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Development Strategy of Hydrogen Energy Industry in China

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Abstract: Hydrogen energy is crucial for building a clean, low-carbon, safe, and efficient modern energy system in China. In this article, we expound on the progress of global hydrogen energy industry and summarize the development status of China's hydrogen energy industry from the aspects of scale, characteristics, and policies. The demand for and problems of China's hydrogen energy industry are analyzed. Our research shows that the strategic layout of China's hydrogen energy industry has been continuously strengthened; the investment in hydrogen energy infrastructure has been gradually increased; and a regional industrial agglomeration effect has initially emerged. However, challenges remain including defective standards systems, severe industrial homogenization, incomplete industrial chain, and limited application scenarios. To promote the high-quality development of China's hydrogen energy industry, we suggest that China should strengthen the top-level design for hydrogen industry development, establish a technical standards system for hydrogen production, storage, and use, promote the pilot demonstration and popularization of the entire hydrogen energy industry chain, and enhance hydrogen technology innovation to achieve a high level of self-reliance.
Keywords: hydrogen energy industry; carbon neutralization; carbon peak; hydrogen production; hydrogen supply; hydrogen use

1 Introduction

Since its first discovery in the 16th century, hydrogen has been taken as an important clean energy for its rich sources, light mass, high energy density, green low-carbon, various storage and utilization ways, and other merits. However, hydrogen energy is mainly used in military, spaceflight, and other sophisticated fields subject to safety, costs, technology, and other constraints. While in fields for civil use, the development is slow with few commercial applications. Recently, as the *Paris Agreement* on global climate has been signed, tackling climate change has become the top strategy for us to develop energy, economy, and society in the long run. Clean energy featured by environmentally friendliness and low carbon has become important direction for energy development in the future. Hydrogen energy, as the most potential secondary clean energy in the 21th century, has drawn global attention and wide concern in China. In the future, it is expected to play a vital role in energy transition, peaking carbon dioxide emissions, and carbon neutrality [1]. Internationally, the United States, European Union, Japan, South Korea, and other developed countries and regions have included hydrogen energy into their national energy development strategies, continuously promoting the development of hydrogen energy industry [2].

Currently, the development of Chinese hydrogen energy industry has entered a new historical period, the *Medium-Term and Long-Term Plan for Hydrogen Energy Industry Development (2021–2035)* has included hydrogen energy into China's energy strategy system, proposing that effort should be made to build a systematic

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innovation system to sustain high-quality industrial development, boost construction of hydrogen energy infrastructures in a unified manner, stably promote diversified pilot applications of hydrogen energy, and never stay rested in building hydrogen energy development policies and institutional insurance systems, and form a 1+*N* policy system centering on the plan. To this end, we need to recognize the importance of developing hydrogen energy, focus on reform and innovation, develop independent core technologies and equipment, and make breakthroughs in technology, market, system, mechanism, and other fields.

2 Development status of hydrogen industry

2.1 Development significance

In the global trends of clean, low-carbon and smart evolution for global energy, developing hydrogen energy industry has become an important direction for energy technology evolution worldwide [3]. Hydrogen energy is an important support for ensuring a clean and diversified energy structure, playing an important role in promoting the clean, low-carbon, high-efficiency, and sustainable development of global energy [4].

Hydrogen energy is an important means to realize large-scale decarbonization and carbon drop in transportation, industrial, architecture, and other high-carbon-emission fields. Traffic and transportation is the second largest emission source around the globe, accounting for 25% totally. Hydrogen fuel cell-borne vehicles feature short hydrogen refueling, long endurance, and zero emission, enjoying unique advantages in heavy-duty, sustainable, and high-intensity traffic and transportation system [5]. In the industrial field, owing to its reducing agent and high heat of combustion, hydrogen can serve as a raw material during the production of steel, metallurgical, petro-chemical, and cement products, or provide high-order thermal energy, so it is an important means in in-depth decarbonization in the industrial field. In architecture, replacing natural gas with hydrogen to supply heat is an important direction to realize low-carbon consumption in the field of architecture.

Hydrogen energy will play an important role in energy diversification and clean energy fields. The scenario of “below 2℃” for global energy transition requires dramatic increase in the proportion of renewable energy in the structure of energy. Hydrogen energy, as important energy carrier, can help deal with trans-temporal adjustment, trans-regional deployment, and trans-species coupling assignment, realizing conversion with other energy species. It can help the consumption of renewable energy, provide long time storage, and optimize regional mass flow and energy flow, thus to build a multi-diversified energy system. In terms of trans-coupling, renewable energy can be used to generate power and make hydrogen, to flexibly meet the consumption demand in the energy end fields. In trans-temporal and trans-regional senses, integrating a high proportion of renewable energy into the power grid will intensify supply and demand imbalance, and through large-scale hydrogen storage, power consumption peak can be adjusted.

