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Development Strategy of the Hydrogen Infrastructure Industry in China

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Abstract: Hydrogen energy is recognized as being fundamental to the construction of an integrated energy supply system dominated by clean energies. Hydrogen development and utilization have become a significant energy development direction for China. However, the inadequate development of hydrogen infrastructure is one of the main reasons hampering the large-scale application and promotion of hydrogen energy in China. This study deeply analyzed the current situation and trend of China's hydrogen infrastructure (focusing on hydrogen refueling stations) and discussed the difficulties and challenges in developing the hydrogen infrastructure industry in China. Referring to the advanced experiences of several developed countries, we proposed an overall development goal and route for China's hydrogen infrastructures, and proposed reasonable suggestions on system safeguard and related policies. The study results would provide a useful reference for the formulation of China's guidance policies on hydrogen development.
Keywords: hydrogen industry; infrastructure; strategy study

1 Introduction

The global energy sector is headed towards the third energy revolution, which will be led by low-carbon/carbon-free, low-pollution sources of energy, and the electrification has become an increasingly prevalent trend worldwide as global energy demand continues to grow. In the future, the share of renewable energy in the global energy structure will increase much more rapidly than that of any other source of energy, and this shall lead to the formation of a diverse energy structure dominated by oil, natural gas, coal, and renewable energy.

Hydrogen energy, a secondary energy source that is clean, efficient, safe, and sustainable, can be obtained from a wide variety of sources, including primary and secondary energy sources, and the industrial sector. Furthermore, hydrogen energy can be utilized by the industrial, construction, transportation, and power sectors. Hydrogen is therefore an important component for the construction of an integrated energy supply system where clean energy sources play a dominant role. The development and utilization of hydrogen energy have become important aspects of the new global energy revolution, and hydrogen energy is also an important strategic high ground for future developments in the automobile industry. Hence, the development of hydrogen energy will accelerate the energy production and consumption revolution in China, thus playing a significant role in the transformation and development of China's energy sector in the new era.

In late 2017, the Hydrogen Council published the world's first report on the future development trends of hydrogen energy, with the support of the McKinsey & Company management consulting company. In this report,

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it noted that, by 2050, the hydrogen energy sector will create 30 million jobs globally, reduce CO_2 emissions by 6 × 10^9 t, create a market with revenues of over USD 2.5 trillion per year, and provide 18% of the world's energy demand. Furthermore, hydrogen-powered vehicles will account for 20%–25% of the global vehicle fleet [1].

The hydrogen industry of China has entered a period of accelerated growth. Since 2017, several breakthroughs have been obtained in critical technologies, and the hydrogen industry has seen an increase in industrial scale. Many regions have also taken the initiative in introducing supporting policies for the hydrogen industry. A fully integrated industrial chain has thus been demonstrated on a small scale. However, as the hydrogen industry continues to grow and the range of applications for hydrogen energy widens further, the inability of China's hydrogen energy infrastructure (especially hydrogen refueling stations (HRSs)) to guarantee a steady supply of hydrogen has become a major constraint for the sustainable development of the hydrogen industry.

2 Importance of and prerequisites for developing the Chinese hydrogen industry

2.1 Hydrogen is an integral component for the construction of a clean and integrated energy supply system in China

2.1.1 Role of hydrogen energy in energy system optimization

Hydrogen energy can be produced by various means and utilized in various areas, unlike conventional energy sources like coal and other clean sources of energy (e.g., renewable energies), which tend to only have a single viable path for their conversion into usable energy. Therefore, hydrogen can be used to interconvert and integrate the various energy systems that exist today. Hydrogen energy is an integral component for achieving large-scale renewable energy utilization, as it allows different types of energy to be distributed in an optimal manner across different regions and seasons, thus leading to the formation of a sustainable and flexible multi-energy system.

2.1.2 Role of hydrogen energy in enhancing energy security

Although the proportion of oil in the energy structure of China is increasing over time, China is not self-sufficient with regards to oil. The oil import dependency of China has reached 69.8% in 2018 [2]. Consequently, the sustainable development of China has been hampered by oil shortages and its dependence on oil imports. Hydrogen energy could be combined with fuel cell technology to enable the large-scale adoption of fuel cell electric vehicles (FCEVs). This will greatly reduce the oil/natural gas consumption of the transportation sector and thus reduce China's oil imports dependency.

