysis water hydrogen production technology. The development trend of the multi-energy complementary system and the hydrogen energy industry chain is also presented, which provides a reference for the development of hydrogen production technology and hydrogen energy utilization of the renewable energy complementary system.
Introduction

At present, global energy is in the process of transformation. As a secondary energy, hydrogen has the advantages of diverse sources, convenient storage and transportation, and wide applications. Therefore, hydrogen energy can promote the development of the existing energy system to a newer and more optimized direction. The interconnection and interaction of renewable energy and hydrogen-electric secondary energy networks will become a major trend in future energy utilization (Apostolou and Enevoldsen, 2019; Bao et al., 2020; Kadri et al., 2020; Widera, 2020). Hydrogen, as a clean and low-carbon new energy, can help the difficult-to-decarbonize industry to achieve the goal of carbon emission reduction; hydrogen energy has enriched the way of renewable energy storage at a lower cost, which can help renewable energy to regulate energy fluctuations and promote energy diversified structure and security of energy supply. At present, fossil fuels are the main raw materials for hydrogen production, which brings problems such as high cost of hydrogen production and environmental pollution caused by carbon emissions. The necessary conditions for the hydrogen production process are clean and efficient without pollution. Hydrogen raw materials are gradually developing from fossil fuels to renewable energy sources (Kikuchi et al., 2019). For example, a multi-energy complementary demonstration base based on wind energy, solar energy, water energy, and energy storage started construction in Jiuquan, Gansu Province at the end of 2019. The completion of the project will not only improve the local wind energy and solar energy consumption issues, but also increase the diversity of hydrogen production sources (Chen et al., 2020; Van der Roest et al., 2020).

The use of renewable energy to replace fossil fuels for hydrogen production will be the future development trend of clean and efficient hydrogen production. In the four links of production, storage, transportation, refuelling and application of the hydrogen energy industry chain, hydrogen production is the leader. To scientifically and rationally select the hydrogen production process path, we must start from the source and take environmental protection, economy, safety, and efficiency as the goal to achieve the supply of hydrogen energy (Li et al., 2020). Obtaining hydrogen energy from renewable energy sources, on the one hand, solves the unreliable factors such as low energy density and poor stability of renewable energy sources; on the other hand, it solves the insecurity of grid connection and the disadvantages of traditional batteries that cannot be stored for a long time. It is of great significance to realize unnecessary waste and local consumption of renewable energy.

In recent years, the development of China’s hydrogen energy industry has accelerated, and the industrial strategic layout has been continuously strengthened. With the guidance of policies, technological breakthroughs and the gradual improvement of industrial construction, as of the end of 2019, there are nearly 140 hydrogen stations under construction, half of which have been completed and put into operation, but key materials and upper-level core technologies still exist Many bottlenecks such as lack of autonomy and insufficient infrastructure construction (Zhang, 2020).
From the energy point of view, although hydrogen energy has not been widely used on a large scale and is not as well-known as electrical energy, it has unparalleled characteristics that we know of all energy sources. Hydrogen energy will soon become an inevitable choice for solving future energy problems. It is the future star of the energy field, and it is also called “ultimate energy” by industry experts. From an economic perspective, in the early stages of China’s hydrogen energy economic development, China’s industrial hydrogen production base has the ability to provide sufficient and cheap hydrogen resources. Hydrogen energy is used as an energy carrier, and its application model involves the fields of new energy supplementary power generation, fuel cell vehicles, and distributed power generation. If it can form an application network where electricity, heating and fuel cross each other in the future, its use cost will be greatly reduced. From a political point of view, for a country like China that lacks energy and needs to import energy on a large scale, the “hydrogen society” is a real national strategy that is related to the country’s survival and operation at all times. Hydrogen society is not just a technical route choice for industrial development, but a strategic choice covering technology, energy utilization, market and consumption system.

To this end, this paper takes the development of China’s future hydrogen energy as a starting point and studies the development of the world’s current renewable energy multi-energy complementary hydrogen energy system. First, the basic principles and topological models of the hydrogen energy system are briefly introduced, and the development level of hydrogen energy technology at home and abroad is systematically analysed. Combined with the current ambiguity and unresolved problems in the hydrogen energy industry, the key technologies in the hydrogen energy system are discussed in depth, and the development trends of hydrogen production, hydrogen storage, and hydrogen use technologies are proposed.

Renewable energy multi-energy complementary hydrogen energy system

The basic principle of renewable energy multi-energy complementary hydrogen energy system

Renewable energy multi-energy complementary hydrogen energy system (Ahmad et al., 2020; Chen and Chen, 2020) is to convert renewable energy into electrical energy through generators such as wind turbines, photovoltaics, and water pumps. Electrical energy is converted into hydrogen through electrolyzed hydrogen production equipment, and hydrogen is delivered to the hydrogen application terminal or it can be integrated into the grid via fuel cells to complete the conversion from renewable energy to hydrogen energy. According to the source of electrical energy, renewable hydrogen technology can be divided into two types: grid-connected and off-grid hydrogen production (Nguyen et al., 2019). Grid-connected hydrogen production is a method of generating electricity by connecting the generator set to the power grid and taking power from the power grid, such as taking power from the grid side of the wind-solar coupling system to produce hydrogen by electrolyzing water, which is mainly used for the dissipation of large-scale wind-solar coupling systems. Off-grid hydrogen production is the generation of electrical energy from the generator set, which is directly supplied to the electrolyzed water hydrogen production equipment for hydrogen production without going through the power grid. It is mainly used for
distributed hydrogen production or local fuel cell power generation and energy supply (Yuan et al., 2019). Based on existing structures such as wind farms, photovoltaic stations, and hydropower stations, combined with the advantages of hydrogen production technology, a renewable energy multi-energy complementary hydrogen energy system topology is established, as shown in Figure 1. The entire hydrogen energy system includes renewable energy Generator sets, electrolytic water hydrogen production systems, hydrogen storage systems, transportation systems, fuel cells, power grids, etc.

**Technical advantages of multi-energy complementary hydrogen energy system**

**Multi-energy complementary high adaptability.** With the country’s policy adjustments in the renewable energy hydrogen production industry, multi-energy complementary and coordinated operations, the pursuit of maximum benefits and win-win results have become inevitable (Liu et al., 2020b). Among the rapidly developing clean and renewable energy sources, wind energy, solar energy and water energy is the most widely used (Chang and Starcher, 2019). Wind energy and solar energy are widely distributed and have great development potential, but there are problems such as low energy density and poor stability; hydropower generation has high stability, but there are problems such as small flow and dry periods, and China’s renewable energy such as wind-solar-water is just in season Complementary, with sufficient solar and water energy in summer and sufficient wind power in winter, just in the dry season, so multi-energy complementary and coordinated power generation system is the focus of future research (Cui et al., 2019; Shin et al., 2019).

