DOI 10.15302/J-SSCAE-2022.03.012

Hydrogen Energy Development Potential and Countermeasures of Port Cities in China

Liu Kemeng[1], Gao Junlian[1], Sun Xudong[1], Zhang Bo[1], Wu Rong[2]

1. School of Management, China University of Mining & Technology-Beijing, Beijing 100083, China
2. Beijing Gas and Heating Engineering Design Institute, Beijing 100032, China

Abstract: The use of hydrogen energy signals an important direction in China's energy transformation and industrial development. Port cities are key areas for China's economic development and play an instrumental part in the opening of China to other countries. Accelerating the transition to green and low-carbon energies and scaling up the development and utilization of hydrogen energy are crucial for promoting high-quality development of port cities in China. This study analyzes the foundation for developing hydrogen energy in China's port cities and assesses their development status, existing planning objectives, and developmental challenges. Based on this, the progress of hydrogen energy development in these regions are discussed. This research indicates that port cities in China have remarkable regional advantages, rich hydrogen energy resources, refined application scenarios, strong research and developmental potential, and high talent concentration. Key hydrogen energy projects can be deployed and implemented through application scenarios, such as using ports, heavy trucks, and buses to convert port cities into international energy hubs with advanced hydrogen energy technology, sufficient hydrogen energy supply, and a complete industrial base. Furthermore, we suggest that the port cities should actively cooperate with each other to build a healthy system, develop a system of innovation by strengthening their weaknesses, promote scenario applications while ensuring the safety-first principle, and encourage technological innovation to stimulate development momentum.

Keywords: port cities; hydrogen technology; hydrogen application; international hydrogen transportation hub

1 Introduction

China has a long coastline and numerous port cities. As an important gateway of China's opening to other countries, port cities have developed rapidly in fields such as freight and industrial transport, with a large demand for energy and an urgent need for energy transformation. As a type of green, efficient, and widely used secondary energy, hydrogen energy is playing an increasingly prominent role in energy transformation. According to the International Hydrogen Energy Committee, the world will utilize hydrogen energy on a large scale by 2030. The proportion of hydrogen energy in global terminal energy consumption will reach 18% by 2040, and its consumption will account for 20% of total energy consumption by 2050 [1]. Major countries in the world are actively promoting the industrial layout, technological research and development (R&D), and construction of supporting facilities for hydrogen energy utilization. For example, major countries and regions, such as the United States, Japan, South Korea, and the European Union, have incorporated the hydrogen energy industry into their national energy development strategies. They continue to increase the support for technological R&D and industrialization development of

Received date: April 03,2022; **revised date:** April 28,2022

Corresponding author: Gao Junlian，Lecturer，School of Management, China University of Mining & Technology-Beijing；Research direction: energy and environmental policy；E-mail: junliangao@cumtb.edu.cn

Funding program: CAE Advisory Project "Research on the development strategy of hydrogen energy and fuel cell in China"(2019-ZD-03)；Project of Basic Science Center of National Natural Science Foundation of China (72088101)

Chinese version: Strategic Study of CAE 2022, 24 (3): 108–117

Cited item: Liu Kemeng et al. Hydrogen Energy Development Potential and Countermeasures of Port Cities in China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2022.03.012

hydrogen, establish projects of R&D, conduct pilot demonstrations, and formulate various policies to lead the promotion of and infrastructure construction for the hydrogen industry [2].

The development of the hydrogen industry in China has entered an accelerative period, and the hydrogen industry will play a more important role in China's energy transformation. In recent years, China has issued a number of policies and plans to support the development of the hydrogen industry [3,4]. With the proposal of China's carbon peaking and carbon neutrality (dual carbon) goals, building a clean, low-carbon, safe, and efficient modern energy system and promoting the transformation of the energy developmental mode have become the main focus of the national energy strategy. Hydrogen can be applied in a variety of scenarios, such as in industry, transportation, construction, and power generation [5]. Port cities have a good foundation and potential for hydrogen energy development, owing to their special geographical advantages.

Presently, research on the hydrogen energy industry in port cities is relatively insufficient. Existing research has mainly focused on the analysis of the current status of the hydrogen industry at national and industrial levels [1,6,7], the status of the application of hydrogen production, storage, and transportation technology [8–13], and hydrogen fuel cell technology and policy analysis [14–17]. Some researchers have studied specific regions, such as the developmental path for hydrogen energy in Yangtze River Delta [18] and the technical route of hydrogen energy preparation in coastal areas [19].

This study considers port cities as the research object, starting from the basis of hydrogen energy development and focusing on the developmental status and present problems of the hydrogen energy industry in port cities. The overall development layout is evaluated, and key development directions, application scenarios, and major engineering demonstration projects are presented to provide reference for the development of hydrogen energy industry in port cities.

2 Basis of hydrogen energy development in port cities in China

2.1 Remarkable geographical advantage and strong radiation capacity

Most of China's port cities are located in the center of the Asia–Pacific Economic Zone, running through the urban agglomerations of Northeastern, Northern, Eastern, and Southern China. They are surrounded by the Bohai Sea, Yellow Sea, East China Sea, and South China Sea, facing Japan, South Korea, and other countries across the sea. They serve as shipping hubs for China's opening-up and important channels from Eurasia to the Pacific Ocean. Among them, Dalian and Ying Kou ports in Liaoning have trade contacts with more than 300 ports from more than 160 countries and regions. The ports of Qinhuangdao, Tangshan, and Tianjin play important roles under the Beijing–Tianjin–Hebei coordinated development strategy. Port cities in Shandong Province are located in the core area of hydrogen energy industry clusters between the Beijing–Tianjin–Hebei area and the Yangtze River Delta, with the Yellow River Economic Zone serving as a hinterland on a large economic scale. The Yangtze River Delta region has many port cities, excellent port resources, close international connections, and a high level of collaboration. Southern port cities such as Fuzhou, Guangzhou, and Haikou are important hubs of the Belt and Road Initiative. In general, the comprehensive three-dimensional transportation system of land, sea, and air within port cities and the superior location conditions provide important foundations for the development of hydrogen energy in port cities. This facilitates the importation of hydrogen to inland areas and shipping of hydrogen abroad, creating the potential for the development of an energy transmission hub.

2.2 Abundant hydrogen energy resources and low cost of hydrogen production

First, port cities are generally rich in renewable energies, such as offshore wind energy and geothermal energy; thus, they can make full use of wind curtailment and geothermal resources to produce hydrogen via water electrolysis. This not only improves the utilization efficiency of new energy but also reduces the electricity cost of hydrogen production and provides abundant power guarantee for zero-carbon hydrogen production. Second, some port cities are important production bases of steel and petrochemical products in China and contain rich industrial by-product hydrogen resources. Chemical enterprises generate massive amounts of the by-product hydrogen from coke oven gas and bio-fermentation biogas, which have great hydrogen production potential and high purity.