2.1.3 Role of hydrogen energy in increasing energy-use efficiency

As an energy conversion medium. Hydrogen could be produced by combining carbon capture and sequestration (CCS) technologies with hydrogen production via the recycling of industrial by-product hydrogen and fossil fuel reforming. This hydrogen may then be widely utilized within the transportation sector, used to replace coke in metallurgy processes, combined with CO_2 to form oxygenates and hydrocarbons, or co-fired with natural gas to generate electricity through gas turbines or provide heating for industrial applications. Hydrogen may also be used as an energy storage medium via hydrogen storage equipment and fuel cell technology to increase the flexibility of the power grid via peak shaving, and to store hitherto "unstorable" electrical energy. This shall allow the power grids of different industries to be harmoniously optimized.

2.1.4 Role of hydrogen energy in decreasing carbon emissions

It is possible to achieve "low carbon emissions in energy production and zero carbon emissions in energy usage" by combining hydrogen energy and fuel cell technologies, which are unparalleled in terms of carbon emissions, with low-carbon, "green" hydrogen production methods. This shall be conducive for the "deep decarbonization" of terminal energy consumption.

2.2 Hydrogen energy as an important strategic direction for the energy technologies and emerging industries of China

The provisions of the *Made in China 2025* explicitly support the development of FCEVs, and *The Outline of the National Strategy of Innovation-Driven Development* states that next-generation energy technologies like hydrogen energy and fuel cell technologies are integral to China's development strategy. The *China Energy Technology Innovation Action Plan 2016−2030* has stated that innovations in hydrogen energy and fuel cell technology are important tasks, particularly for the integration of hydrogen production, storage, transportation, and usage at large scales and low costs, and the standardization and promotion of in-situ hydrogen storage and hydrogen

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production in HRSs. Moreover, the *13th Five-Year Plan for Strategic Emerging Industries Development* also urges the development of vehicular hydrogen storage systems, hydrogen production, storage, transportation, and filling technologies, as well as the construction of HRSs, as China aims to mass produce FCEVs and increase the scale of FCEV demonstration projects by 2020.

2.3 China already possesses the requisite conditions to develop and utilize hydrogen energy

China's advantages in hydrogen energy development lie in its excellent hydrogen production infrastructure and enormous market. For instance, industrial hydrogen production has already reached 2.5×10^7 t in China [3]. Furthermore, China possesses large, as yet untapped sources of hydrogen, as the curtailment of wind, solar, and hydroelectric power in China was approximately 1.0229×10^{11} kW·h in 2018 alone. Furthermore, there still exists some unrecyclable by-product hydrogen in the chemical industry. China also has the world's largest automobile and new energy vehicles (NEV) market. In addition to civilian vehicles, heavy trucks for mines and ports, logistics trucks, heavy-duty diesel-powered vehicles, rail transport, ship- and shore-side power equipment, and aircraft could all potentially utilize hydrogen energy. Hence, China already possesses the requisite hydrogen supplies and market space for the large-scale utilization of hydrogen energy.

In recent years, China has obtained breakthroughs in a number of critical hydrogen energy technologies and mastered the technology of developing and utilizing hydrogen infrastructure and fuel cell technologies. China now has the capability to produce industrial hydrogen energy equipment and FCEVs, and a few small-scale projects have been successfully piloted in China. A strong foundation has thus been laid for the large-scale commercialization of hydrogen energy and fuel cells. In the future, the acceptance of hydrogen energy and the scale of the hydrogen market will mainly depend on the price, safety, and environmental friendliness of hydrogen in terminal applications. The coordination of hydrogen production, transportation/storage, and refueling facilities will play extremely important roles in these aspects.

3 Current state of development of China's hydrogen infrastructure and industries

3.1 The intensity of hydrogen energy investments has increased significantly, and the number of hydrogen-fueling stations in China is growing rapidly

The hydrogen industry of China has been growing at an explosive rate since 2017. At present, the hydrogen market of China is dominated by fuel cell electric buses and logistics trucks. To meet their FCEV targets, a number of regions have begun to plan and construct safe HRSs on a large scale; as of March 2019, 25 HRSs were operational in China (including two stations that were modified for hydrogen refueling), which is an increase of 14 stations compared to 2017 (Fig. 1). The 25 constructed HRSs consist of 11 permanent HRSs and 14 skid-mounted HRSs. In addition, there are 17 HRSs that are under construction. These HRSs are mainly located in Guangdong, Jiangsu, Shanghai, Hubei, and Hebei (Table 1).