**Safety, cleanliness and efficiency of hydrogen production by electrolyzed water.** Hydrogen production by electrolyzed water is an electrochemical hydrogen production technology, which mainly
includes alkaline electrolysis hydrogen production, acid electrolysis hydrogen production, chlor-alkali electrolysis hydrogen production, high temperature electrolysis hydrogen production, and solar column electrolysis water hydrogen production (Brauns and Turek, 2020). The production of hydrogen from ionized Joule membrane acidic electrolyzed water is the reverse process of hydrogen fuel cells, the schematic diagram of its electro-hydrogen conversion is shown in Figure 2, the energy efficiency can reach 80%–90%, the operation process is acidic and high voltage process, there are problems of device corrosion and damage; the current industrialized hydrogen production It is alkaline electrolyzed water to produce hydrogen. Its system damage is small, its safety is high, and its efficiency is 30%–40%. Its process is an electrochemical reaction. It is a process with zero pollution and zero emissions. The only products are hydrogen and oxygen. Chlor-alkali in the electrolytic hydrogen production technology, a chlorine gas and sodium hydroxide are added, which are commonly used in the industry. The development of the diaphragm of the ion joule membrane has made this technology relatively mature in all aspects, will not cause pollution to the environment, and is in line with the concept of developing pure green energy. Electrolyzed water hydrogen production technology has high efficiency and high purity of hydrogen generation. In addition, the overall reaction speed can be adjusted by adjusting the voltage in the tank to achieve the control of the hydrogen production rate (El-Shafie et al., 2019).

The role of various power sources in multi-energy complementation. Power generation from renewable energy sources such as wind energy and solar energy has an effective capacity of basically zero, with large output fluctuations and uncontrollability. Therefore, it is necessary to coordinate with other forms of energy to play a role in cutting peaks and filling valleys. In addition to using river runoff to generate electricity, conventional hydropower stations with regulating capacity can also use their reservoirs for water storage regulation, and operate with wind power and photovoltaic compensation to exert greater capacity benefits. The unit’s response speed is fast, and it can basically adapt to the output fluctuation of wind power and photovoltaic. The pumped storage power station undertakes the system’s rapid response capacity and peak shaving tasks, and has the functions of frequency modulation, phase modulation, emergency backup, black start, etc., to improve the grid’s ability to accept wind power and solar power.

There are various forms of complementary utilization of various energies, which can not only ensure the safe and stable operation of the power grid, but also achieve coordinated and sustainable development of energy and the environment. Wind farms of different sizes in the
same area can alleviate the dramatic fluctuations in wind power output by complementing them and bundle them together to increase the utilization rate of wind power and reduce the scale of power transmission (Bothun, 2019). Wind power can be complementary to solar power generation. Although wind power and solar power are random and do not have complementary conditions, in some areas, wind power has a large output at night and a small output during the day, which can complement solar power (Mohammed and Sun, 2019). The wind and solar in the same area complement each other and jointly deliver energy, which improves the economics of hydrogen production to a certain extent. The complementary application of conventional hydropower stations and wind energy can appropriately reduce the energy storage output when wind energy and solar energy are relatively large, and increase the amount of electricity generated when wind energy and solar energy are relatively small. Reservoir scheduling is used to convert wind and solar energy in the form of reservoir water storage, and redistribute in time. Because the hydropower unit starts and stops quickly, it can adapt to the changes of wind energy and solar energy output to a certain extent. The complementary of pumped storage power station and wind energy is mainly to use the energy storage function of the storage power station for the storage and conversion of wind energy. The construction site of the pumped storage power station has greater choice, and has the functions of absorbing electricity and pumping water. Complementary to wind power is relatively stronger. The main function of the complementarities between the two is that the pumped storage power station acts as a “battery” for wind energy, which can stabilize the instability of wind energy output, reduce wind abandonment, and increase wind energy delivery at the same energy transmission scale. The complementarity of pumped storage energy plants with solar energy is similar to that of wind energy. The main purpose is to use the energy storage function of energy storage power stations to store and

| Characteristics   | Content                                                                                                                                 |
|------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Environmental    | Can accommodate a variety of clean energy, while improving the efficiency of traditional fossil energy use.                             |
| Economy          | Contains a large number of clean power sources, which can optimally distribute various energy outputs according to the formulated economic operation strategy, so as to optimize the overall economic benefits. At the same time, the energy supply system is close to the user end, which can reduce energy transmission and distribution losses and improve efficiency. |
| Safety and reliability | Peak shaving problems, backup problems, improve power supply reliability and power supply quality.                                      |
| Independence     | A multi-energy complementary system is an energy system composed of multiple energy sources and loads. It is generally connected to a large energy grid through a single point, that is, it is a controllable unit or load from the perspective of the energy grid. Under certain conditions, it can run independently. |
| flexibility      | Can run in grid-connected mode and isolated network mode. The grid-connected mode is a normal operating mode. In this mode, it can either absorb power from the main network or deliver power to the main network. When the main network fails, it automatically enters the isolated network mode. After the fault is cleared, it can automatically resume grid-connected operation. |
convert solar energy, convert a part of the photo-electricity into the peak consumption required by the system, and improve the effective power of the hydrogen production system.

**Multi-energy complementary hydrogen production characteristics and technical advantages.** The implementation of multi-energy complementation has close internal links with energy micro-grid systems, smart energy, energy internet, etc. It has the characteristics of environmental protection, economy, safety, reliability, independence, flexibility and so on. Specific characteristic analysis is shown in Table 1.

In terms of the hydrogen production industry, as of the beginning of 2020, global hydrogen production will be close to 100 million tons, of which 96% comes from fossil fuels, of which 48% comes from the cracking of fossil fuels, 30% comes from alcohol cracking, and 18% comes from coke oven gas, electrolyzed water accounts for about 4%. The main reason for the small proportion of electrolyzed water is that the cost of hydrogen produced by electrolyzed water is very high, which is more than twice that of fossil fuels (Li et al., 2019c). Electrolyzed water hydrogen production technology can adapt to the discontinuous and unstable power supply defects of renewable energy power generation systems such as wind-solar-water, reduce the cost of hydrogen production by electrolytic water, extend the service life, and promote the economic development of distributed energy (Rashid et al., 2015); Renewable energy such as wind-solar-water produces hydrogen and uses hydrogen as an intermediate energy carrier to store and convert energy, making the energy supply to users more flexible and convenient. Its structural composition is shown in Figure 3. Therefore, the rise of renewable energy multi-energy complementary electrolyzed water hydrogen production technology is inevitably, it is also the only way for us in the future (Hao et al., 2018).