2.3 Outstanding application scenarios and large market demand

With the development of the transportation industry in port cities, there is great demand for hydrogen-fueled heavy-duty truck transportation in ports, factory areas, and agglomeration areas. This provides broad application platforms and application scenarios for the demonstration of hydrogen-fueled heavy-duty trucks and supports the

DOI 10.15302/J-SSCAE-2022.03.012

foundation required to build a hydrogen-fueled heavy-duty truck logistics base. Depending on the port application scenario, there is also great potential for the application of hydrogen energy for special vehicles such as tractors and dump trucks. Some port cities mainly develop heavy industries and have great potential in developing hydrogen metallurgy.

2.4 Rich research and development (R&D) personnel and strong manufacturing capacity

Presently, China's port cities have strong R&D capabilities in hydrogen production, storage, transportation, and refueling. In addition, many universities and research institutes in China have strong R&D strength in the field of basic research on hydrogen energy; these institutions include Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Energy Research Institute of Shandong Academy of Sciences, Shandong University, Tianjin University, Shanghai Jiao Tong University, Zhejiang University, Yangtze Delta Region Research Institute of Tsinghua University, Zhejiang, Fuzhou University, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, South China University of Technology, Guangzhou Institute of Energy Conversion, and Chinese Academy of Sciences. These institutions conduct long-term research on the preparation and utilization of hydrogen energy. Meanwhile, China's port cities also have a strong manufacturing capacity. Some port cities have a strong industrial foundation, which is an important base for modern industrial development in China.

In summary, with inherent location advantages, the hydrogen energy industry should be vigorously developed in accordance with the developmental needs of port cities. Furthermore, a comprehensive reform strategy for urban energy is also necessary. This can provide a new impetus for the transformation of the economic and energy structures of port cities.

3 Current status of hydrogen energy development in China's port cities

3.1 Current development status of hydrogen energy industry

3.1.1 R&D and manufacturing capabilities are increasingly prominent

Presently, Dalian has become a hub of basic research and technological innovation of hydrogen energy and hydrogen fuel cells and has taken a leading position in many basic research fields. It has obtained more than 300 authorized invention patents in key materials, core components, and stack systems of fuel cells and has led the formulation of more than 50% of the national standards for fuel cells. Tianjin has made a series of breakthroughs in on-board power technology and distributed generation/combined heat and power technology, developing and producing the first domestic hydrogen fuel cell forklifts, solid hydrogen storage fuel cell engine systems, and fuel cell forklifts supporting a hydrogen refueling device. Some progress has been made in key aspects of the industrial system. Hydrogen energy enterprises in Shandong's port cities have built a complete set of R&D test stands for single cells, stacks, engines, and vehicles. With complete fuel cell system and vehicle R&D test capacities, the power technology index of the latest developed fuel cell stack is at an advanced level globally. Port cities in Zhejiang continuously improve the equipment R&D capacity. Regarding hydrogen production, the annual production capacity of high-purity hydrogen in Ningbo, Jiaxing, can reach over 1×10^5 t. Fuzhou has enterprises such as Southeast (Fujian) Motor Co., Ltd. and Fujian Benz Automobile Co., Ltd., along with other vehicle production and R&D bases. It already has the industrial infrastructure for the development of fuel cell vehicles.

3.1.2 The hydrogen energy industrial chain has been basically formed

Port cities in China have formed a relatively complete hydrogen energy industry chain (Fig. 1). Tianjin, Qingdao, Dalian, Shanghai, Fuzhou, and Guangzhou have developed the entire industry chain projects covering hydrogen energy production, storage, transportation, refueling, fuel cell power systems, and hydrogen energy application and have formed a number of leading enterprises. Relying on the petrochemical industry, Tianjin has developed an advantageous hydrogen energy industry, forming an entire industrial chain of hydrogen production, refueling, and use. Qingdao International Academician Park cooperates with Tongji University and SAIC Motor Co., Ltd. to conduct projects pertaining to hydrogen energy production, storage, transportation, refueling, fuel cell power systems, and hydrogen energy application. Dalian has many enterprises with rich experience in hydrogen production, storage, transportation, hydrogen fuel cell systems and components, hydrogen fuel cell vehicles, and other aspects. It initially formed a relatively complete hydrogen energy industry chain. Shanghai has introduced a number of enterprises in the hydrogen energy industrial chain, developing a relatively complete hydrogen energy industry framework, which includes the development of membrane electrodes and other key parts, production of fuel cell power systems, and establishment of a supporting infrastructure for hydrogen refueling stations. Fuzhou has a

foundation in hydrogen supply, core components of fuel cells, vehicle production, and R&D. Some hydrogen energy enterprises in Guangzhou have integrated the entire supply chain system of core components of hydrogen energy, hydrogen supply systems, vehicle manufacturers, and other upstream and downstream industries, promoting the accelerative development of the local hydrogen energy industry.