The hydrogen vehicles that are currently operating in China are currently limited to small fuel cell electric buses and pre-production test vehicles. Hence, the permanent and skid-mounted HRSs of China, despite their small hydrogen storage capacities, can have sufficient hydrogen fueling capacity to meet current demands for hydrogen fuel on the application scenario that the vehicles are being refueled in an orderly manner and refueling time is not an important priority. It is estimated that there are 10 operational HRSs with hydrogen fueling capacities of 500 kg per day or more.

3.2 Breakthroughs are continuously being achieved in key technologies, and the progress of equipment localization is accelerating

Hydrogen production technologies: China already possesses the technical capacity to build large hydrogen production capacities; the coal gasification, natural gas reforming, and methanol reforming facilities that have hydrogen production capacities of > 2×10^5 m^3/h, 8×10^4 m^3/h, and > 4×10^4 m^3/h, respectively, have been constructed. China also possesses the key technologies required for hydrogen liquefaction. In addition, the alkaline water electrolyzers of China are able to produce 1000–1200 m^3/h per unit, and China possesses all intellectual property rights related to the production and integration of these devices.

HRSs: China possesses independently developed and manufactured 35 MPa HRSs, and the development of experimental 70 MPa hydrogen stations has also been completed. Compressors: China has independently developed and manufactured 45 MPa low-flow compressors and gained the capacity to independently construct medium-flow compressors by importing a few critical parts. Experimental 87.5 MPa compressors have also been constructed in China. Permanent HRSs: China has full intellectual property rights to the design and production of 45 MPa and 98 MPa permanent hydrogen storage vessels. In particular, 45 MPa storage vessels with water volumes up to 20 m^3 and service life ratings of >50 000 refills have been constructed, and 98 MPa permanent hydrogen storage vessels up to 1 m^3 have been made in China. In addition, a few enterprises already have the capacity to optimize HRS control algorithms and integrate hydrogen products. At present, the usable hydrogen capacity of an HRS can reach 70%–75%.

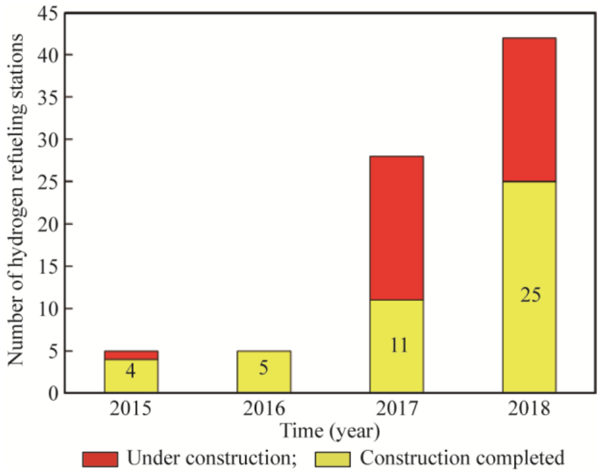

Fig. 1. The construction of hydrogen refueling stations in China (as of March 2019).

Table 1. Distribution of hydrogen refueling stations in China.

City	Number of stations
Dalian	1
Zhangjiakou and Baoding	2
Beijing	1
Weifang	1
Zhengzhou	1
Yancheng, Nantong, Changshu, and Zhangjiagang	5
Shanghai	3
Wuhan and Shiyan	3
Chengdu	1
Foshan, Yunfu, and Zhongshan	7

3.3 Local hydrogen energy policies have been introduced, and a regional hydrogen supply network is beginning to emerge

Fourteen provinces (cities) in China have already begun to deploy and promote their hydrogen industries, including Guangdong, Shandong, Jiangsu, Hubei, Hebei, Shanxi, Zhejiang, Sichuan, Beijing, Tianjin, Jilin, Liaoning, Anhui, and Henan. Many of these regions have introduced supportive policies, established fuel cell or automobile industries, initiated the construction of HRSs, and launched demonstration projects. For example, Foshan City in Guangdong Province already has a comprehensive set of industrial policies, and the Provincial Government of Guangdong also issued the *Opinions on Accelerating the Development of Innovations in the NEV Industry* on June 2018, which stated that electrolytic hydrogen production plants will enjoy the same electric tariffs as cooling-related applications. The People's Government of Nanhai District (Foshan City) promulgated the *Measures for Promoting the Construction and Operation of Hydrogen Refueling Stations and the Operation of Hydrogen Energy Vehicles*, which established subsidies of up to 8 million CNY and 20 CNY/kg for the construction and operation of HRSs, respectively. The introduction of regional plans and policies has been conducive for the construction of a regional hydrogen supply network, and they have also accelerated the cultivation of an ecosystem for the hydrogen industry.