![Figure 3. Structure of hydrogen station system.](image)
Research status of hydrogen energy technology development based on renewable energy

Development status abroad

As an important secondary energy source, hydrogen energy is one of the most promising energy sources to solve the future energy crisis. It is the main path for global energy to transition to sustainable development and the main clean green energy source in the future. In recent years, countries around the world have raised the development of hydrogen energy to a national-level strategy, formulated action plans, mapped out development roadmaps, and actively explored the way forward. In 2001, the U.S. proposed the “Integrated Energy System Development Plan” and vigorously developed microgrids and smart grids to increase the proportion of clean energy supply and utilization. In 2002, the U.S. Department of Energy released the “National Hydrogen Energy Development Roadmap”, taking hydrogen energy as a development goal, formulated a detailed development plan to promote large-scale hydrogen energy production and application, and transferred the construction of the “hydrogen energy society” from the plan into action. In 2009, the EU launched the “Renewable Energy Directive”, which is the core of promoting the implementation of clean energy policies. Since then, member countries have begun to implement national renewable energy action plans. In 2011, the European Union formulated the “2050 Energy Technology Roadmap”, taking decarbonisation as one of its core goals, and taking hydrogen energy as an important component of the energy system. Together with fuel cells, it will become a major factor in the future energy system structural transformation. In 2014, the United States formulated the Comprehensive Energy Strategy, which aims to develop low-carbon technologies that can lay the foundation for clean energy, and clearly demonstrates the leading role of hydrogen energy in transportation transformation (He, 2015; Wang et al., 2019). In 2016, Japan formulated the Plan for the 2050 Energy and Environment Innovation Strategy, dedicated to the construction of smart communities, promoting the full social coverage of the hydrogen energy network, achieving integrated integration with infrastructure, and ultimately building a clean “Hydrogen society.” Germany also revised its hydrogen energy strategic plan in the same year, focusing on the coordinated development of the energy supply chain and industrial chain. France formulated the Hydrogen Energy Plan in 2019, carried out carbon-free reforms in the industry, realized renewable comprehensive energy production of hydrogen and hydrogen-electric conversion, and built an energy network. In 2019, the European Fuel Cell and Hydrogen Energy Joint Organization released the European Hydrogen Energy Roadmap, which proposed a medium-term (2010–2020) and long-term (2020–2050) hydrogen energy development roadmap.

Foreign researchers have also analysed and improved the hydrogen production technology of renewable energy integrated energy systems. Billah (2017) of Bangladesh uses sufficient solar and wind energy in Patenga area to combine with tidal energy to produce hydrogen, and proposes a coastal power system based on energy storage. In this system, the hydrogen is used to drive the generator to reduce the THD (total harmonic distortion) of the power grid, and no carbon dioxide is generated during the entire process. The feasibility of the power system was confirmed through experiments, which laid the foundation for the development of a variety of renewable energy hydrogen production technologies. Australian Furat et al. (2020) proposed the use of hydrogen to generate electricity for storing variable
renewable energy (RE) to achieve a 100% renewable and sustainable hydrogen economy. The hydrogen energy system (energy-hydrogen-electricity) is divided into four main stages of production, storage, safety and utilization. It is pointed out that the hydrogen production route and specific technology choice depend on the type of energy and raw materials available and the required end-use purity. The paper summarizes the hydrogen production pathways and related technologies, and illustrates the interconnection and interdependence of the various corners of the hydrogen grid. Zaenal (2019) of Russia conducted research on hydrogen production technology when the output power of renewable energy is below the threshold studied the impact of power fluctuations on the hydrogen production process and the overall efficiency of the system. The hydrogen system runs on the grid when the power is lower than the hydrogen production threshold to improve the quality of hydrogen. Yilmaz et al. (2020) in Turkey designed an integrated cycle system including wind power, photovoltaics, hydrogen production and hydrogen storage, and carried out a detailed thermodynamic performance assessment. It shows that an increase in reference temperature will reduce power plant performance, net power generation and hydrogen production. It is also pointed out that solar and wind energy is the most widely used energy sources in renewable energy. When solar radiation is insufficient or at night, the combination with wind turbines can provide many advantages for a clean and sustainable future. The proposed study highlights the importance of clean hydrogen production for its environmental benefits. Serna et al. (2017) considering the important components such as electrolytic cells and supercapacitors in the microgrid, proposed a long-term and short-term MPC control of the microgrid based on hydrogen energy. This control can independently optimize the operation process of the electrolytic device and ensure the Health status of hydrogen production in tanks. Canada’s Seyam et al. (2019) used the NSGA-II algorithm to find the best combination of energy efficiency, hydrogen production quality and cooling load in a hybrid renewable energy system. The analysis was based on actual data in Egypt and Saudi Arabia, which confirmed that this algorithm can improve hydrogen production efficiency. Human et al. (2019) of South Africa introduced an optimization method for scale and power management of a small independent renewable energy hydrogen production system, combining SPEA algorithm with GA algorithm to optimize system efficiency, cost and reliability. The analysis shows that the proposed method can optimize multiple targets simultaneously. Yamashita et al. (2019) of Japan proposed a system to control the imbalance of current between the load and power source and the power flow inside the system based on the fluctuation of renewable energy. Through simulation verification, the method can control the stepwise and random changes of input and output power. The high-frequency fluctuations in power demand are compensated by the battery. The remaining low-frequency fluctuations are processed by the electrolytic cell. The two cooperate with each other to improve the stability of the system.

The scale of the global hydrogen energy market has been further expanded, the development strategy of the hydrogen energy industry in major countries in the world is clear, the pilot demonstration of hydrogen energy and multi-field application research and development have been promoted, and major hydrogen energy projects have been launched. In 2013, Brandenburg, Germany, built the world’s first hybrid energy power station using hydrogen energy as a power storage intermediary. The hydrogen obtained from its electrolysis was used to drive a generator through combustion, and the generated electricity continued to electrolyze hydrogen production. In 2015, the Mainz Energy Project (Wang, 2018) was officially launched and is currently the world’s largest hydrogen station. The main
The purpose of this project is to convert clean renewable energy into hydrogen for use and storage, effectively alleviating the potential fluctuations caused by the integration of renewable energy systems into the grid. In 2018, Germany’s hydrogen-powered trains officially rolled off the line, working on about 100 km of the line between Cuxhaven and Buxtehude, becoming the earliest demonstration projects for the combined use of hydrogen energy and fuel cells. In 2019, Brunei’s “hydrogenation plant” was built, and the world’s first global hydrogen supply chain based on organic liquid hydrogen storage will be put into use in 2020, and it can deliver 210 tons of hydrogen to Japan every year. In the future, the project will also use Brunei’s wind power resources to develop renewable energy electrolysis to produce hydrogen to achieve the supply of low-carbon clean hydrogen.