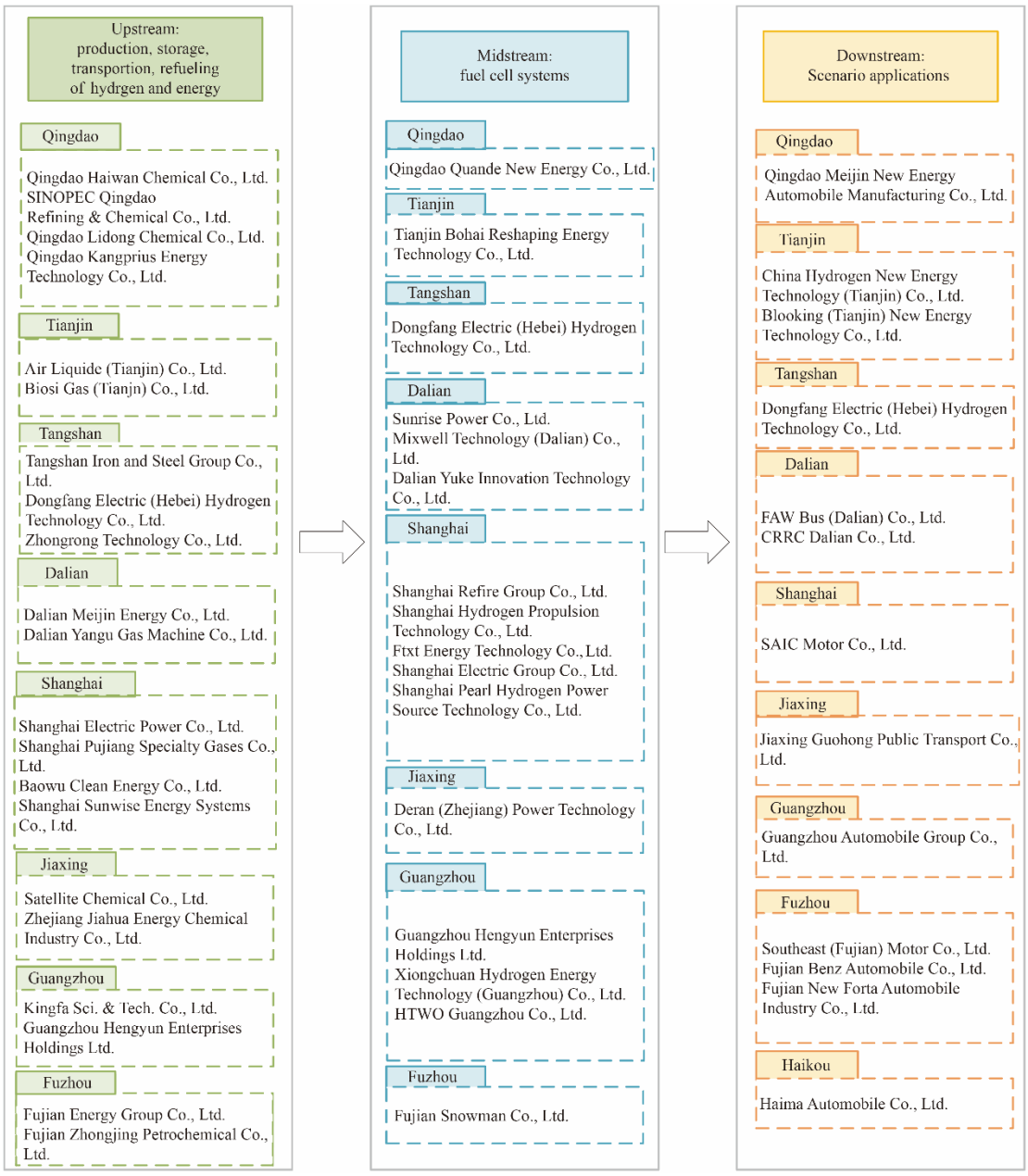

Fig. 1. Hydrogen-related enterprises in some port cities in China.

3.1.3 Hydrogen energy innovation platforms are improving

The construction of hydrogen energy industry innovation systems in port cities in China is accelerating, and platforms for innovation are constantly being developed. The Qingdao Innovation Base of National Fuel Cell Vehicle and Power System Engineering Research Center of Tongji University has provided a powerful innovation platform for R&D and the application of the hydrogen energy industry. Suzhou Hydrogen Energy Industry Innovation Center is jointly supported by Suzhou Science and Technology Bureau, Zhangjiagang Municipal Government, and Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, which has been successfully incorporated into the list of provincial industrial innovation centers. A pilot test platform for hydrogen fuel cell materials, components, stacks, and systems has been established. Cooperation from deep production, study, research, and application components has been encouraged in Shanghai. Shanghai continues to accelerate the construction and improvement

DOI 10.15302/J-SSCAE-2022.03.012

of the Academician Research Achievement Transformation Center, Jiading Tongji University Science Park, and the Carbon Neutral Innovation Center of Yangtze River Delta to conduct research on key technologies of fuel cell vehicles, forming a source of innovative technologies and promoting the transformation and industrialization of technological achievements. Guangzhou has introduced internationally renowned electrochemical and fuel cell experts and established the hydrogen energy innovation center, which is committed to conquering core technologies in related fields.

3.1.4 Hydrogen energy application demonstrations have achieved initial results

(1) In terms of hydrogen energy operation demonstration, the first batch of hydrogen fuel city buses manufactured by Qingdao Meijin New Energy Automobile Manufacturing Co., Ltd. have been put into operation, which indicates that Qingdao has officially entered the commercial demonstration operation of hydrogen fuel cell buses. (2) In terms of hydrogen fuel cell trams, the world's first commercial hydrogen fuel hybrid 100% low-floor modern tram, developed by CRRC Tangshan Co., Ltd., was put into commercial passenger operation for the first time in October 2017. In 2019, Jiashan county in Jiaxing opened hydrogen buses in the Yangtze River Delta integration demonstration zone, and connectivity with Shanghai and Suzhou was achieved. (3) In terms of hydrogen refueling, Hainan's first hydrogen refueling station was officially put into operation in Boao in 2021. The Haima integrated hydrogen production and refueling station was officially completed by Haima Automobile Co., Ltd. and 101 Research Institute of China Aerospace Science and Technology Corporation. The independent R&D and demonstration of hydrogen fuel cell vehicles is to be promoted simultaneously to open up pathways upstream and downstream of the hydrogen energy industry. (4) The construction of hydrogen refueling stations has also begun to take shape. In Shanghai, Guangzhou, Jiaxing, Qingdao, and other regions, a large number of hydrogen refueling stations have been put into operation, and the number of hydrogen refueling stations under construction or planning is also gradually increasing. In the future, the number of completed hydrogen refueling stations will continue to rise to meet the demonstration demand of hydrogen fuel cell vehicles.

3.2 Target analysis of existing hydrogen-energy-related plans

Under the guidance of the "dual carbon" goal, the future of hydrogen energy as clean energy has been written into the 14th Five-Year Plan by 30 provinces across the country, and port cities such as Dalian, Tianjin, Tangshan, Qingdao, and Guangzhou have issued development plans for the hydrogen energy industry. In this paper, the development plan of the hydrogen energy industry for top port cities is specifically introduced, and the development goals of the hydrogen energy industry are sorted out accordingly.