Hydrogen energy has flexible and wide application, so existing infrastructures for energy can be employed. In the traffic and transportation field, hydrogen fuel cell automobiles have comprehensive advantages regarding cruising mileage, fuel supply speed, energy saving and emission, and noise reduction. Its human–machine interaction is closer to traditional fuel car, more in line with users’ preference. In the energy and architecture fields, hydrogen can be mixed into natural gas pipelines for mixed burning, or hydrogen can be synthesed into ammonia, methyl alcohol, and methane; therefore, existing terminal equipment can be repeatedly used in a large scale, and there is no need to conduct large-scale transformation and upgrading of infrastructures.

2.2 Development background

In 2015, 196 national and regional governments signed the *Paris Agreement* to cope with climate change, determining an overall objective that the global warming until 2050 shall not exceed 2˚C compared with that before industrial revolution. Hydrogen energy as a zero-carbon energy has excellent carbon reduction capacity. According to the International Hydrogen Energy Committee, by 2050 large-scale application of hydrogen energy will reduce 6 billion tons of CO_2, accounting for 20% of the target reduction amount. To this end, major developed countries and regions worldwide have proposed a series of policies and measures to continuously promote hydrogen energy industry development, by strengthening top-level development policy guidance, investing more investment into research and development (R&D), speeding up infrastructures and pilot application demonstration programs, and so on.

The United States has proposed rich and complete policies, paying close attention to developing the entire industrial chain and promoting commercial application. Currently, it boasts the biggest hydrogen energy market worldwide. The US Fuel Cell and Hydrogen Energy Association in *Road Map to a U.S. Hydrogen Economy* points

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out that by 2030, hydrogen demand in the United States will break through 17 million tons, 5600 hydrogen stations will be built, and the overall industrial output will reach 140 billion USD. European Union put hydrogen energy as a main form for new energy development strategy and low-carbon economy, actively planning strategies and holding strong policy support to gradually build a complete hydrogen industrial chain under market operation. In the most representative country Germany for example, the integration and development of hydrogen energy and renewable energy has become an important component of their sustainable energy system and low-carbon economy. To this end, Germany has established its national hydrogen energy technological organization to advance relevant works. Japan has a national strategy to realize a hydrogen energy society. In its Basic Energy Plan in 2014, Japan has positioned hydrogen energy as a core secondary energy parallel to electrical power and thermal energy, and proposed scenario of building up a hydrogen energy society. They try to apply and popularize hydrogen in transportation, household, industry, and other social fields, to realize real energy security. South Korea has made hydrogen energy a strategic investment field, issuing many policies to accelerate fuel cells application and popularization in transportation and power generation. It is estimated in *Road Map to a Hydrogen Economy* that by 2040, its annual hydrogen supply will reach 5.26 million tons, hydrogen stations 1200, and hydrogen fuel cell vehicles 6.2 million in total.

As mentioned above, the United States, European Union, Japan, and South Korea have taken hydrogen development as their national strategies, and provided policy guidance to allow major corporations to build up hydrogen-related industries, accumulating advanced core technologies in hydrogen making, storage, refueling, and usage. In accordance with input of the above countries and regions in hydrogen energy industry and their plan for the future, hydrogen energy will gradually see large-scale application and play a vital role in the energy field.

3 Strategic demand for hydrogen industry development in China

China will make more independent contributions, taking better measures and policies to peak carbon dioxide emission by 2030, and realize carbon neutralization by 2060. China is the largest energy consumer, and for a long time, coal has dominated its energy structure. To realize carbon peaking and carbon neutralization, China need to accelerate coal-dominated energy structure transformation. In addition to developing renewable energies, other carbon-zero energies need to be added as important supplements. Hydrogen energy will have its role as follows:

3.1 Carbon reduction in large scale in traffic, steel, chemical, and other fields.

In the traffic field, hydrogen fuel cell automobiles do not require long refueling time, and have long cruising mileage. Compared with electric cars, hydrogen fuel cell heavy-duty trucks are more in line with end users' habits. Considering green hydrogen production, hydrogen fuel cell cars are one of the major approaches to promoting carbon reduction in the traffic field. In the industrial field, for steel, chemical, and other high-energy consumption industries that are not dependent on electricity, their industrial flows are still highly dependent on fossil energy. The key to reducing the coal consumption of the steel industry is to change the existing blast furnace ironmaking technology that uses coal as the dominated reducing agent and fuel. Metallurgical technology involving green hydrogen is the ultimate direction for low-carbon green steel industry development. Electric and hydrogen energy replacement and carbon dioxide capture technology can significantly lower carbon emission in the chemical industry. Producing green synthetic ammonia by green hydrogen replacement, making methyl alcohol, ethyl alcohol, and other fuel by adding hydrogen to carbon dioxide, and synthesizing the most fundamental chemical raw materials by using ethylene, propylene, aromatic hydrocarbon, and other organic materials, to solve the problem of large-scale utilization of carbon after carbon dioxide capture, is an important approach to realize carbon neutrality in the chemical field. Thus, hydrogen energy is an important solution for optimizing energy consumption structure and in-depth decarburization in relevant field.