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4 Lessons from the hydrogen infrastructure developments of other countries

4.1 Japan

The *Strategic Road Map for Hydrogen and Fuel Cells* released by Japan provides a detailed description of Japan's 2014–2040 development targets with regard to hydrogen production, hydrogen storage/transportation, hydrogen filling and hydrogen use, as well as their approaches for achieving these targets. In terms of hydrogen energy infrastructure, this road map has also set hydrogen production and HRS construction targets based on the energy resource endowments of Japan: By 2030, Japan plans to have 1000 HRSs, reduce the cost of each HRS to 200 million JPY, and reduce the cost, insurance, and freight (CIF) price of hydrogen in Japan to < 30 JPY/m^3.

As of 2018, Japan has already constructed 106 HRSs, with 80 being open to the public and the remainder being reserved for buses and fleet customers [4]. Each of these HRSs currently cost 400–500 million JPY, and the Japanese government subsidizes approximately one-half of this cost.

4.2 Germany

As of the end of the end of 2018, there are 152 operational HRDSs in Europe [5], with 60 of these in Germany alone. In 2018, 17 HRSs were put into operation in Germany, thus giving Germany the second largest number of HRSs in the world [4]. Furthermore, Germany intends to construct 400 HRSs by 2023 to cover 60% of the German population, and 1000 HRSs by 2030 to cover all of Germany.

In 2006, the German government launched the *National Innovation Programme for Hydrogen and Fuel Cell Technology* (NIP), which was assigned a budget of €1.4 billion for projects up to 2016. A research program on the hydrogen supply infrastructure of Germany was then initiated in 2009, followed by the announcement of an implementation road map at the end of 2011. On February 2015, 27 enterprises joined hands to launch the H2 Mobility (H2M) company, whose aim is to commercialize and promote the hydrogen industry. With the support of the German government, H2M has planned a nationwide hydrogen refueling network, and they have begun work on the construction and operation of HRSs. Their goal is to construct an HRS network consisting of 429 HRSs that will cover all of Germany, with one HRS every 90 km. The implementation of this plan has been divided into three stages: validation, test launch, and commercial launch. In addition, the asset allocation schemes for financing, procurement, operation, and market competition have been planned in detail. H2M will continue to invest in and operate HRS projects in Germany, until the HRS business begins to become profitable. The resources of H2M will then be assessed and made available for repurchasing (with priority given to the companies that participated in the H2M joint venture) to establish a market-led mode of development in Germany's hydrogen industry.

4.3 The United States of America

Ever since the US Department of Energy (DOE) invested 6.3 billion USD in clean energy research (including hydrogen energy and fuel cells) in 2012, the DOE has worked with US universities and enterprises to jointly conduct research on key hydrogen energy and fuel cell technologies, which culminated in the formation of the Fuel Cell and Hydrogen Energy Association (FCHEA). In 2013, the DOE launched the H2USA plan in conjunction with car makers and other stakeholders to jointly formulate detailed plans for the establishment of a hydrogen fueling infrastructure in the US, as well as financing schemes and market expansion plans to this end. The ultimate aim of the H2USA initiative is to place the US at the forefront of integration technologies and equipment manufacturing for hydrogen infrastructure. As of today, the US has 42 operational HRSs that are open to the public [4]. Besides, there are some private HRSs in the US, the number of which is currently unknown.

4.4 South Korea

On January 2019, the South Korean government announced the *Hydrogen Economy Plan*, whose aim is to create the world's most advanced hydrogen economy in South Korea through a set of milestones from 2022 to 2040. This plan provides a detailed description of South Korea's development targets and implementation pathways for all parts of their hydrogen industry. The 2022 milestones of the plan include a total hydrogen supply of 4.7×10^5 t/a, a hydrogen price of 6000 KRW/kg, and 310 operational HRSs. By 2040, South Korea aims to have a total hydrogen supply of 5.26×10^6 t/a, a hydrogen price of 3000 KRW/kg, and more than 1200 operational

HRSs. In addition, South Korea plans to domestically manufacture all of the core equipment for their hydrogen infrastructure and construct a hydrogen pipeline network that will cover all parts of South Korea to facilitate the distribution of hydrogen gas on a large scale.