(1) Dalian has issued *Guiding Opinions on Accelerating the Development of Hydrogen Energy Industry in Dalian* and the *Development Plan of Hydrogen Energy Industry in Dalian (2020–2035)*. In this plan, by 2035, more than 30 leading enterprises at the international level will be established, with a total social capital of more than 250 billion CNY, and the total production capacity of hydrogen fuel cell vehicles will exceed 1×10^5 cars. In terms of technical innovation, Dalian strives to achieve 100% localization rate of key components. In terms of application and promotion, the number of hydrogen fuel cell vehicles in the city (including buses, passenger cars, heavy-duty trucks, traction cars, and sanitation vehicles) will reach more than 57 000, and the number of hydrogen fuel cell ships will reach 500. (2) Tianjin has issued the *Action Plan for Hydrogen Energy Industry Development in Tianjin (2020–2022)*, *Policies of Tianjin Port Free Trade Zone on Supporting Hydrogen Energy Industry Development*, and other policies. From these plans, by 2022, the total output value of the hydrogen energy industry is expected to exceed 15 billion CNY. Approximately 2–3 leading enterprises with international competitiveness will be established in hydrogen fuel cells and core components, power system integration, inspection, and testing fields. Plans also involve the building of three pilot demonstration zones for the promotion and application of hydrogen fuel cell vehicles. (3) Tangshan issued the *Development Plan of Hydrogen Energy Industry in Tangshan (2021–2025)*. The Tangshan plan indicates that by 2025, the city's hydrogen production capacity will reach 60 000 t/a, and the number of hydrogen fuel cell vehicles in operation will reach more than 3000, including at least 2000 hydrogen heavy-duty trucks. (4) Qingdao has issued the *Development Plan of Hydrogen Energy Industry in the West Coast New Area of Qingdao (2021–2030)* and the *Development Plan of Hydrogen Energy Industry in Qingdao*. Among them, the development of hydrogen energy industry in the West Coast New Area is divided into three stages: the industry cultivation stage, industry acceleration stage, and industry maturity stage. The cumulative output value of the hydrogen energy industry will reach 5 billion, 10 billion, and 30 billion CNY in these stages, respectively. (5) Zhoushan issued *Guiding Opinions on Accelerating the Development of Hydrogen Energy Industry in Zhoushan*. It indicates that Zhoushan will be largely built into an influential city for the marine application demonstration of hydrogen energy

by 2035. (6) According to the *Development Plan of Hydrogen Energy Industry in Guangzhou (2019–2030)* released by Guangzhou, more than 100 hydrogen refueling stations will be built by 2030, and the output value of the hydrogen energy industry is estimated to be more than 200 billion CNY.

In summary, the developmental goals of the hydrogen energy industry in China's port cities mostly focus on innovative R&D, the industrial scale, infrastructure, promotion, and application. These goal are focused on developing key technologies as soon as possible to raise the core of the hydrogen energy field to the advanced international level and take the hydrogen energy industry to a leading position.

4 Challenges of hydrogen energy development in China's port cities

4.1 Industrial chain is scattered, and regional cooperation needs to be strengthened

The development of the hydrogen energy industry in China's port cities is in the initial stage. Although the hydrogen energy industrial chain has been formed, further development is necessary. There are a few connections between upstream and downstream enterprises of the hydrogen energy industry. Most hydrogen produced by hydrogen production enterprises cannot be directly supplied to downstream enterprises, and the production, manufacturing, R&D, and demonstration of hydrogen storage and transportation equipment products are still not widely performed. The layout of existing hydrogen energy enterprises is relatively scattered, and there is a lack of coordinated overall planning for regional hydrogen industries. It is impossible for enterprises to effectively cooperate with each other. R&D activities of all linkages tend to be closed, resources cannot be shared, and it is difficult to break through the technological barrier of large-scale mass production.

4.2 Incomplete infrastructure and weak market operation foundation

The operational basis for the launch of terminal hydrogen energy products into the market is relatively weak. The lack of supporting facilities has become a key constraint for the application and promotion of hydrogen energy technology in port cities in China. In particular, hydrogen refueling stations as a part of infrastructure are seriously lacking, and the number and performance of these stations still lag behind those of developed countries. The operation and maintenance costs are high, the scale of hydrogen use is small, and it is difficult to achieve a break-even point during operation, resulting in the rise of costs when equipment refuels in ports. The insufficient layout of a hydrogen energy infrastructure and the difficulty caused by popularization are not conducive to the cultivation of the application market of terminal hydrogen products.

4.3 R&D competitiveness is insufficient, and key technologies need to be developed urgently

Some hydrogen technologies of port cities in China are near the advanced international level; however, there is still a large gap between the overall core technology level and the advanced foreign level. There is a certain gap from international advanced technology in terms of hydrogen purification, hydrogen storage materials and equipment, hydrogen refueling station equipment manufacturing, and other fields. In the field of hydrogen fuel cells, core technologies of proton exchange membranes, carbon paper, low platinum catalysts, metallic bipolar plates, hydrogen recirculation components, air compressors, and solid oxide fuel cell system integration have not yet achieved a complete breakthrough. There is still a large gap between the key technical indicators of the high-capacity fuel cell systems of heavy-duty trucks and those of the advanced international level, and production to scale and market application is still far away.

4.4 Development environment and industrial policies need to be improved

Although several port cities in China have issued relevant plans for the development of the hydrogen energy industry, there is still a lack of supporting policies, management methods, approval procedures, laws and regulations, and safety-guarantee mechanisms related to the hydrogen energy industry. For example, the overall level of policy preparation for fuel cell vehicles is low, and few port cities have issued specific policies for fuel cell vehicles. Presently, the technical standards system for hydrogen energy in China is not perfect, and the rigor of the test standards still needs to be improved. As key areas of safety management for provinces and cities, port cities should ensure the reliability of hydrogen energy application. Meanwhile, hydrogen is still managed as a dangerous chemical in China. There are certain institutional obstacles encountered during the approval, implementation, and operation of hydrogen energy industry projects, and there is a lack of overall management and supporting policies and measures.

DOI 10.15302/J-SSCAE-2022.03.012

5 Developmental directions and path selections of hydrogen energy in China's port cities

5.1 Overall layout

To turn port cities into hydrogen energy cities with sufficient hydrogen energy supply, the development of the heavy-duty truck industry, advanced hydrogen energy technologies, and international hydrogen energy transportation hubs should be completed. With the guaranteed availability of hydrogen production resources, producing a hydrogen energy supply will ensure domestic demand and "make exports more competitive (both domestically and internationally)". Fuel cell heavy-duty truck demonstration bases should be constructed, featuring the logistics chain of hydrogen energy fuel cell heavy-duty trucks. The supply and application of hydrogen energy in cities should be integrated, and distinct and independent hydrogen energy technologies, refined through R&D, should be established. The full use of port advantages should be ensured to build influential international hydrogen energy hubs.