3.2 Hydrogen production by electric energy to promote high-efficiency utilization of renewable energy and sustain secure operation of electrical system with high proportion of renewable energy

During the 14th Five-Year Plan, Chinese residents' energy consumption is expected to grow 2% annually. In 2025, energy demand will reach 5.5×10^9 tce, and the total energy consumption increase potential is huge. Making more efforts in developing renewable energy is China's main approach to ensuring energy security under the constraint of resources and carbon emission. Along with growing renewable energy power generation capacity, high-proportion renewable energy scenarios are several times of load capacity. The long-duration and high output of renewable energy poses huge challenges to consumption, safety, and storage technologies of electric systems.

During low-output period, the electric system needs non-renewable generator sets for power balance. It is estimated that by the end of the 14th Five-Year Plan, the business area of the State Grid will see flexible resource demand of 7×10^8 kW, whose load peak and valley difference adjustment demand account for over two third, and renewable energy peak adjustment demand account for 15.7%. In the future, the flexible adjustment capability of the electric system is vital, for it directly related to the safety and balance of the electric system and determines the renewable consumption level. Giving full play to hydrogen's large-scale and longtime storage advantage, we can deploy electrolyzed water in a large scale as flexible resources, tracking supply side and grid side for renewable energy volatility, flexibly respond to and reduce redundancy power in the system, realize temporal and spatial electric transfer of renewable resources, and effectively promote the energy supply quality and renewable energy consumption utilization level [6].

3.3 Diversification of energy supply to ensure energy supply security

China is rich in coal, poor in oil, and has scarce gas, so it is dependent on coal for a long time domestically and on oil and gas from foreign countries. In 2021, we consumed 5.23×10^9 tce; clean energy consumption accounted for 25.3% and coal consumption account for 56%. Energy supply and consumption are singular, mainly featuring coal, and then petroleum. Energy supply and demand and energy price stability are susceptible to international market change and major crises. Using electric energy to make hydrogen can help realize renewable energy development and diversified utilization. Under the new resource endowment outlook of renewable energy and green energy, hydrogen and electricity in collaboration can constitute a diversified clean energy supply system, promote the planning for hydrogen-mixed natural gas pipelines, improve the peak adjustment ability of natural gas, and enhance energy supply security. Moreover, hydrogen fuel cells can be used as backup power supply, to play a role in maintaining public security. In the future, along with construction of 5G base stations and big data centers, hydrogen energy backup emergency supply application scenarios will go wider. Considering hydrogen energy's application in fuel cell batteries, green chemical, and green steel fields, replacing oil and coal with hydrogen can promote end users to go diversified and clean. Combined with green hydrogen supply, the two-way collaboration of energy supply and demand sides can be promoted, ensuring energy supply and demand security [7].

3.4 Acceleration of renewable energy and green hydrogen deployment in the Northeast, northern part of North China, and Northwest, realizing low-carbon, green, and sustainable development of local society

The Northeast, northern part of North China, and Northwest (the Three North areas) are home to wind and photovoltaic (PV) resources. However, due to transportation and consumption limitations, wind, electric, and PV energies there have not been well explored. Take Illumination II region as an example. After taking into account hydrogen making equipment and operation & maintenance fees, hydrogen making in the wind and PV power generation grid can realize the cost of less than 20 CNY/kg. After further large-scale production, the cost can drop down to no more than 15 CNY/kg. It takes no more than 10 tons of water to prepare 1 ton of hydrogen through electrolysis of water. Exploring green hydrogen in the Northwest will not lead to water shortage. The purity and quality of hydrogen obtained through electrolysis of water is relatively high. Considering costs for purification and decarburization, currently making hydrogen with renewable energy is preliminarily economic in wind- and PV-rich areas. Based on green hydrogen supply and the establishment of a green industry system, the Three North areas will become a high-energy-bearing industrial cluster area without increasing local pollution and carbon emissions, and form emerging industry clusters for renewable power generation equipment making, water-electrolytic hydrogen making equipment fabrication, green chemical, green metallurgical, and so on by relying on renewable energy exploration, to establish an economic stainable and circulation mode in Northwest China.