In this plan, HRSs have been divided into hydrogen pipeline stations, tube trailer stations, and integrated electrolytic hydrogen production and refueling stations, according to their hydrogen supply modes. The construction and operation of HRSs are also subsidized by this plan, and the maximum subsidies for HRS construction and operation are 2.9 billion KRW and 220 million KRW, respectively. The Hydrogen Economy Plan also seeks to improve the layout of South Korea's HRS network. To this end, it has encouraged the construction of mixed natural gas and hydrogen refueling stations, permitted the installation of HRSs in bus stops within restricted areas, and promoted to gradually decrease the safety distance for hydrogen refueling stations. In addition, the South Korean government has implemented various measures (including standardization, laws, talent, international cooperation and industrial ecosystems) to comprehensively increase public awareness about hydrogen safety and improve industrial safety management systems.

5 Challenges faced by the hydrogen infrastructure industry in China

5.1 Lack of a systematic development strategy

The positioning of hydrogen energy in the energy production and consumption system of China has yet to be clarified, which will prevent hydrogen energy from having the effect it should have had in China's energy revolution. Furthermore, a systematic set of development goals and implementation pathways have yet to be established for the hydrogen energy and fuel cell industries, which is not conducive for maximizing the utility of current industrial factors, nor the establishment of policy safeguards for industrial development.

5.2 China is lagging behind in terms of the number and performance of its hydrogen refueling stations

The number of HRSs that have been constructed in China is only one-fourth that of Japan and far behind those of Germany and the US Most of the HRSs in China are test stations and skid-mounted stations, which tend to have low hydrogen storage capacities and low-performance hydrogen compressor systems. As the size of China's hydrogen car fleet grows larger, the HRSs in China will not be able to meet the demands of commercial applications, which typically involve random entry times and require short refueling time. In skid-mounted stations, refueling time completely depends on the hydrogen pressure of the hydrogen tube trailer and the system's compression performance. As the hydrogen pressure of the hydrogen tube trailer will decrease in continuous refueling scenarios, the system's compression performance will also decrease in proportion, which increases the refueling time of each vehicle.

5.3 Breakthroughs are urgently needed in critical technologies and the cost of hydrogen

Although China already possesses the key technologies and equipment integration capabilities needed to produce 35 MPa HRSs, China is still lagging behind other advanced nations in its domestic manufacturing capabilities and certain metrics.

(1) Compressor technology: The 45 MPa compressors that are completely made in China are only capable of relatively low flow rates, and they have high failure rates in actual use. Furthermore, some of the key components for these compressors must be imported for further assembly in China. In addition, there are no domestic manufacturers with the capability to produce 87 MPa compressors.

(2) Permanent hydrogen storage tanks: Most of the hydrogen storage equipment in China are steel-lined filament wound tanks. Consequently, 45 MPa and 98 MPa permanent hydrogen storage tanks cost more than 0.2 million CNY and 1 million CNY per cubic meter water volume, respectively.

(3) Hydrogen refueling technologies: All hydrogen refueling nozzles must be imported, as Chinese-made 70 MPa refueling nozzles are still being tested and validated. Furthermore, the specifications of Chinese-made refueling nozzles are far inferior to the 70 MPa refueling nozzles that are in commercial use in other countries. In addition, the high-pressure pipes and valves used in China's hydrogen infrastructure must still be imported, and the process control systems in China's HRSs still require further validation and optimization through commercial operation.

Furthermore, China does not have an adequate set of standards for 70 MPa HRSs, hydrogen gas inspections, hydrogen pipelines, and the assessment of HRS projects for investment and financing. This is because China has

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yet to fully master hydrogen infrastructure technologies and lacks confirmatory data.

5.4 Management and monitoring systems have yet to be established for the hydrogen industry

HRSs are urban infrastructure-type fixed asset investments. Given the amount of investment involved in HRSs, these projects will be managed according to their filing type in most areas of China, and the filling authority for HRS projects is generally devolved to district and county-level governments. During the project verification period, all environmental impact, planning, safety, energy conservation, land, and stability preservation assessments must be completed. During the construction application stage, the project must be approved by the bureau of planning, bureau of housing, fire department, bureau of work safety, and department of market regulation. Approval must be gained for all of the aforementioned items before a project can become operational. However, actual references and case examples for the evaluation of HRS projects are scarce, and there is a lack of technical evidence and standards at all levels. Consequently, HRS projects often encounter difficulties and long application times during the approval process. Mature safety supervision systems already exist for hydrogen production facilities, due to their long service as ancillary facilities in large chemical engineering, electronics, and energy projects. However, a safety supervision system has yet to be established for HRSs, which are hydrogen distribution points for urban transport systems. This imbalance will be detrimental to the high-quality development of the hydrogen industry.