Presently, the hydrogen energy development layout of major port cities in China are as follows. (1) Dalian will be the main hub of port cities in Liaoning Province. A green and efficient world-class port cluster with coordinated development will be built, promoting the integration of hydrogen energy resources in Liaoning's coastal ports with transportation resources in the hinterland of northeastern China. A multimodal transport system, combining highway, sea, and railway, should be vigorously developed, which will foster the development of new land–sea logistics channels that will be integrated into the hydrogen economy. Furthermore, new trade patterns in Northeast Asia should be opened, and an important support system for the development of new energy in the hinterlands should be formed. (2) Port cities in Tianjin and Hebei will use location advantages as important nodes of the Beijing–Tianjin–Hebei development axis, focusing on the development of hydrogen energy logistics. In this vein, hydrogen refueling station networks will be constructed, and cross-regional cooperation with coordination from the cities Beijing, Tianjin, and Hebei will be promoted. (3) Port cities in Shandong province will focus on the layout of green port construction, and port hydrogen energy will be further promoted and applied to accelerate the construction of a "leading international smart green port." (4) Port agglomerations in Jiangsu, Zhejiang, and Shanghai will take full advantage of the opportunity provided by the national strategy of Yangtze River Delta integration to strengthen industrial cooperation and exchange, maximize the advantages of hydrogen fuel cell vehicle technology, and contribute to the development of the domestic hydrogen energy and fuel cell industry. (5) Port cities in Fujian province will establish Fuzhou as the core to build the entire industry chain of hydrogen energy, incorporating key enterprises such as Xiamen King Long Motor Group Co., Ltd. and Fujian Snowman Co., Ltd., and expand the production scale of hydrogen fuel cell vehicles to build an important hydrogen fuel cell and automobile manufacturing hub, core technology innovation zone, and demonstration application base on the west coast of the straits. (6) Port cities in Guangdong province will accelerate the construction of the entire industrial chain of hydrogen energy, develop a large-scale application of hydrogen energy, and drive the development of the hydrogen energy industry in the Guangdong–Hong Kong–Macao Greater Bay Area. Complete sets of hydrogen energy equipment and key components will be exported to China and the world. (7) Port cities in Hainan province should exploit the Hainan Free Trade Port to attract a number of hydrogen energy enterprises to establish themselves there and tackle the development of the hydrogen energy industry, providing new drivers for the construction of free-trade ports.

5.2 Key directions of industrial development

5.2.1 Ensuring adequate supply of hydrogen energy

The geographical advantages of port cities should be exploited, taking full advantage of the availability of industrial by-product hydrogen and renewable hydrogen energy sources, developing diversified hydrogen production systems, and building a hydrogen supply base that is based on hydrogen extraction from by-product gas and effectively supplemented by hydrogen production from renewable energy sources. First, high-quality industrial by-product hydrogen should be vigorously produced and hydrogen production from industrial tail gas, natural gas reforming, methanol cracking, solar energy photolysis, and other technologies should be established to achieve diversified hydrogen production and reduce the cost of hydrogen production. Second, the availability of abundant renewable resources in port cities should be utilized. Green hydrogen production technologies, such as hydrogen production from electrolytic water, which are important supplements to hydrogen sources that can be used to cope with the future demand for "green hydrogen," should be vigorously developed [20]. Third, the development of a hydrogen purification process and purity detection technology, as well as hydrogen production technologies for

efficient transformation and pressure swing adsorption (PSA), should be promoted. This would necessitate the development of core equipment, catalysts, and other key technologies. Furthermore, adsorption and conversion efficiency should be improved, and the production capacity of high-purity hydrogen should be enhanced. Fourth, the development of important hydrogen supply bases in coastal areas should be accelerated, whereby the scale of hydrogen energy supply and demand would be expanded and a market scale would be established as soon as possible.

The construction of hydrogen energy supply networks within cities should be promoted. Coke oven gas, an industrial by-product produced by urban enterprises, is integrated into pipe networks. According to the demand of hydrogen fuel cell vehicles, hydrogen transmission and supply should be rationally distributed in each city. In conjunction with transportation routes, hydrogen refueling stations and networks should be constructed [21]. Adhering to the priority of comprehensive utilization of resources, locations and scientific decision-making methods for the establishment of hydrogen refueling stations should be explored [22]. The feasibility of constructing various forms of hydrogen refueling stations such as gas-to-hydrogen conversion, combined construction and expansion of gas and hydrogen, and liquid hydrogen refueling stations should be actively sought at the locations of gas stations, and focus should be placed on regional layouts. Through the construction of basic pipe networks, information management technologies such as fifth-generation mobile communication technology (5G) and advanced intelligent decision-making methods should be used, facilitating the management of interconnected networks of hydrogen supply between vehicles and hydrogen refueling stations, between sets of hydrogen refueling stations, and between hydrogen refueling stations and highways, as well as the connectivity, complementarity, and coordination of the entire network.

5.2.2 Layout of the hydrogen heavy-duty truck industry

First, fuel cell heavy-duty truck manufacturing bases should be built. Using hydrogen fuel cell heavy-duty truck manufacturing as the core, supported by fuel cell stacks and key components, the introduction and development of enterprises with independent intellectual property rights and core technologies should be accelerated. Efforts should be made to open up the entire industrial chain of hydrogen heavy-duty truck equipment manufacturing and assembly, and integrated manufacturing bases of hydrogen fuel cell heavy-duty trucks should be established. Enterprises with heavy-duty truck production implementing traditional energy, new energy, and hydrogen energy should be developed. By means of joint venture, equity participation, and technology introduction, equipment manufacturing industries such as vehicle-mounted hydrogen storage bottles, hydrogen fuel cells, and key components will be gradually promoted, and the construction of heavy-duty truck industrial clusters will be gradually improved. Fuel cell heavy-duty truck manufacturing bases should be built in port cities to meet the demand for fuel cell heavy-duty truck vehicles. Hydrogen fuel cell heavy-duty truck manufacturers should strive for the international advanced level in vehicle manufacturing technology to form national fuel cell heavy-duty truck supply bases.

Second, the entire industrial system for hydrogen heavy-duty trucks that comprises “manufacturing, transportation, station” and “research, production, use” should be built. During the application scenario of heavy-duty truck transportation in ports and docks, the chain operation mode of “fuel cell heavy-duty trucks + hydrogen refueling stations + long tube trailer” is created. Demonstration zones should be built for “replacing diesel fuel with hydrogen,” taking advantage of heavy-duty truck capacity, and the demonstration application of hydrogen fuel heavy-duty trucks should be promoted. The development of hydrogen fuel cell heavy-duty truck businesses should be accelerated, examination of hydrogen fuel cell heavy-duty truck operation should be performed, and the feasibility of large-scale commercial operations should be further verified.