In recent years, major countries around the world have attached great importance to the development of hydrogen energy and fuel cells. The developed countries such as the United States, Japan, and Germany have raised hydrogen energy to the level of national energy strategy, and continuously increased the research and development and industrialization of hydrogen energy and fuel cells. The United States is the first country to adopt hydrogen energy and fuel cells as an energy strategy. The investment amount exceeds US$1.6 billion, and it has mastered core technologies such as liquid hydrogen gas storage tanks and hydrogen storage tanks. It has absolute advantages in terms of liquid hydrogen production scale, liquid hydrogen production and price. Japan attaches great importance to the development of the hydrogen energy industry and proposes to “become the first country in the world to realize a hydrogen energy society.” It has the world’s largest number of patents for “hydrogen energy and fuel cell technology”, and has achieved large-scale commercial promotion of fuel cell vehicles and domestic cogeneration systems. The EU regards hydrogen energy as an important guarantee for energy security and energy transformation. In the past six years, the total hydrogen energy budget is 665 million euros, and there are nearly 200 hydrogen refuelling stations in operation. Germany’s promotion and application of hydrogen energy is in the forefront of Europe, and it has good applications in fuel cell vehicles, communication base stations, domestic combined heat and power stations, and hydrogen refuelling stations. To build hydrogen infrastructure for fuel cell vehicles in the country, and provide a good environment for the development of fuel cell vehicles in Germany. Australia has developed 57 hydrogen energy strategic actions in the areas of regulations, infrastructure, transportation and R&D, aiming to position Australia as a global leader in hydrogen production and export. South Korea has great ambitions in the field of hydrogen energy and fuel cells, and the current development focus is on large fuel cell power plants.

To sum up, foreign research on hydrogen production technology from renewable energy started earlier, but there are still phenomena of low hydrogen production efficiency and high hydrogen production cost. The research on hybrid renewable energy hydrogen production technology is in its infancy. Its main hydrogen production technology is mainly based on microgrid. There is relatively little research on renewable energy complementary hydrogen production technology. There are problems with the adaptability of wide power fluctuations and the failure and safety analysis of the entire system. At the same time, the conversion technology from hydrogen to electrical energy will also promote the development of hydrogen energy. The coordinated control of the hydrogen production technology of the energy complementary system can not only improve the energy utilization rate, but also reduce the cost of hydrogen production, which will become the future development direction of hydrogen energy. In the future, lower capital costs, improved hydrogen production efficiency, more compact design, and safer systems will become the future development direction.
Domestic development status

In recent years, the rapid development of renewable energy hydrogen energy systems and the rise of the electric vehicle industry have increased the market’s expectations for hydrogen technology, and China attaches great importance to the development of the hydrogen energy industry. Since the beginning of 2012, China began to study the multi-energy complementary hydrogen energy system, and at the end of 2013 it was clearly pointed out that the future smart grid is the “energy Internet”. In 2016, China released the “Roadmap for Key Innovation Actions in the Energy Technology Revolution,” which proposed “achieving large-scale, low-cost production, storage, transportation, and application of hydrogen.” In the same year, the “Thirteenth Five-Year Plan” National Science and Technology Innovation Plan were issued, focusing on the development of technologies such as hydrogen energy that can lead to industrial change. In 2018, the National Development and Reform Commission and the National Energy Administration formulated the Clean Energy Consumption Action Plan (2018–2020). In 2019, “hydrogen energy” was first written in the national government report. The National Energy Administration released the “Guide Catalog of Green Industry” to actively encourage the development of hydrogen energy. At the same time, Zhejiang, Shanxi and other places proposed local hydrogen energy development policies, and the government increased subsidies. At present, China has formed seven hydrogen energy industry clusters and has formulated three major development stages to support the development of the hydrogen energy industry.

The domestic research on hydrogen production technology started relatively late, and there is less research on hydrogen production technology from renewable energy. In 2019, Vargas Mira et al. (2019) analyzed the economics of hydrogen production technology, analysed several existing industrial hydrogen production technologies, and found that the economics of hydrogen production technology is closely related to the cost, location and scale of hydrogen production equipment. Jin et al. (2019) proposed the use of hydrogen production technology to solve the problem of abandoning wind and solar from the consideration of the current cost, life and efficiency of hydrogen production. The current research status and application prospects of hydrogen storage technology provide two development ideas for fuel cell hydrogen energy storage and hydrogen-mixed natural gas. Based on the economic performance of hydrogen production technology, innovative research has also been carried out on hydrogen production technology itself. Cai et al. (2016) established a comprehensive energy hydrogen production system based on a DC bus structure. The PV maximum power point tracking (MPPT) algorithm was used to predict energy. For different operating conditions of hybrid power systems, designing corresponding control strategies can improve the stability of the hydrogen production system in the entire system. Wang (2018) explored the interaction between renewable energy and the power grid. By controlling the hydrogen production system, not only can it reduce the intermittent nature of renewable energy, integrate multiple energy sectors, but also better integrate energy Power system. In 2019, Li (2018) established a model for hydrogen production from distributed energy sources, and analysed the effects of energy storage and non-storage systems and changes in wind speed and light intensity on hydrogen production efficiency. The hydrogen production efficiency is significantly improved, and the power fluctuation caused by renewable energy can be smoothed.

In order to promote the development of the hydrogen energy industry and further clarify the positioning of the hydrogen energy industry, China is actively carrying out pilot
demonstrations of the application of hydrogen energy and fuel cells. In 2016, the demonstration project of the “Twelfth Five-Year Plan” 863 project in Dalian built China’s first wind-solar hybrid power generation hydrogen production station, integrating hydrogen production technology, ultra-high pressure storage technology and filling technology into one. In 2018, the National Energy Administration developed a comprehensive energy demonstration zone in Guangzhou to realize the advanced layout of the core technologies of the hydrogen energy industry, exert the agglomeration effect, and actively build the “China Hydrogen Valley.” The State Grid Global Energy Internet Research Institute studies volatile new energy hydrogen production technology and breaks through the bottleneck of efficient hydrogen conversion. In 2019, the construction of the world’s largest wind power hydrogen production project, the Guyuan Wind Power Hydrogen Comprehensive Utilization Project, has entered the final stage. After completion, it can form an annual production capacity of 17.52 million standard cubic meters of hydrogen, integrate with fuel cells and other resources, and resolve Local abandonment of wind and solar. Guodian Dadu River Basin Hydropower Development Company actively builds the “Western Sichuan Hydrogen Energy Road”, makes full use of local hydropower resources, and completes hydrogen refuelling station and hydrogen bus demonstration operation (He et al., 2019). With Jinan as the core, Shandong Province builds a trinity hydrogen energy economic circle with a hydrogen energy technology park, a hydrogen energy industrial park, and a hydrogen energy exhibition and business district. Leading companies represented by Yankuang Group have first-class hydrogen production technology, create an industrial system for the production and storage of hydrogen energy, and promote the demonstration application of centralized and distributed energy supply systems for hydrogen energy.

Through research, it is found that synergistic hydrogen production from renewable sources such as wind and solar is feasible. However, renewable energy is affected by the environment, which results in large output power fluctuations and strong intermittent performance. It is difficult to apply it on a large scale. China’s water resources are abundant, and reservoir water storage can suppress energy fluctuations and regulate wind and solar energy. Complementary energy and coordinated power generation can improve energy efficiency and promote the development of industry and life towards a more low-carbon and cleaner direction. The process of producing hydrogen by electrolyzing water can also effectively alleviate power fluctuations caused by renewable energy sources, which will run through the entire process of hydrogen energy development. The research and development of renewable energy hydrogen production technology in China started late, and the progress is relatively slow. At present, there is no commercial operation of a mature renewable energy hydrogen energy system. There is insufficient experience in designing large-scale renewable energy hydrogen demonstration projects, and it has not achieved substantial results in terms of system key technologies, efficiency improvements, and economics.