4 Status quo of hydrogen industry in China

4.1 Industrial scale

Recently, Chinese hydrogen energy industry has been developing rapidly, with a growing industrial scale. According to the data of *China Hydrogen Energy and Fuel Battery Industry White Paper 2020* [8], Chinese hydrogen production capacity is approximately 41 million tons a year, and the production is approximately 33.42 million tons a year. By the end of 2021, we have built 255 hydrogen refueling stations, and are home to 9315 hydrogen fuel cell automobiles, which has made China the biggest hydrogen producer and hydrogen cell commercial vehicle market. In terms of industrial plan, currently, tens of provinces and municipalities and regions including Beijing, Hebei, Shanghai, Henan, Zhejiang, Shandong, Sichuan, Chongqing, Shanxi, Inner Mongolia,

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Guangzhou, Wuhan, Suzhou, Foshan, and Lanzhou have issued their hydrogen energy industrial development plans. According to these issued plans, it is estimated that by 2025 over 150 000 hydrogen fuel cell vehicles will be on the road as promoted, with over 1000 hydrogen refueling stations, and hydrogen energy industrial accumulated value over 960 billion CNY. Moreover, although China did not plan and deploy early in R&D, it have gradually become the country of the highest increase in R&D budget [9].

4.2 Industrial layout

After tackling hard-nut problems in science and technology for many years, China has gained some hydrogen infrastructures and fuel cell related core technologies, formulating and issuing 112 national standards, and having some industrial equipment and fuel cell vehicle production capability. Currently, China's hydrogen energy industry has the following overall features: first, rapid industrial development. Many provinces have issued documents and policies, cultivating a batch of enterprise with core hydrogen industry technologies, core equipment, and innovation capabilities. China have started to launch major projects regarding key materials, core components, hydrogen production, storage and transportation, refueling stations, fuel cell automobiles, fuel cell power generation. Domestically, hydrogen energy industry shows rapidly development trend. Second, large energy enterprises began to come in. With "promoting electricity charging and hydrogen refueling and other facilities construction" added to 2019 State Council Government Work Report, and Sinopec, State Energy, PetroChina, State Power Investment, and other large energy enterprises have more industrial deployment in this industry, starting to gradually invest in hydrogen energy infrastructures fields. Third, clear regional feature. Regional industrial cluster effect is preliminarily shown. For example, Beijing, Zhangjiakou, and Tianjin in the North, Wuhan, and Zhengzhou in the Center; Jinan, Qingdao, and Weifang in the East; Shanghai, Suzhou, and Ningbo in the Yangtze River Delta; Chengdu in the Southwest; Foshan and Guangzhou in the Pearl River Delta all have issued their industrial development plans based on their own natural endowment, and pioneered in promoting hydrogen energy and fuel cell industrial development.

4.3 Industrial policies

Recently, China have issued some policies and documents to encourage and support hydrogen energy development. In March 2019, China included hydrogen energy development into the Government Work Report. The National Energy Commission puts forward that effort should be made to accelerate tackling hard-nut problems in energy development and utilization, and major equipment fabrication, explore advanced energy storage and hydrogen commercialization roadmap, and develop new industry, new business, and new mode dependent on the Internet. Meanwhile, China issued *China Manufacturing 2025*, *National Innovation-Driven Development Strategy Outline*, *Sci-Tech Innovation Plan in the Energy Fields during the 13th Five-Year Plan*, and other policies to encourage industrial development. In March, 2022, the State Development and Reform Commission, and the National Energy Bureau jointly issued the *Medium- and Long-Term Plan for Hydrogen Energy Industry Development (2021–2035)*, evaluating highly of hydrogen energy in the national energy system in the future, and pointing out the direction for its industrial development in industrial objective, equipment building, and application demonstration.

5 Major problems and challenges

5.1 Lagging hydrogen positioning and top-level design

Different from developed countries' national energy system, it is quite late for China to position hydrogen energy and have top-level design. Until recently, China issued its medium- and long-term plan for hydrogen energy and officially made clear the positioning of hydrogen energy in its energy system; however, China have not established a vertical industrial management and supervision system. Meanwhile, in-depth research needs to be conducted in terms of national-level strategic targets, sci-tech innovation, major equipment R&D, pilot projects, industrialization directions, and so on; the policy guarantee system and implementation roadmap for hydrogen energy industrialization needs to be further explored; and a long-term top-level design for national hydrogen energy industrialization needs to be enhanced.