5.5 Studies about business models and sustainable pathways for the hydrogen industry are urgently needed

Owing to the complexity of the hydrogen filling process, the investment and operational costs of an HRS are far greater than those of a natural gas station. A simple permanent HRS with a hydrogen refueling capacity of 600 kg per day costs more than 10 million CNY in essential equipment and engineering costs alone, and its static total investment may reach 15 million–20 million CNY. Fig. 2 illustrates the predicted break-even curves for an HRS for a variety of static total investments, daily hydrogen sales, and sale margins. It is shown that a 600 kg HRS with a static total investment of 12.5 million CNY will break even if the sale margin (hydrogen sale price minus hydrogen purchase price) is 14.35 CNY/kg, assuming an ideal state of operation (full load at all times). If the static total investment of the HRS is 22 million CNY, a sale margin of 19.25 CNY/kg is required to break even. If the HRS is small and has high non-technical costs (e.g., land price), such that 17.5 million CNY is required to construct a 400 kg HRS, a sale margin of 24.35 CNY/kg is then required for the HRS to break even, even if one assumes an ideal state of operation. As the hydrogen demands of the market are currently quite low, and the equipment and processes of HRSs in China have yet to undergo stability validation under high-load operation, it is likely that the operational costs of an HRS will exceed these theoretically predicted values and current empirical values.

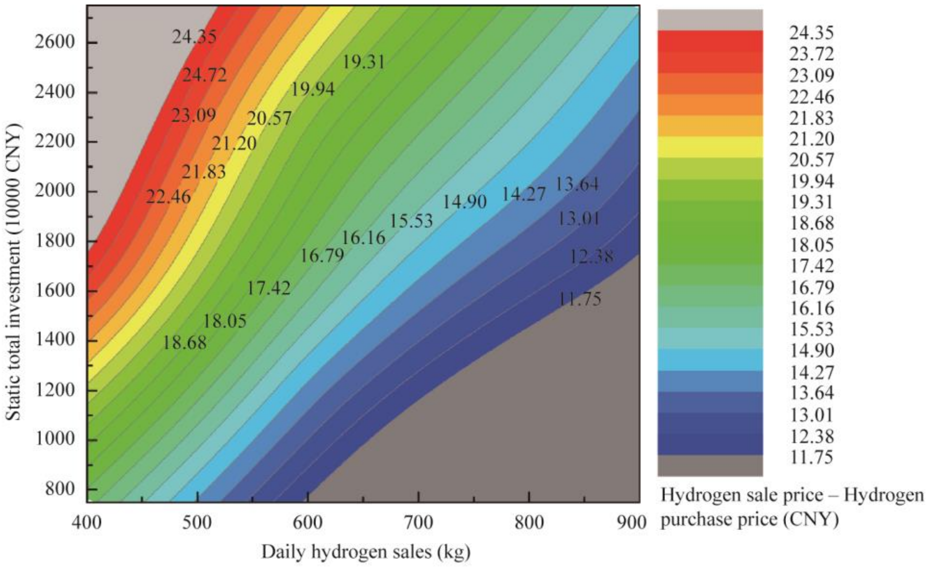

Fig.2. Predicted break-even curves based on the key parameters of a hydrogen refueling station.

Note: The methods of assessment are based on the third edition of the *Construction Projects Economic Evaluation Method and Parameter* and China's current fiscal and taxation systems. The selection of assessment parameters was based on the investment decision management system of CHN Energy, as well as the *Economic Evaluation Parameters of China National Petroleum Corporation Construction Project* and current engineering experience.

If hydrogen sale prices are set according to the operational cost of petrol cars, it is extremely difficult for an HRS to break even without subsidies, owing to the current cost of hydrogen production and transportation. Therefore, it is unlikely that the hydrogen industry will be sustainable if the industry simply relies on a simplistic business model (i.e., invest in HRSs, purchase hydrogen from external sources, and sell hydrogen at HRSs). Furthermore, it will be difficult to reduce hydrogen supplying costs, if no efforts are made to optimize the hydrogen infrastructure to synergize hydrogen production, storage, and refueling. These issues are generally detrimental to the sustainability of the hydrogen industry.

6 Strategies for the hydrogen infrastructure industry of China

6.1 Development goals and pathways for the hydrogen infrastructure industry

In the next 30 years, the development of China's hydrogen infrastructure industry will occur in three stages.

First stage (present day–2025): During this period, a clear top-level road map will be formed, and most of the necessary industrial policies will be established. Safety supervision systems will be established, as well as fair and orderly market competition. Business model innovations will emerge continuously. Furthermore, industrial agglomeration will accelerate, and the production of critical equipment and technologies for hydrogen refueling will be moved to local enterprises. In this way, robust foundations will be established for the sustained development of the hydrogen infrastructure industry.