The technology of producing hydrogen through electrolysis of water from renewable energy will continue to mature and the cost of hydrogen production will gradually decrease. The source of hydrogen production tends to produce hydrogen from electrolyzed water, as shown in Figure 4, it is expected that by 2100, the proportion of electrolytic water will reach about 50%. Hydrogen production from electrolyzed water will gradually meet commercial needs and realize distributed hydrogen production, which can not only produce hydrogen centrally and regionally, but also build small electrolyzed water hydrogen production devices to realize the intelligent interconnection of hydrogen energy.
Research on key technologies of multi-energy complementary hydrogen energy system

The renewable energy multi-energy complementary hydrogen energy system has a wide range of power sources, including solar energy, water energy, wind energy, tidal energy, biomass energy, etc. In recent years, China has developed rapidly in the use of renewable energy sources such as constant frequency conversion wind power generation technology, large-scale photovoltaic power generation, hydropower installation and biomass energy, and has been at the forefront of the world. However, due to the randomness and volatility of renewable energy itself, higher requirements are placed on the grid’s ability to resist fluctuations, coupled with factors such as geographical restrictions and consumption capacity, leading to serious energy waste (Malik et al., 2019; Zhu, 2016).

In order to improve energy system utilization efficiency and local consumption capacity, and comprehensively consider system economy, grid security, and user comfort, China has proposed the implementation of a multi-energy complementary system integration optimization project (Cai, 2018; Jayasuriya et al., 2019; Yu et al., 2016). At present, the development of renewable energy multi-energy complementary hydrogen energy technology is still immature. There are many problems in various links such as complementary energy and hydrogen production technology. The key technologies that need to be developed and urgently addressed include coordinated control strategies for multiple energy sources, energy storage and capacity allocation, energy management, and electrolytic water hydrogen production technologies.

Collaborative optimization control strategy

In a hydrogen energy system, there are multiple energy sources. The coupling of the power supply and the energy storage device increases the requirement for smooth operation of the

Figure 4. Proportion of various hydrogen production technologies.
system. Therefore, the research of multi-energy complementary coordinated control strategy becomes the most important. The basic control principle is shown in Figure 5. Not only must we consider the combination of renewable energy, power grids, energy storage, loads, etc., but we also need to rely on coordinated control strategies to make hydrogen energy system safe, reliable, clean, efficient, and economically convenient (Zhong et al., 2018). The control strategy of the multi-energy complementary hydrogen energy system needs to predict the generation and load consumption of renewable energy, and integrate information such as regional electricity prices and natural gas prices to perform multi-energy complementation and optimize the scheduling of renewable energy systems (Liu, 2018).

As distributed renewable energy is continuously connected to the power grid on a large scale, the frequency control of the power grid has become increasingly difficult. Scholars at home and abroad have applied various algorithms such as predictive control, adaptive control, and deep learning to the complementary energy generation system (Sun et al., 2017; Kong et al., 2018; Moghadam and Modares, 2018; Xi et al., 2018; Yin et al., 2018). Xi et al. (2020) aimed at the randomness and the strong disturbance caused by the transient nature of renewable energy sources. A deep reinforcement learning algorithm based on proportional priority sampling mechanism was proposed to improve the control performance and convergence speed. Masaki et al. (2019) proposed a two-layer control strategy to easily integrate supercapacitors into grid-connected solar photovoltaic-cell hybrid renewable energy systems, and applied an additional control layer at the bottom of the original control system. The design of the new model predictive control layer and its coordination with the original model help to provide a stable power flow between the hybrid renewable system and the utility grid, and eliminate rapid changes in battery power. Optimal coordinated control of regional energy sources has enabled safe operation of multi-energy complementary systems. Starting from the environmental and economic benefits, the multi-energy complementary system has been optimized (Hao et al., 2019; Li et al., 2018; Sanjari et al., 2015). By establishing a mixed integer programming (MILP) model of the multi-energy complementary integrated system, an optimal mixed power flow algorithm was proposed. The integrated energy system planning methods, scheduling strategies, and consumption capacity are studied. In order to ensure that the multi-energy complementary system meets the planned indicators, Ye et al. (2018) comprehensively analysis the multi-energy complementary system evaluation indicators, and uses the complementary coefficient

Figure 5. Basic control principle.
as the bridge joint subsystem and integrated power generation system to establish an evaluation system that can comprehensively and objectively evaluate the intra-day time scale Comprehensive energy complementary system. Cheng et al. (2020a) aimed at the lack of economic considerations of the current multi-energy complementary power generation technology and its related evaluation indicators, based on the Grey-forecasting model and Weibull distribution model for power prediction, and proposed a multi-index multi-energy complementary strategy.

At present, the research on the control strategy of renewable energy multi-energy complementary hydrogen energy system is still in its infancy. Although researchers have conducted some research in this field, with the continuous development of various renewable energy power generation technologies, research on coordinated control of multi-energy complementary systems will continue to increase. Therefore, in view of the difference in time and space between different energy sources in a multi-energy complementary system, it is necessary to study a coordinated control strategy that comprehensively considers indicators such as safety, economy, and efficiency.

Energy storage technology and capacity allocation strategy
China’s research on renewable energy is a little later than in Western countries, so there is a gap between infrastructure and core technologies. Especially with the rise of renewable energy multi-energy complementary hydrogen energy systems, due to low energy utilization, the difference between economic and environmental benefits is more obvious compared to Western developed countries. The original intention of the multi-energy complementary hydrogen energy system is to coordinate and complement each other to save energy. This also makes energy storage technology and its capacity allocation the core foundation of multi-energy complementary systems, thereby accelerating the large-scale application of renewable energy (Gabrielli et al., 2020). For renewable energy storage technology, it improves the impact of wind and solar energy volatility and intermittency on system safety and stability, and plays an important role in the development of multi-energy complementary systems.
At present, according to the form of energy storage, energy storage devices used in renewable energy are divided into: mechanical energy storage (pumped energy storage, etc.), electrochemical energy storage (lithium ion batteries, etc.), electromagnetic energy storage (super capacitors, etc.), heat storage, hydrogen storage, etc. (Liu et al., 2020a; Sheikholeslami et al., 2019; Sun et al., 2019; Wieme et al., 2019). Figure 6 is a structural diagram of a hybrid energy storage system. Electric-hydrogen conversion technology can realize the mutual conversion between electric energy and hydrogen energy. Compared with other energy storage methods, hydrogen production technology improves the utilization rate of renewable energy and provides a new way for energy consumption (Dong et al., 2019). Reducing the consumption of fossil fuels; As a clean chemical raw material, hydrogen can also be made into fuel cells and converted into electricity (Wang et al., 2018). Hydrogen storage technology has completed energy storage and subsequent clean utilization, which is an important research direction for future energy storage methods (Guo et al., 2020). Hydrogen storage technology has huge advantages and broad prospects. However, due to emerging technologies in recent years, there are still many deficiencies in hydrogen storage materials and mechanisms. Researchers at home and abroad have done a lot of research for this. Yang (2019) briefly explained the three traditional hydrogen storage methods, focusing on the summary of solid hydrogen storage materials. The mechanism, advantages and disadvantages of the materials are compared, and the future research focus of hydrogen is pointed out. Hirscher et al. (2020) summarizes the development of hydrogen storage materials, methods and technologies (including electrochemical and thermal storage systems) in the past 5 years, covering porous materials, liquid hydrogen carriers, composite hydrides and intermetallics. On the basis of hydrides, electrochemical storage of energy, thermal energy storage, and hydrogen energy systems, the future and research prospects of hydrogen storage technology are proposed.