5.2.3 Building gas energy hubs

First, the application of international hydrogen ports should be promoted. Presently, Australia and Brunei have successfully exported hydrogen to Japan. China also has advantages in international hydrogen trade. China has an inherent advantage in being closer to Japan and South Korea than Australia. Therefore, green-hydrogen-related industries can be vigorously distributed in port cities to take advantage of geographical advantages for hydrogen export [23]. Resources and logistical transportation markets of port cities should be utilized, and focus should be placed on building international hydrogen ports. Considering the requirements listed in *Outline for Building a Leading Transportation Nation* issued by the State Council, focus should be given to the important role of hydrogen energy in building green transportation, logistics, and ports. Furthermore, national and local pollutant control standards should be strictly implemented, and green ports should be built. Demonstration applications of hydrogen energy in port sanitation vehicles, logistics vehicles, power machines, and fuel cell ships should be developed. The

DOI 10.15302/J-SSCAE-2022.03.012

proportion of hydrogen energy in the energy consumption structure in port areas should be increased, highlighting its use in fuel cell rail transit, distributed generation, and backup power devices and port machines.

Second, the liquefied hydrogen storage industry should be developed, and liquid hydrogen hubs should be built. Advanced technologies should be applied in port cities, developing the liquefied hydrogen storage industry and promoting efficient storage and utilization of hydrogen resources. Meanwhile, surplus industrial by-product hydrogen in port cities should be planned and utilized, and factories and demonstration refueling stations of liquid hydrogen should be built. Through the construction of liquid hydrogen factories and liquid hydrogen storage and transportation, coastal liquid hydrogen hubs and production bases should be constructed. Based on actual hydrogen energy application and development in coastal cities, abundant, high-quality, and low-cost hydrogen sources in port cities can be distributed to downstream urban areas. Liquid hydrogen supply networks that can cover a radius of 2000 km should be gradually planned and built. Furthermore, port cities should be transformed into supply bases in areas that have hydrogen source demand to drive the coordinated development of the hydrogen energy industry in surrounding urban agglomerations. In addition, in accordance with the concept of demonstration pilot projects, early planning, and layout, participation in promoting the process of the civil use of liquid hydrogen in China should be ensured.

5.2.4 Enhancing the capability of technological innovation

First, core technology innovation in hydrogen energy and fuel cells should be strengthened. Focus should be placed on the R&D of key technologies, such as production, storage, transportation, refueling, and energy storage generation. The promotion of low-cost hydrogen production technology, industrial by-product hydrogen purification and purity detection technology, efficient water electrolysis hydrogen production technology, hydrogen production from offshore wind power, and distributed hydrogen production from natural gas should be accelerated. Diversified hydrogen storage (transportation) technologies such as gas-state, liquid-state, solid-state, organic liquid, and natural gas hydrogen mixing pipeline transportation should be developed. This includes the development of hydrogen storage tank equipment for high-pressure gas over 70 MPa, liquid-state hydrogen storage, solid-state hydrogen storage, and other front technologies [24,25]. Solid-state hydrogen storage devices should be explored as well and developed for vehicles and stations. R&D of metal materials for hydrogen transport pipelines should be performed, and special hydrogen transport pipelines should be built. This would facilitate the breaking-through of bottlenecks in the development of core hydrogen refueling technologies. Furthermore, core hydrogen refueling devices, high-speed air compressors, core equipment and core components of hydrogen stations, and other key technologies of the hydrogen energy industry should be developed. Key material for hydrogen fuel cells, fuel cell membrane electrodes and stacks, fuel cell vehicles, ships, rail transit, fuel cell distributed generation, and other core technologies with integrated application should be developed in the equipment industry.

Second, the acceleration of technological and model innovation should be led by research teams from large- and medium-sized technology enterprises, and research institutes and universities should be encouraged to participate. Platforms of technology R&D should be built, with attention paid to cutting-edge technology trends in the field of hydrogen energy. Developmental models should be explored for the hydrogen energy industry, integrating hydrogen energy with big data, artificial intelligence, and other digital technologies to create new modes of hydrogen energy application. Hydrogen energy should also be combined with renewable energy to open up new modes of energy development. Scientific achievement should be accelerated through the advancement in technology R&D by industrial enterprises, and product systems with advanced technologies and independent intellectual property rights should be developed.

5.3 Application scenarios and engineering demonstrations

The future energy arrangement will be dominated by new energy on the supply side, and the applications and usage scenarios of hydrogen energy will be more abundant. The healthy development of the hydrogen energy industry requires an acceleration of the pace of industrial development, maintaining a balance in the growth of all areas in the industrial chain. This will support the exploration of application demonstration scenarios in many fields, in which key hydrogen energy projects are implemented and the decarbonization potential of hydrogen energy is fully realized.

The future application scenarios of hydrogen energy in port cities mainly include three aspects (Fig. 2). Hydrogen port application demonstration zones should involve the development of high-pressure gas-state hydrogen storage and liquid hydrogen industries, as well as international liquid hydrogen hubs. The use of port resources and logistics markets should be encouraged, demonstrating applications of hydrogen energy in port transportation. Centered

around the electricity demand of ports, applications of the distributed generation of fuel cells should be promoted. Furthermore, market applications of hydrogen fuel cells should be promoted to provide stand-by power. Hydrogen heavy-duty truck demonstration areas in port cities should be constructed with a focus on the application of fuel cells in heavy-duty trucks, and hydrogen refueling stations and dimensional pipeline network pilots of hydrogen transportation and storage should be established. Hydrogen refueling stations will support the development of hydrogen bus demonstration zones in areas with rapid hydrogen energy industrial development to comprehensively promote the application of hydrogen transportation.

According to the overall layout and basis of the hydrogen energy industry in port cities, 10 key projects can be implemented. By promoting the orderly construction of the primary engineering infrastructure and supervising and implementing key industrial projects, effective support will be achieved for the development of the hydrogen energy industry in China's port cities.