In this stage, the positioning and strategic goals of hydrogen energy in China will be defined. Guiding opinions, approval management, and fiscal/tax incentives will be established for the development of the hydrogen industry at all levels. Furthermore, an informatization-based safety network will be established for the national hydrogen infrastructure of China. The development roadmap for this stage is as follows. During this stage, most of China's hydrogen supplies will be sourced from the hydrogen by-product of industries around the cities, as well as the small-scale fossil fuel reforming facilities that are ancillary to the chemical engineering and electronics industries. These hydrogen supplies will be supplemented with electrolytic hydrogen in a few regions. During this period, most of China's hydrogen supplies will be stored at 20 MPa. 45 MPa hydrogen storage/transportation technologies and standards will be refined and validated for practical use. HRSs will first be constructed in cities that were included in demonstration projects, and there will be more than 100 publicly accessible commercial HRSs. China will also gain full mastery over the technology for 70 MPa hydrogen filling nozzles, 90 MPa compressors with average flow rates greater than 200 m^3/h, and 45 MPa compressors with average flow rates greater than 800 m^3/h. Almost all of these critical equipment and technologies will be manufactured domestically.

Second stage (2025–2035): Sound industrial policies will be put in place, as well as comprehensive supervision and management mechanisms for the hydrogen infrastructure industry. Fair and orderly market competition will be present, and the business models of the industry will have matured. All of the critical equipment and technologies for hydrogen refueling will be produced domestically, and a highly efficient, safe and cost-efficient hydrogen supply network will be developed. These developments will serve as the cornerstone for the high-quality development of the hydrogen infrastructure industry.

In this stage, sound and mature industrial policies and supervision/management mechanisms will have been established. Furthermore, subsidies and fiscal incentives will begin to be withdrawn, as the hydrogen infrastructure industry will be poised in a market-driven state of development, where orderly market competition is present and gradually intensifying. The development roadmap for this stage is as follows. The hydrogen supplies of China will mainly be derived from large concentrated sources of hydrogen like coal gasification (combined with CCS technology in some instances) and green electrolytic hydrogen, with industrial by-product hydrogen being used as a supplementary source of hydrogen. All potential sources of hydrogen that exist in the market will be fully utilized. In this way, a scenario that requires large-scale hydrogen transportation will be created. Work will then begin on the construction of a highly efficient, safe, and cost-efficient national hydrogen supply network. Hydrogen storage and transport will be conducted at pressures of 45 MPa or more, and the technologies and standards for liquefied hydrogen transport/storage will be comprehensively refined. Long-distance liquefied hydrogen transport and liquid hydrogen refueling stations will come into use. A national hydrogen refueling backbone will begin to emerge, and there will be more than 1000 publicly accessible commercial HRSs in operation. All critical hydrogen infrastructure equipment and technologies will be produced in China, and China will lead the world in hydrogen technology.

Third stage (2035–2050): A highly efficient low-carbon hydrogen supply network will be formed, and the

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hydrogen infrastructure industry will be poised in a high-quality, market-led state of development, with scientifically sound regulations and market mechanisms. The development road map is as follows. The hydrogen supplies of China will be dominated by renewably-generated hydrogen (e.g., hydrogen produced by solar water splitting technology) and supplemented by hydrogen from coal gasification (combined with CCS technology). In each region, a suitable "deep green" hydrogen supply solution will be selected according to the state of industrial and resource development in that region, which will then be matched a suitable hydrogen transport solution (e.g., urban hydrogen pipelines). The industrial, power, construction, and transportation sectors will ultimately be integrated with the hydrogen supply network, to varying degrees. A hydrogen refueling network that covers all of China will be formed, and there will be more than 10 000 commercial, publicly accessible HRSs throughout China. China will now lead the world in HRS equipment and technologies.

6.2 Recommendations

6.2.1 Strengthen strategic studies on the hydrogen industry

Research on the integration of hydrogen energy into the energy system of China should be accelerated, so that hydrogen energy will become an important component of China's energy strategy. In addition, a detailed road map should be drawn up for the development of the hydrogen industry. Strategic studies should be performed to determine the contributions of the hydrogen industry towards the realization of a green, low-carbon and circular economy in China, driving China's energy revolution, and the establishment of China as a strong manufacturing power. Scientific analyses should be conducted to create a technical roadmap, timetable, and list of key tasks for high-quality, sustainable development in the hydrogen infrastructure industry. Importance should be paid to the planning of highly efficient, safe, low-carbon, and circular hydrogen supply networks and use cases, to deeply integrate hydrogen energy with the industrial, electric power, construction, and transportation sectors. Hydrogen energy should be tightly integrated with the deployment of modern economic systems in China, to provide a strong start for the hydrogen infrastructure industry and to ensure that the implementation of hydrogen energy is high quality and sustainable. In addition, studies should be performed to conceive work plans for the major National Science and Technology projects on hydrogen energy and fuel cell development.