The energy storage system has powerful functions, but improper operation may cause damage to components in the system, and in severe cases, fire may occur. In order to ensure the safe operation of the system and reduce the operating costs, it is necessary to reasonably configure the production capacity, storage and consumption processes of various energy sources. One of the research priorities is to make reasonable planning for the energy storage capacity and power allocation of the multi-energy complementary hydrogen energy system, and to improve the economic efficiency of the entire system (Li et al., 2019a; Marocco et al., 2020).

There are two main types of energy storage system operation: island operation and grid connection operation (Ge et al., 2019). Some researchers have established multi-energy complementary systems with complementary energy, such as wind, solar, electricity, and hydrogen (Akagi et al., 2020; Chen et al., 2019; Georgios and Stavros, 2020; Wang et al., 2020). Aiming at the wind power model, photovoltaic power model, and energy storage system power model in island mode, the power, the goal is to predict loads and reduce operating costs. Using optimization methods such as weak robustness and multi-objective solving, a capacity allocation strategy for a multi-energy complementary system in an island operation mode is proposed to achieve maximum island operation utilization and optimal capacity allocation. Teketay et al. (2020) studied the capacity allocation scheme of renewable energy complementary systems based on the Philippine islands, taking into account factors such as cost and floor space, using entropy weights and “order preference technology similar to the ideal solution” (TOPSIS) method to Evaluate the optimal capacity configuration and apply its ideas to other off-grid systems. Li et al. (2020) based on multi-energy
coordinated optimization and optimal operating efficiency as the starting point. In a simplified multi-energy complementary system model, a multi-objective particle swarm optimization algorithm was used to conduct in-depth research on the capacity allocation and economic benefits of energy storage systems. Combined with the corresponding demonstration projects, the configuration scheme was verified. Jia et al. (2019) proposed a two-layer optimized configuration method that considers economy and efficiency in the distribution network, and based on this, realized short-term operation optimization layout, making the optimized configuration method more in line with actual operating conditions. Donado et al. (2019) used genetic algorithms to optimize for multiple objectives such as climate and economy, taking into account factors such as initial cost, life cycle cost, and probability loss of power supply to achieve the optimal capacity allocation of renewable energy systems.

For multi-energy complementary hydrogen energy systems with different energy types, the capacity optimization scheme is also different. Most of the current capacity allocation schemes are combined with more traditional energy storage systems in the past, or single wind energy hydrogen storage energy storage (Hou et al., 2017), photovoltaic hydrogen production storage (Temiz and Javani, 2020), etc. Research on large-scale hydrogen energy systems for hydrogen storage and energy storage is scarce. Therefore, hydrogen energy as a future energy storage method with broad development prospects, hydrogen production and multi-energy complementary systems and other technologies will become the main research direction in the future.

Integrated energy management system

The energy management system covers energy flows such as power grids, renewable energy, loads and energy storage, and plans and regulates them through information flows. It is an important part of the renewable energy multi-energy complementary system, which is conducive to ensuring the safe and stable operation of the multi-energy complementary hydrogen energy system (Wu, 2018). For the renewable energy multi-energy complementary hydrogen energy system, establish a comprehensive optimization management platform, through energy forecasting, performance analysis and strategy formulation, organically combine the power grid, renewable energy, energy storage system, load, etc. to formulate corresponding multi-dimensional comprehensive decisions. At present, after decades of development, the energy management system of the traditional power industry has matured. Hydrogen energy systems contain a variety of renewable energy sources, and the energy sources themselves are random and volatile (Li et al., 2019b). When various energy sources are coupled, time and space will be different, so traditional energy management systems have little impact. In order to realize the effective use of energy, coordinated output between energy and reasonable load distribution, it is very important to detect and control energy. Therefore, in-depth research on energy management of multi-energy complementary systems is urgently needed (Shayeghi et al., 2019; Tian et al., 2018).

The research on energy management of renewable energy multi-energy complementary systems has just begun. The establishment of the theoretical basis of the system and the management system requires the joint efforts of researchers. Zhan et al. (2019) based on the wind-solar-firewood-storage energy storage system and considered the operating constraints of various types of energy equipment, proposed an energy management control strategy that can operate stably in the on/off-grid state. In the grid-connected state, peak-cutting and valley-filling, and peak arbitrage; in the off-grid state, limit power and automatically absorb.
It is of great significance for the long-term stable operation of the system, extending the life of equipment and reducing operating costs. Trianni et al. (2019) proposed an innovative energy management assessment model based on energy management practices, and validated and applied the model through case studies of manufacturing companies in Italy and Sweden. It proves that the model can fully describe the status of energy management, and benchmark the level of adoption of energy management practices against specific benchmarks. Zhao et al. (2019) built a complete multi-energy complementary energy management system based on the emerging big data, completed the software and hardware design of the LINUX operating system, NOSOL database, and controller of the multi-energy complementary energy management system. The efficiency of the management system is 25% higher than before, which proves that the designed multi-energy complementary energy management system has extremely high efficiency, and also points out the shortcomings of the system. The next research is still in progress.

At the same time, the coordinated autonomous optimization of multi-interconnected multi-energy complementary systems in layers and stages is also one of the research methods that have attracted much attention. Cheng et al. (2020b) based on a two-layer, two-stage framework of active control, to achieve the optimal energy supply between energy sources, authorizing each independent energy system to optimize to independently provide local demand and collaborate with each other, energy interconnection. The proposed “two-stage TC framework” guarantees that collaboration takes place in a distributed and scalable manner, and that convergence is fast. Xu et al. (2020) proposed a two-stage optimal coordination strategy. The prediction result was used as the upper model, and the actual result was used as the lower model. The particle swarm algorithm was improved through chaos algorithm to achieve optimal collaborative supply of multiple energy forms and maximize economic benefits. The current multi-energy coupled energy management system has broad development prospects, and future research will focus on multi-energy complementary energy management systems combined with current big data and intelligent autonomous optimization design.