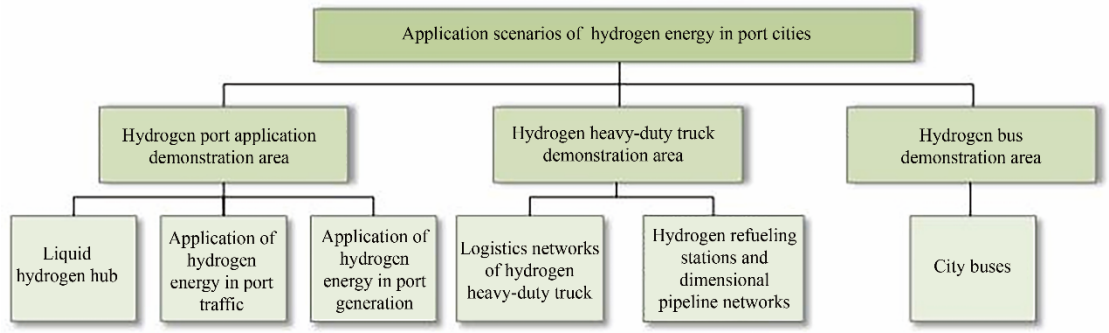

Fig. 2. Layout of hydrogen energy application scenarios in port cities.

5.3.1 Construction project of coke oven gas network

Based on the original pipeline network, the unified utilization of a hydrogen source is achieved by constructing a coke oven gas pipe network in reverse. All the industrial byproduct coke oven gas produced by all enterprises in the city will be incorporated into the pipe network, which will be collected and transported to hydrogen production bases.

5.3.2 Demonstration project of large-scale and low-cost hydrogen production

Abundant industrial by-products in port cities will be utilized to build a base of R&D for centralized hydrogen production, based on sources collected by the unified coke oven gas pipeline project. Efficient conversion and hydrogen production based on PSA technology would be developed and core equipment, catalysts, and other key technologies would be mastered, improving the production capacity of high-purity hydrogen and promoting large-scale industrial hydrogen production projects.

5.3.3 Demonstration project of hydrogen heavy-duty truck manufacturing

With the manufacturing of hydrogen fuel cell heavy-duty trucks as the core, fuel cell stacks and key components will support the introduction and development of a number of enterprises with independent intellectual property rights and core technologies. These technologies will focus on developing the production line of hydrogen fuel cell systems, whereby the assembly line project of hydrogen fuel trucks is regarded as a key demonstration project.

5.3.4 Demonstration project of hydrogen metallurgy

The construction of hydrogen metallurgy engineering projects will facilitate coordination with related institutions of hydrogen metallurgy technology to develop a new iron and steel metallurgical production process with hydrogen energy as the core. The demonstration application of hydrogen metallurgy projects will be accelerated, and traditional metallurgy methods will be gradually replaced to promote industrial decarbonization.

5.3.5 Pilot demonstration project of hydrogen refueling station construction

According to the actual needs of demonstration areas, some petrol stations or gas stations will be selected as demonstration sites, where the construction of hydrogen refueling stations will be explored. Here, the focus will be replacing gas and oil with hydrogen, and the integration of gas, oil, and hydrogen will be promoted. The pilot construction of hydrogen refueling stations will be accelerated. "Gas, oil, and hydrogen" integrated energy supply service stations will be built to guarantee the operation of hydrogen heavy-duty trucks and buses.

DOI 10.15302/J-SSCAE-2022.03.012

5.3.6 Hydrogen fuel cell vehicle demonstration project

In accordance with the layout of hydrogen refueling stations in the port cities, the demonstration of hydrogen fuel cell vehicles will be studied, including the formulation of plans to promote these vehicles in the future. Key projects of hydrogen fuel cell vehicle demonstration have been carried out, including the establishment of hydrogen fuel cell bus lines, heavy-duty truck lines, tourist bus lines, commuter bus lines, and inter-provincial transport lines (freight).

5.3.7 Green hydrogen port demonstration project

The international hydrogen energy hub project of "hydrogen +5G" will be implemented with port sanitation vehicles, logistics vehicles, power machines, and hydrogen fuel cell ships as the core. The intelligent development of ports will be promoted, utilizing big data and information technologies, hydrogen energy transportation routes will be scientifically planned, and efficient and low-cost transportation distribution networks will be constructed.

5.3.8 Demonstration project of hydrogen production from water electrolysis

High-efficiency and low-cost hydrogen production technology, exploiting the use of water electrolysis, will be developed, high-pressure compact alkaline water electrolysis technology will be studied, and new electrode and diaphragm materials will be produced. This will promote the use of non-noble metal catalysts, high-efficiency film materials, and diffusion layer materials, reducing the load on proton exchange membrane noble metal catalysts. High-temperature solid oxide water electrolysis technology will be developed, research will be conducted on advancing membrane technology of electrolytes, and new sealing materials and connective materials will be formulated.

5.3.9 Project of hydrogen energy collaborative innovation center

Hydrogen energy industry research institutes will be established in collaboration with well-known domestic research universities, research institutions, and domestic and foreign hydrogen energy enterprises. Collaborative research on technological innovation will be strengthened in the hydrogen energy and fuel cell industries. Incubation bases for scientific and technological innovation and entrepreneurship as well as science and technology service platforms that support the development of the hydrogen energy industry will be created.

5.3.10 Smart hydrogen big data platform

Smart big-data platforms for hydrogen will be built and utilized, and real-time monitoring of hydrogen data throughout its life cycle will be performed to ensure the safety of hydrogen during the entire process of production, storage, transportation, refueling, and use. Smart big-data platforms integrating hydrogen energy logistics, industrial supervision, and safety provisions will be built.

6 Policy suggestion

During the 14th Five-Year Plan period, the hydrogen energy industry stands ready to embrace new opportunities, as the development potential of the hydrogen energy market is vast. Port cities in China have remarkable advantages in location, rich hydrogen energy resources, refined application scenarios, and abundant talent in R&D. To this end, the *Medium- and Long-Term Development Plan for Hydrogen Energy Industry (2021–2035)* should be effectively implemented. The strategic opportunity of development of the hydrogen energy industry should be grasped, utilizing existing advantages as well as considering the important role of hydrogen energy in the energy transformation of port cities to achieve a win-win result in terms of ecological and economic development in the coastal areas. The economic infrastructure of China's coastal areas should be improved, and support should be geared toward achieving the "dual carbon" goals of China.

6.1 Fostering a sound ecosystem through active cooperation and availability

Port cities should rely on regional advantages to strengthen cooperation with neighboring countries in the hydrogen energy industry by utilizing technologies, standards, and personnel to achieve mutual benefit. Hydrogen trade should be conducted to promote common development and sharing of the fruits of that development. Active participation in the construction of an international hydrogen energy system should be encouraged, integration into the supply chain of global hydrogen energy should occur as soon as possible, and the international competitiveness of hydrogen energy development should be promoted.

6.2 Focusing on key points and strengthening weak links to build an innovation system

Addressing the weak links in the supply chain of port cities, effective hydrogen energy enterprises should be cultivated and introduced, highly competitive enterprise groups should be developed, and hydrogen energy

enterprises should be promoted in port cities to develop industrial clusters. The mechanism by which construction is implemented should be strengthened, facilitating the establishment of innovation systems of hydrogen energy that will support the development of the hydrogen energy industry, through which innovation and core technologies can be continuously promoted.