5.2 Unclear hydrogen management department and unsound standards system

A complete standards system for the production–storage–transportation–application links of the hydrogen energy industrial chain is lacking. Relevant fuel cell standards system has been gradually improved; however, China's standards in hydrogen production carbon emission, vehicle-borne hydrogen storage bottle sets, liquid hydrogen for civil use, and hydrogen safety are still weak. During the hydrogen development process, various places have taken initiative to try, which has greatly improved the speed of hydrogen energy development. Participants in various links and non-unified standards have presented management problems. Currently, no competent authorities have been assigned to manage the planning, safety, standards, and project verification of hydrogen relevant links. Different from a "state domination, local practice, and corporate promotion" mode of electric cars, Chinese hydrogen energy industry has shown a bottom–up trend, and local governments and enterprises have dominated the development.

5.3 Homogenous local industry

Hydrogen energy industry involves energy, materials, equipment manufacturing, and other fields. It can effectively drive traditional industries to transform and upgrade, and incubate new industrial chain. Therefore, local governments are active in developing energy industrial parks, and various enterprises are seeking for projects. However, because coordination between the upper, middle, and down streams of the hydrogen industry chain lacks, local governments and enterprises have quite similar plans, and even low-level repeated construction. Within a short period, they see the risk of production capacity redundancy. Meanwhile, various regions always pay more attention to application, less attention to R&D, always attaching importance to short-term effect instead of long-term investment. Various places are competing against each other in exploring hydrogen energy, seeking technology, professionals, and projects, currently in an unorderly manner.

5.4 Incomplete industrial chain and application scenarios to be explored

After rapid development in recent years, China has achieved system integration of the hydrogen energy industrial chain and independent making of key components; however, materials and fundamental manufacturing such as electrobath film catalysts, hydrogen bottle seal valve materials, and hydrogen refueling pipe hoses, as well as hydrogen safety mechanism research and test equipment technologies are still weak. Meanwhile, Chinese hydrogen energy industry has started late, and the industrial chain still needs improvement. Owing to technological, cost, and infrastructure constraints, the application of hydrogen energy in China concentrates in the traffic field, and China's hydrogen industry chain is lagging behind its global industrialization.

6 Development targets and implementation path of hydrogen energy industry in China

Considering international and domestic status quo as well as existing problems and challenges in hydrogen energy development in China, we should fully exploit the role of hydrogen energy industry development in green low-carbon development, promoting energy revolution and strengthening the manufacturing sector. The key tasks and implementation roadmap for high-quality sustainable development should be analyzed from the key links such as hydrogen energy making, storage, and application, to crackle difficult problems through reforms and innovation and realize high-quality development of the hydrogen energy.

6.1 Development targets

6.1.1 2021–2025: Policy-guided local pilot demonstration

By 2025, a favorable institutional policy environment for hydrogen energy industry development will be formed and a relatively complete hydrogen supply chain and industrial system will be built. China is supposed to make remarkable achievement in hydrogen pilot demonstration, with hydrogen production, storage, and usage technologies improved a lot, and competitive in the market. A preliminary hydrogen supply system will be established.

6.1.2 2026–2035: Market-driven commercial mode cultivation

By 2035, a relatively complete hydrogen energy technology innovation system will be established, with a rational industrial chain layout, wide application of hydrogen production through renewable energy, and remarkably increased consumption. Hydrogen will become competitive in traffic, energy storage, industrial, and other fields, playing a backbone role in peaking carbon dioxide emissions and achieving energy transition [10].

6.1.3 2036–2060: Mature green and smart industrial ecosystem

The hydrogen energy industry will become mature during this period, and hydrogen will enter traffic, power stations, energy storage, and other market segments. By 2060, hydrogen energy will account for approximately 20%

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of end user consumption, providing systematic solutions for converting green energy into power in China and worldwide.

6.2 Implementation path

6.2.1 Hydrogen making

(1) Effort should be made to have better understanding of electrolysis of water for hydrogen making under the condition of renewable energy power supply, speed up renewable energy direct hydrogen making technology, and conduct application pilot demonstration. Effort can be made for better data support to conduct analog simulation and demonstrative operation for water electrolysis equipment's response to renewable electric power, renewable energy volatility's impact on electrolysis efficiency and equipment life, electrolysis equipment connection mode to renewable electric power, and configuration and operation mode of plant-level electrolysis water equipment in wind and PV farms. Moreover, pilot demonstration should be conducted for combining renewable energy electrolysis hydrogen making with green hydrogen consumption.