**Research on water electrolysis technology**

With the development of hydrogen energy system, it has played a good role in promoting the development of electrolysis water hydrogen production technology. Reducing the energy consumption of the electrolysis process and improving the energy conversion efficiency has become a problem that needs to be solved urgently. Researchers have done a lot of work for this. In the hydrogen energy system, the electrolysis water technology is used to convert the generated electric energy into hydrogen and oxygen, and the generated gas is directly provided to the load or converted into electric energy and integrated into the power grid, thereby improving the utilization rate of power generation. Supplement system energy and solve the problem of power waste. It can also ensure the safe and stable operation of the power system, which is the only way for future large-scale renewable energy. China and some European and American countries have conducted extensive research on this and established demonstration projects in certain fields. The electrolyzed water technology equipment is simple, the process is mature, no pollution, and has been applied in industry.

According to the type of electrolyte, it can be divided into three types: alkaline, proton exchange membrane, and solid oxide. The traditional alkaline electrolyte has low hydrogen production efficiency and large power loss, which limits its application range (Liu et al.,
Most proton exchange membranes use higher cost precious metals, and they will be degraded during use. At present, costs are mainly reduced by reducing the catalyst load and developing alloy catalysts. Schuler et al. (2020) aim at the limitation of the current polymer proton exchange membrane catalyst and the thickness, a material with different microporous layers with three advanced interface characteristics was manufactured, which was made of titanium powder with higher economy, which improved the exchange membrane. The interfacial performance and surface roughness make the catalyst utilization rate tripled. The working temperature of solid oxide electrolyzed water is 500–800°C, and the hydrogen production efficiency is higher than the above two electrolytes. In order to improve the performance of nickel-based cathodes in solid oxide electrolytic cells (SOEC) at moderate temperatures (600–800°C), iron was added to nickel to suppress the coarsening of Ni particles to enhance the performance of Ni-based cathodes, and passed the test. The optimal molar content of iron was determined, a higher current and good stability were obtained at the same battery potential, indicating that the proper proportion of Ni-Fe bimetal can enhance the performance of Ni-based cathodes (Ji et al., 2020). American scientists have developed a solid polymer electrolyte (SPE), Das and Ghosh (2020) synthesized a polyvinylidene fluoride-co-hexafluoropropylene-based polymer electrolyte. An electric double-layer capacitor was prepared using a synthetic polymer electrolyte. The physical and chemical properties of the polymer nanocomposite were studied using X-ray diffraction, differential scanning calorimetry, and Fourier transform infrared analysis. The main polymer PVDF-HFP was found the crystalline phase is reduced, the maximum voltage stability is obtained, the ionic conductivity is improved, and the energy consumption of the electrolytic process is reduced.

For the technology of hydrogen production by electrolyzed water, alkaline electrolyzed water is cheap but has low energy efficiency; PEM electrolyzed water has high cost, poor durability, and cannot be used on a large scale (Li, 2019d); solid electrolyzed water is required to work at higher temperatures, and it is still in the laboratory stage. Therefore, more in-depth research is needed on the electrolyzed water technology, which is conducive to promoting the widespread application of hydrogen energy systems.

**Trend forecast of renewable energy complementary hydrogen energy system industry chain**

Hydrogen energy is an important development direction of the global energy technology revolution and an important part of the future of sustainable and safe energy. Accelerating the development of the hydrogen energy industry can not only cope with the global environmental crisis, but also ensure energy supply and achieve sustainable development of national energy. According to the “Hydrogen Energy Future Development Trend Report” published by the IEA, it is estimated that by 2050, the consumption of hydrogen energy will be 10 times the current consumption. Countries around the world are vigorously developing hydrogen production technology and occupying the commanding heights of international hydrogen energy.

**Multi-energy complementary technology development trend**

The application prospect of multi-energy complementary technology is very broad. In 2016, the “Implementation Opinions on Promoting the Construction of Multi-energy
Complementary Integration and Optimization Demonstration Projects” issued by the National Development and Reform Commission and the National Energy Administration pointed out that China will build nearly 20 national-level terminal integrated energy supply demonstration projects. It aims to promote China’s multi-energy complementary integration model in the “terminal integrated energy supply system” and continuously increase the proportion of renewable energy used, such as wind energy, tidal energy, and solar energy. China’s ongoing energy system reform, multi-energy complementarity will become an important breakthrough for China to promote energy modernization transformation and build a clean, low-carbon, safe and efficient energy system. Combined with system reforms in other energy fields, it will gradually break the operation mode of single power grid, heat grid, and gas grid, and break the difficulties of coordination, inconsistent planning, and inefficient operation. From the perspective of the development of multi-energy complementary projects in countries around the world, most of the pilot projects are carried out at the small-scale regional grid level, but the efficient application of multi-energy complementary is not limited to the micro-grid level. The large-scale energy internet will be the future trend. The future energy network will develop towards a more intelligent, low-carbon, efficient and sustainable direction. Multi-energy complementarity will develop in the direction of accommodating the high-volatility renewable energy power generation, transmission, distribution, storage, and use integration, combined with large-scale energy networks and coordinated development.

**Trend prediction of hydrogen production from renewable energy**

Hydrogen production technology is at the upstream of the development of hydrogen energy. At present, the mainstream green hydrogen production technologies mainly include hydrogen produced by electrolysis, hydrogen produced by biology, and hydrogen produced by solar energy. According to the China Hydrogen Energy Alliance, the long-term goal of China’s hydrogen energy production is to achieve the continuous use of renewable energy to electrolyze water to produce hydrogen by 2050, and vigorously develop biological hydrogen production and solar photolysis of water to produce hydrogen.

*Hydrogen production technology by electrolytic water.* At present, the mainstream hydrogen production methods are coal gasification hydrogen production and natural gas hydrogen production. From a cost perspective, coal gasification hydrogen production has the lowest cost and there is already a profit margin. Electrolyzed water production of hydrogen accounts for only 4%. The main factor is that the cost is too high and the return is negative; from the perspective of green environmental protection, hydrogen production from electrolytic water is low-carbon and sustainable. Compared with the current mainstream hydrogen production technology, it is sustainable and low-polluting. It is theoretically the most ideal hydrogen production technology and is in line with sustainable national policies. The future development of hydrogen production technology is mainly affected by factors such as technological level, economic benefits, and environmental benefits. The latest report released by the International Energy Agency shows that by 2030, the cost of producing hydrogen from renewable energy sources may drop by 30% (Wang, 2020). With the development of renewable integrated energy systems, the technology of hydrogen production by electrolyzed water will become the mainstream method of hydrogen production in the future, and the
development prospect is broad. By 2050, the electrolyzed water generated by renewable energy will become the mainstream hydrogen production technology.