6.2.2 Establish sound industrial policies, safety supervision systems, and technical standards

The relevant ministries and commissions should jointly promulgate guiding opinions for the development of the hydrogen industry, thus strengthening cooperation between administrative agencies at all levels. Top-down management and technical demonstration schemes for key approval items (like safety evaluations) should be established to construct a specialized "safe and green" approval channel for hydrogen infrastructure projects. The refinement of a system of standards for hydrogen energy in China should be accelerated to further improve standards related to the design, construction, and acceptance of hydrogen infrastructure. Guiding opinions for the incorporation of HRSs into urban construction plans should be based on current guiding opinions for charging facilities and should be promulgated as soon as possible. The establishment of third-party testing mechanisms should be sped up. Efforts should be made to establish robust industry entry and exit mechanisms, quality tracking systems for hydrogen infrastructure and equipment, quality and safety evaluation for enterprises in the hydrogen industry, and producer responsibility extension systems, which shall be interlinked with subsidy policies and financial support. The possibility of establishing an all-encompassing informatization-based safety supervision platform for hydrogen energy should be explored. Context-dependent guidance should be provided to gradually remove restrictions on the location of electrolytic hydrogen production stations, which are currently limited to chemical industry parks. Hydrogen energy should be promoted further in popular science, so as to establish an amicable atmosphere for the development of the hydrogen industry and attract societal resources.

6.2.3 Establish long-term mechanisms that will facilitate independent research and development on key technologies and core equipment for the hydrogen infrastructure

Research platforms like national engineering and technology centers, national laboratories, and national manufacturing and innovation centers should be jointly established by key enterprises in the hydrogen industry, scientific institutes, and universities to facilitate collaborative research on critical hydrogen infrastructure technologies, and establish intellectual property sharing mechanisms with respect to hydrogen energy. In this way, intellectual properties that are currently idle and scattered between different institutions and enterprises can be shared efficiently, thus maximizing the value of these resources. National and regional key research and development programs should increase support for research on critical hydrogen energy technologies and equipment. The establishment of hydrogen industry demonstration zones should be supported in regions that possess the requisite conditions, so that they can utilize their inherent advantages to accelerate industrial agglomeration and deploy major hydrogen energy demonstration projects that will serve as leading beacons in this industry. International exchanges should be strengthened, and the implementation of major scientific programs and projects on hydrogen energy should be encouraged to form mechanisms for international cooperation.

6.2.4 Increase subsidies and financial support for all parts of the hydrogen infrastructure industry

A scientific reference for adjudging investment benchmarks (e.g., benchmark yield) in each link of the hydrogen industry chain should be established as soon as possible, and a market-dominated and policy-driven approach to developing the hydrogen industry should be maintained. Furthermore, quality assurance measures should be strengthened, and a scientifically informed set of subsidy policies and subsidy withdrawal mechanisms should be established progressively. The possibility of reducing the value-added tax (VAT) on hydrogen to that of natural gas should be explored, and a 50% VAT drawback policy may also be considered for the hydrogen industry. HRSs should be included in the list of state-supported public infrastructure so that enterprises in the hydrogen industry will be able to enjoy a three-year tax exemption and half-tax for the next three years. The base electricity tariff for electrolytic hydrogen production should be gradually eliminated. In addition, the establishment of an electricity trading mechanism between hydrogen production enterprises and ultra-low-emission units/renewable energy projects should be explored, especially for power production units that exceed the guaranteed utilization hours of their respective regions or have achieved grid parity, thus allowing these power production units to maintain power production efficiency during valley periods. Investment channels for the hydrogen industry should be expanded to encourage the formation of a diverse investment system consisting of governmental financing platforms and societal resources, and each locality should be supported in setting up special funds for the development of the hydrogen infrastructure industry. Furthermore, each region should also be encouraged to provide financial incentives, risk compensation, and financing discounts for cutting-edge hydrogen infrastructure/equipment manufacturers, and hydrogen transportation/storage/refueling projects that are pioneering research findings from National Science and Technology Projects.

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