(2) It is necessary to improve alkaline electrolysis of water, and lower the costs for renewable energy electrolysis for hydrogen. Currently, costs of electrolysis for hydrogen making are still higher than fossil energy hydrogen making. To reduce the costs, the kWh cost of renewable energy needs to be further lowered and the progress of water-electrolysis hydrogen making are also required. Alkaline electrolysis of water is the most potential technology that can make green hydrogen at a low cost. Increasing the current intensity of alkaline electrolysis of water is an important approach to reducing costs for making hydrogen. When the current density increases from 0.4 A/cm^2 to 0.8 A/cm^2, in the same electrobath, hydrogen output increases one time and hydrogen cost can be reduced around by 2 CNY/kgH_2. The International Renewable Energy Agency in its 2020 report proposed that the current intensity target for alkaline electrolysis of water is ⩾2A/cm^2, which will significantly reduce hydrogen cost and realize small compact construction of electrolysis equipment.

(3) The proton exchange membrane (PEM) and solid oxide electrolysis cell (SOEC) water electrolysis technology should be further developed. PEM electrolysis of water make uses of PEM, precious metals platinum and iridium as hydrogen evolution and oxygen evolution catalysts. It has the advantage of high-current density (≥1A/cm^2), high hydrogen purity, high pressure resistance, small volume, and low mass. This technology has clear advantage in application scenario where places have limitation and pressure is required, for example on-the-spot hydrogen making for hydrogen refueling stations, pipeline hydrogen refueling, and distributed hydrogen refueling stakes. Different from PEM technology, SOEC electrolysis of water is a high-temperature water electrolysis technology. Its operating temperature is 700–850^{o}C, more efficient than PEM, and applicable to high-temperature hot-source scenarios. For the two hydrogen making technologies, targeted efforts should be made in R&D of cost and life to promote technology application.

(4) Pilot demonstration and technological R&D of carbon capture, utilization and storage (CCUS) technology should be accelerated. CCUS technology is a must for fossil raw materials to make hydrogen, whose large-scale industrialization depends on technological maturity, economical efficiency, natural condition bearing capacity, and industrialization feasibility. CCUS technology is the key technology for China to build a green and diversified energy system and has been widely applied in various fields, which can realize large-scale low-carbon utilization of fossil energies and work with renewable energies to realize zero emission. The CCUS technology is in a stage of pilot demonstration worldwide. The energy consumption and cost for carbon capture and storage should be continuously lowered, the conversion and utilization approach extended, and utilization efficiency increased, thereby achieving a breakthrough in developing guarantee technologies for onshore pipeline transportation, as well as economical and safe sealing and monitoring methods [11].

6.2.2 Storage and transportation

(1) R&D for high-pressure hydrogen gas storage and transportation should be accelerated. Raising the storage pressure grade to increase hydrogen storage density and improve storage efficiency is currently one of the most effective methods to lower storage costs. In terms of high-pressure hydrogen transportation, effort can be made to develop 50 MPa and 70 MPa high-capacity bottles, gradually replacing the existing type I and II bottles with type III and IV bottles, and raise the hydrogen storage density to be higher than 5wt%. In terms of vehicle-mounted high-pressure hydrogen storage, breakthrough should be achieved in 70 MPa and type IV bottle design, manufacturing of bottle mouth combination valves, high-performance carbon fiber materials, carbon fiber winding, and complete equipment. The 35 MPa bottle mouth combination valve technology should be optimized. In terms of fixed hydrogen-storage equipment, the 50 MPa and above large-volume fixed hydrogen storage material and

technology should be optimized, solving the problems of storage room and costs. In terms of safety testing, China's capability for 70MPa hydrogen storage vessels and supporting equipment verification and performance overall evaluation should be improved.

(2) The R&D of key technology for large-scale hydrogen liquidation and liquid hydrogen storage and transportation should be accelerated. In terms of transportation cost, storage purity, and metering convenience, liquid hydrogen storage and transportation are far more advantageous than high-pressure storage and transportation. In the stage where transportation pipelines are not practical, hydrogen liquidation is a direct and effective means to solve the problem of large-scale hydrogen storage and transportation [12]. For long-distance large-volume hydrogen storage and transportation, breakthroughs need to be achieved in large-volume hydrogen liquidation technology and complete set equipment, to realize large-scale, high-efficiency, and low-cost storage and transportation. In terms of liquid hydrogen making, the key is to conduct research on a large-scale hydrogen liquidation system with low energy consumption, high-efficiency large-flow turbo expanders, and flexible heavy-duty catalysts. In terms of liquid hydrogen transportation, efforts should focus on developing mobile liquid hydrogen vessels with low leakage and a high storage proportion. In terms of liquid hydrogen storage and transportation, effort can be made to optimize large-volume fixed ball-type liquid hydrogen storage tank and deep cool storage tank technology for transportation, to improve performance and lower daily evaporation rate. It is necessary to conduct research on vehicle-mounted deep cooling + normal pressuring hydrogen storage technology, promote a deep cooling + super-critical high-pressure hydrogen storage technology system, and develop pump scheme design and technologies applicable to refueling fixed storage tanks and vehicle-mounted hydrogen storage bottles with liquid hydrogen that has normal pressure and large volume, or high pressure and low volume. Effort should be made to depend on large-scale hydrogen liquidation and liquid hydrogen storage key technologies and demonstration projects to improve hydrogen liquidation technologies and equipment level.