**Biomass hydrogen production technology.** The raw materials for biological hydrogen production are wide and non-polluting, the reaction environment is normal temperature and pressure, and the production cost is low, completely overturning the traditional energy production process. As an environmentally friendly renewable energy source, if we can use biomass energy to achieve the industrialization of hydrogen production, it will not only have a positive effect on the optimal use of energy, but also reduce environmental pollution. Biological hydrogen production refers to the conversion of energy stored in organic compounds (such as carbohydrates and proteins in plants) into hydrogen energy through the action of hydrogen-producing bacteria. It is a bio-engineering technology that uses microbial metabolism to efficiently produce hydrogen. The main ways of biological hydrogen production are photolysis of water, light fermentation, dark fermentation hydrogen production and light-dark coupling fermentation, etc. (Mishra et al., 2019; Safari and Dincer, 2019). Compared with traditional physical and chemical methods, biological hydrogen production has many outstanding advantages such as energy saving, renewable and no consumption of mineral resources, and it is an important way for large-scale hydrogen production in the future.

**Solar hydrogen production technology.** Among the technologies for producing hydrogen from renewable energy sources, solar hydrogen production is a new technology being researched and developed by researchers in recent years. At present, the methods for producing hydrogen by solar energy mainly include photochemical hydrogen production, photocatalytic hydrogen production, and artificial photosynthesis hydrogen production (Huang et al., 2019; Chiu et al., 2019). With the deepening of the research, it was found that the thermo-chemical hydrogen production technology can reduce the temperature requirements by using photocatalysts under solar conditions, and a thermochemical cycle hydrogen production method was proposed. The current research work of photocatalytic water splitting hydrogen production technology is mainly to improve the hydrogen production efficiency by improving the catalyst performance. Graphene has super strong mechanical properties, electrical conductivity, thermal conductivity, and light transmittance, is inexpensive, and has high hydrogen production efficiency. Reforming graphene provides great hope for low-cost hydrogen production in the future (Liu et al., 2020c; Zhang, 2019). Organic matter in wastewater is a good electronic conductor. Combining wastewater treatment with photocatalytic hydrogen production can achieve solar hydrogen production and solar decontamination at the same time. The solar hydrogen production technology is still in the preliminary research stage. With the large amount of investment, the development and progress of the technology will be larger and larger. The photocatalyst hydrogen production technology can be further improved, and the hope of further improving the hydrogen production efficiency will Bigger, and the prospects are very broad.

**Hydrogen storage and transportation development forecast**

Hydrogen storage and transportation technology is the key to the efficient use of hydrogen and an important bottleneck restricting the large-scale industrialization of hydrogen energy. Therefore, it has become one of the focuses and difficulties of the current development of
hydrogen energy industrialization. Hydrogen storage methods mainly include: high-pressure gaseous hydrogen storage, cryogenic liquefaction hydrogen storage, porous materials and metal alloys, and other solid hydrogen storage. The storage and transportation methods have been compared in the foregoing, and will not be repeated here. At present, hydrogen gas storage and transportation are mainly gaseous, mainly because of its low cost, easy operation, and fast gas charging and discharging, but there are generally hidden safety hazards. Low-temperature liquid hydrogen storage is difficult to achieve breakthrough development in the short term due to technical difficulties, high cost of liquefaction, large energy loss, and the need for excellent thermal insulation devices for heat insulation. The solid hydrogen storage material has excellent hydrogen storage performance, which is the most ideal hydrogen storage method among the three methods, and also one of the forefront directions in the field of hydrogen storage research. In the future, with the improvement of convenience and cost reduction of hydrogen storage alloys, it is expected to become the mainstream hydrogen storage method in the future.

In addition, with the deepening of research, hydrogen storage by inorganic substances and hydrogen storage by organic substances have appeared (Navas et al., 2020). Inorganic hydrogen storage refers to the combination of chemical bonds with ionic non-metal hydrides (complex metal hydrides NH3BH4, NaBH4, etc.) for hydrogen storage and release. Similar to the principle of hydrogen storage alloys, hydrogen can be released by heating. Organic hydrogen storage refers to the use of liquids such as benzene or toluene to react with hydrogen to generate cycloethane. In this way, hydrogen storage and transportation do not require pressure vessels and low-temperature equipment. When they need to be released, they can be dehydrogenated through a catalyst. It is a hydrogen storage technology that attracts much attention in the future.

**Hydrogen application development forecast**

Hydrogen has huge development prospects in providing clean, safe, reliable and abundant energy, and has a wide range of applications. As industrial raw materials, it can be used in the fields of petroleum refining, synthetic ammonia, methanol, etc. A small amount is used in industrial fields such as steel, glass, electronics, aviation, etc. In addition, it can also be used in transportation; the hydrogen fuel cell vehicle industry under development has just started. As of the end of 2018, global fuel cell electric vehicle (FCEV) inventory reached 11,200 units, with sales of about 4,000 units that year (an increase of 80% over 2017). It is expected that by 2030, the fuel cell vehicle industry will achieve substantial development, and the forecast trend is shown in Figure 7.

At present, China’s hydrogen energy development has been upgraded to a strategic level, but there are still problems such as high cost, low safety, and weak infrastructure. In the early days, local consumption should be the main priority and hydrogenation demonstration infrastructure and hydrogen fuel cells should be given priority, in the early days, local consumption should be the main focus, and priority should be given to the development of hydrogenation demonstration infrastructure and hydrogen fuel cells. From localization to regionalization, we should accumulate experience for China’s industrial development, technology cultivation, and infrastructure construction. With the large-scale application of renewable energy systems, the production cost of fuel cells has dropped significantly. Domestic fuel cell vehicles and hydrogen stations will increase significantly. Hydrogen energy will become an important part of China’s energy consumption structure, which
will help achieve “energy independence”. The hydrogen energy industry will gradually expand from regional development to major markets. Hydrogen and natural gas mixed transport relying on the national natural gas pipeline network will achieve large-scale operation, and a national infrastructure including a hydrogen energy transmission pipeline network and a hydrogen station will be basically formed. As a clean energy source, hydrogen will be applied in more and more fields.

**Conclusion**

The development of renewable energy supplement technology and hydrogen production technology has begun to take shape. The development of China’s single-energy hydrogen production industry and small-scale complementary hydrogen production technology started earlier, and the technological level has reached the international first-class level. Renewable energy complementary hydrogen production technology provides an effective way for energy consumption and has become a hot spot for sustainable development. This paper discusses the current research status at home and abroad, and highlights four key technologies for the development of multi-energy complementary hydrogen production technology. It can be seen from this that multi-energy complementarity can give play to the advantages of various energy sources and provide more high-quality power for the grid. This is an effective way to consume new energy. However, it still faces many problems. The economics of solar hydrogen, wind hydrogen, and biological hydrogen that can be industrialized at present are not ideal, and it is less competitive than hydrogen produced by fossil energy. China’s development of renewable energy complementary
hydrogen energy systems is relatively slow, and domestic policies and regulations need to be further improved, increasing and long-term investment in funds. The healthy development of China’s renewable energy industry and the continuous optimization of its energy structure require accelerated research and development and application of hydrogen production, hydrogen storage, and hydrogen fuel cell technologies. The research and application of renewable energy complementary hydrogen energy system is of great significance to promote the healthy development of China’s renewable energy industry.

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