6.3 Promoting scenario applications with an emphasis on safety

The implementation of hydrogen energy safety strategies and measures should be followed, and investment in hydrogen storage and transportation with regard to technologies, standards, equipment, facilities, and personnel expertise should be increased. A coastal hydrogen energy industrial belt should be built on the basis of safety, and the hydrogen energy industrial base should be extended to the development of hydrogen ports, heavy-duty trucks, buses, and other tools to provide a more intelligent, environmentally friendly, efficient, and safe energy supply framework.

6.4 Accelerating technological innovation to stimulate developmental momentum

Focus should be placed on tackling key technologies and equipment and accelerating efforts to break bottlenecks in core technologies and materials. By promoting breakthroughs in technical equipment, China's ability to operate independently will be enhanced. The developmental model of the hydrogen energy industry should be addressed, with a focus on integrating hydrogen energy with digital technologies, such as big data and artificial intelligence, and combining hydrogen energy with renewable energy.

References

[1] Yin Y L. Present situation and prospect of hydrogen energy industry [J]. Chemical Industry and Engineering, 2021, 38(4): 78-83. Chinese.

[2] Wei F, Ren X B, Gao L, et al. Analysis on transformation and characteristics of American hydrogen energy strategy under carbon neutralization goal [J]. Bulletin of Chinese Academy of Sciences, 2021, 36(9): 1049-1057.Chinese.

[3] Wu X Y, Lu X B, Dong J X, et al. Local policy for fuel cell vehicles [J]. Energy Storage Science and Technology, 2021, 10(6): 1987–1997.Chinese.

[4] He Q, Meng Z X, Shen Y, et al. Analysis and thinking of hydrogen energy policies in China under "double carbon" target [J]. Thermal Power Generation, 2021, 50(11): 27-36. Chinese.

[5] Liu W, Wan Y M, Xiong Y L, et al. Outlook of low carbon and clean hydrogen in China under the goal of "carbon peak and neutrality" [J]. Energy Storage Science and Technology, 2022, 11(2): 635-642.Chinese.

[6] Xu S, Yu B Y. Current development status and prospect of hydrogen energy technology in China [J]. Journal of Beijing Institute of Technology (Social Sciences Edition), 2021, 23(6): 1-12. Chinese.

[7] Meng Z X, He Q, Hu H W, et al. Development situation and consideration of hydrogen energy industry in China [J]. Modern Chemical Industry, 2022, 42(1): 1-6, 12. Chinese.

[8] Cao J W, Zhang W Q, Li Y F, et al. Current status of hydrogen production in China [J]. Progress in Chemistry, 2021, 33(12): 2215-2244.Chinese.

[9] Yu H M, Shao Z G, Hou M, et al. Hydrogen production by water electrolysis: progress and suggestions [J]. Strategic Study of CAE, 2021, 23(2): 146-152.Chinese.

[10] Yin Z C, Yang G, Liu H, et al. Research status and prospect analysis of key technologies for hydrogen energy storage and transportation [J]. Modern Chemical Industry, 2021, 41(11): 53-57. Chinese.

[11] Li X G. Status and development of hydrogen preparation, storage and transportation [J]. Chinese Science Bulletin, 2022, 67(4-5): 425-436.Chinese.

[12] Cao J W, Qin X F, Geng G, et al. Current status and prospect of hydrogen storage and transportation technology [J]. Acta Petrolei Sinica (Petroleum Processing Section), 2021, 37(6): 1461-1478.Chinese.

[13] Ling W, Liu W, Li Y L, et al. Development strategy of hydrogen infrastructure industry in China [J]. Strategic Study of CAE, 2019, 21(3): 76-83. Chinese.

[14] Zhu M Y, Liu W B, Liu Y, et al. Key scientific and technological principles of hydrogen energy and fuel cells: Challenges and prospects [J]. Journal of Shanghai University (Natural Science Edition), 2021, 27(3): 411-443.Chinese.

[15] Yu G X, Ji Q H, Liu Q, et al. Analysis and consideration on bottlenecks of hydrogen energy and fuel cell industries [J]. Modern Chemical Industry, 2021, 41(4): 1-4, 10. Chinese.

[16] Shao Z G, Yi B L. Developing trend and present status of hydrogen energy and fuel cell development [J]. Bulletin of Chinese Academy of Sciences, 2019, 34(4): 469-477.Chinese.

[17] Liu Y D, Guo H X, Ouyang X P. Development status and future prospects of hydrogen fuel cell technology [J]. Strategic Study of CAE, 2021, 23(4): 162-171.Chinese.

DOI 10.15302/J-SSCAE-2022.03.012

[18] Zhu S Q, Sun S E, Li X, et al. Outlook for development path of hydrogen energy industry in China's Yangtze River Delta region for "carbon neutral" goal [J]. Modern Chemical Industry, 2021, 41(5): 1-6. Chinese.

[19] Li J F, Wu S Q, Wang X M. Discussion on hydrogen production routes in coastal areas [J]. Modern Chemical Industry, 2021, 41(7): 26-28, 34. Chinese.

[20] Du Z X, Huang S X, Cao D X. Challenges and suggestions of low carbon transformation for petrochemical industry to green hydrogen business [J]. Acta Petrolei Sinica (Petroleum Processing Section), 2021, 37(6): 1452-1460.Chinese.

[21] Xiang Y. Hydrogenation infrastructure network optimization considering industrial layout and customer satisfaction [J/OL]. Chinese Journal of Management Science: 1–13(2021-08-06). [2022-04-22]. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=ZGGK20210805006&DbName=DKFX2021. Chinese.

[22] Zhang X, Fan X Y. Discussion on sustainable development model of hydrogen energy [J]. Modern Chemical Industry, 2021, 41(10): 1-6. Chinese.

[23] Meng X Y, Gu A L, Wu X G, et al. Prospect of high quality development of hydrogen energy industry in China [J]. Science & Technology Review, 2020, 38(14): 77-93. Chinese.

[24] Cao X H, Wei Z Q. Technologies for the safe use of hydrogen and construction of the safety standards system [J]. Strategic Study of CAE, 2020, 22(5): 144-151.Chinese.

[25] Wang L, Jin Z J, Huang X W. Research progress on hydrogen production and solid hydrogen storage [J]. Natural Gas Industry, 2021, 41(4): 124-136.Chinese.