(3) Large-scale hydrogen transportation through pipelines and comprehensive utilization technologies should be developed. Considering the long distance, large-scale hydrogen transportation, and diversified hydrogen terminal decraboniation demands, effort should focus on research on key technologies for hydrogen-mixed natural gas pipeline transportation and hydrogen utilization pilot projects, to promote the decarbonization in application fields such as traffic, architecture, industrial, and power generation and improve the reutilization of traditional resources infrastructures. We shall research into applicability and safety boundary of natural gas pipelines and equipment for hydrogen-mixed transportation, hydrogen separation for the mixture of natural gas and hydrogen, detection of hydrogen-mixture gas pipelines, scheme design and construction of demonstration projects for hydrogen-mixed natural gas pipeline transportation, applicability testing of hydrogen-mixed transportation terminal equipment (i.e., gas stoves, water heaters, and boilers), and techniques and equipment development for hydrogen separation and purification. Demonstration of pure-hydrogen pipeline transportation should also be promoted.

(4) A large-volume, low-energy-consumption, quick hydrogen-refueling technology and equipment system should be established. Efforts can be made to research into design and manufacturing of 90 MPa compressors, optimize 45 MPa compressor technologies, and achieve breakthroughs in metal diaphragm and reciprocating compressor equipment with a large discharge capacity, large pressure ratio, low power consumption, and high reliability. Efforts can be made to complete testing and verification of 70 MPa hydrogen refueling gun technology and equipment, and realize domestic manufacturing of core parts and components including hydrogen refueling hoses, snap valves, and flow meters. Technological problems of liquid hydrogen refueling stations in terms of material, structure, insulation, and sealing need to be solved to realize industrialization and large-scale application of liquid hydrogen stations. A 35/70 MPa hydrogen refueling machine and compressor performance evaluation and verification system should be formed, comprising performance indicators such as reliability, metering, power consumption, refueling rate, and service life. A hydrogen station security monitoring and evaluation system should be established. Considering the high costs for hydrogen storage and transportation in China, efforts should be made to conduct key technology research on and implement demonstration projects for hydrogen making and refueling integrated stations, achieve breakthroughs in highly intensive hydrogen making and purification technologies, and develop high-performance hydrogen-refueling machines, compressors, and process control systems, so as to lower equipment costs for hydrogen station enterprises.

6.2.3 Hydrogen use

(1) Traffic field: diesel-to-hydrogen demonstration using heavy-duty track, bus, and other commercial vehicles as examples. At the early stage of application in the traffic field in China, hydrogen refueling facilities are not complete, the application scenarios and routes for commercial vehicles are fixed, and thus they do not highly

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depend on hydrogen refueling infrastructures. Fuel cells can be used in commercial vehicles as they have large power and can replace diesel, and hydrogen refueling can be solved. Based on the large-scale demonstration of commercial vehicles, overall coverage of refueling facilities can be gradually realized, thereby promoting its application among passenger vehicles.

(2) Power generation field: an “energy storage via hydrogen + fixed fuel cell stations” mode. Fuel cell power generation system needs suitable power generation scenarios and regions. Currently, the developed power grid and relatively low electricity price make it difficult for large distributed fuel cells to develop. Moreover, relevant incentive policies are lacking, and fuel cell technologies of China are lagging behind other countries. As renewable energy develops and fuel cell costs decreases, fixed power generation in combination with hydrogen energy storage will be a direction in China.

(3) Architecture field: Mixing hydrogen into natural gas pipelines can effectively solve the problem of large-scale renewable energy consumption. Hydrogen produced by wind and PV power can be added into natural gas and transported using existing natural gas pipelines. The hydrogen-mixed natural gas can be directly used or separated for respective usage. Natural gas pipelines in local communities and buildings can be transformed to be capable of delivering hydrogen-mixed natural gas, thus to meet residents’ demand for heating and cooking. Considering the security factor, the compatibility of existing pipeline materials with hydrogen-mixed natural gas must be tested to assess the transportation risks of using existing pipelines.

(4) Energy storage field: Hydrogen energy storage is more competitive in large-volume, long-duration energy storage systems. Hydrogen energy storage has been taken as an emerging energy-storage approach and is crucial for Chinese smart grid construction and large-scale renewable energy power generation [13]. To promote hydrogen storage, the key is to realize high-efficiency transfer from electric power to hydrogen energy, lower the cost for large-scale hydrogen storage, and improve the overall utilization efficiency of hydrogen. Effort should focus on breakthroughs in key technologies such as fluctuant hydrogen production using wind, solar, and hydraulic powers, pipelines interconnection, and collaborative control, to build a high-efficiency, low-cost, and large-scale hydrogen storage system.

7 Recommendations

7.1 Strengthening top level design for energy industry development

Effort should be made to speed up China’s pace to develop a 1+N policy support system for national energy development, and make a detailed implementation roadmap for hydrogen energy industry development. Hydrogen energy industry development should be emphasized as it contributes to the green low-carbon circulation development, energy revolution, and manufacturing power strengthening. Therefore, it is necessary to scientifically analyze the technological route, timetable, and main tasks for high-quality and sustainable industrial development. Provincial governments should coordinate the development demand and implementation resources in a unified manner, and accelerate the construction of hydrogen energy application demonstration zones. Backbone enterprises should be guided to cluster on some fundamental and advantageous industrial areas. The international communication of the hydrogen energy industry should be encouraged, and China should take the initiative to participate in international hydrogen energy industrial chain to build a collaborative, win-win, and secure supply chain system.

7.2 Optimizing the standards system for the entire industry chain of hydrogen energy

It is necessary to accelerate the development of hydrogen standards system, establish and improve the metering–detection–verification standards and systems for key equipment of the entire industrial chain, and actively guide the industry to conduct high-quality technological innovation and standards formulation. Effort can be made to develop high-speed and efficient hydrogen fuel testing and metering method, establish hydrogen fuel quality evaluation procedures, and construct a national hydrogen fuel quality test center in due time. Referring to electric charging facilities, guidelines should be issued for including hydrogen stations into urban construction the soonest possible. A supervision mechanism regarding hydrogen energy should be established to ensure fundamental supervision for this industry, and energy industry development in different regions and enterprises should be clarified using the China Hydrogen Alliance big data platform. Research on carbon reduction standards and mechanisms should be promoted. Considering the carbon footprint lifecycle and *Standard and Evaluation of Low-Carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen*, carbon footprint standards and measurement indicators based on the hydrogen energy industry should be established, the path for hydrogen energy chain development should be formulated, and a low-carbon, clean, and high-efficiency production supply chain should be formed. A security management system covering the entire hydrogen lifecycle and a maintenance record database should be established to ensure secure development [14].

7.3 Promoting pilot demonstration and popularization of the entire industrial chain

As the entire industrial chain of the hydrogen energy industry is immature, pilot demonstration should be conducted at the early stage, and then wider application can be promoted. Effort should be made to advocate hydrogen energy key regions as pilots with policy support, bettering market environment supervision for the industry, controlling the consumption of coal, petroleum and other chemical energy sources, and strictly implementing carbon tax, carbon emission trade price and other mechanisms, to support industrial market cultivation and its orderly development. Considering the pilot demonstration for hydrogen energy and fuel cells, it is necessary to issue a 14th Five-Year Special Plan for hydrogen energy. Centering on diversified traffic, industrial, and storage applications, and an effective hydrogen energy commercialization path should be formed via rational deployment. Referring to some international pilots, effort should be made to support a batch of demonstration bases for producing hydrogen via renewable energy sources, so that they can have large scale to reduce costs. Innovative development modes such as wind–PV–hydrogen–storage integration and oil–hydrogen–gas–electricity comprehensive stations should be encouraged, and for industries that have big demand for emission reduction, newly added green hydrogen should not be included into total consumption.

7.4 Improving sci-tech innovation in hydrogen energy and becoming independent

A sound and complete basic R&D system should be developed. Based on the market demand, leading enterprises can lead and cooperate with upstream and downstream enterprises as well as research institutes to build a collaborative innovation platform that covers the entire industrial chain, focus on key and core technologies, and develop and test equipment, material, parts and components, and other generic technologies. Resources shall be gathered to promote key technology R&D in top enterprises, an independent evaluation system for major hydrogen technologies and equipment should be established and included in the *Guidance Catalog for Major Energy Equipment Popularization*, and relevant research institutes should be provided with research fees and tax preference. Industrial chain security should be considered in advance, domestic enterprises should be encouraged to have technological cooperation, and capital and industrial linkage can be strengthened via industrial funds, thus to establish an independent and reliable production supply system.

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