博士論文

Economic and environmental evaluation on the application of hydrogen in Shanghai

上海市における水素利用の経済性･環境性の評価に関する研究

北九州市立大学国際環境工学研究科

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ECONOMIC AND ENVIRONMENTAL EVALUATION ON THE APPLICATION OF HYDROGEN IN SHANGHAI

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ABSTRACT

Under the development goal of "carbon peak in 2030 and carbon neutrality in 2060" clearly proposed by China, hydrogen energy, as one of the intermediate forms of energy, is the best energy application carrier to achieve large-scale and deep decarbonization in transportation, construction, energy and other fields. Therefore, expanding the application of hydrogen in multiple scenarios and improving the utilization rate of hydrogen will be an inevitable development trend. However, at present, the development of hydrogen application is limited by technological and economic factors. Therefore, this paper takes Shanghai as the research object, evaluates the economic and environmental effects of hydrogen energy application in different forms in different fields, and analyzes the potential of hydrogen energy applications in Shanghai, with a view to providing reference for the development of hydrogen energy in other cities.

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THIS STUDY. This chapter analyzes the hydrogen energy development strategies of countries and regions such as the United States, the European Union, Japan, South Korea, and China, and clarified that each country is actively promoting the research and industrialization of hydrogen energy technology, seizing the opportunity and commanding heights of industrial development. Then, a study was conducted on the environmental and economic assessment of hydrogen energy application in Shanghai, which already has a foundation for hydrogen energy development, with a focus on analyzing the current situation of hydrogen energy application and supply in Shanghai. Finally, the research logic and content of the article were explored.

In Chapter 2, LITERATURE REVIEW OF HYDROGEN APPLICATION. This chapter analyzes the application methods of hydrogen energy and its main applications in industries, transportation, construction, energy, and other fields. Then, the application and research status of Hydrogen fuel cell vehicles and their infrastructure Hydrogen station, which are relatively mature in the transportation field, as well as the application and research status of Hydrogen fuel fuel cell Cogeneration system, hydrogen burning and hydrogen doped gas turbines, are emphatically analyzed.

In Chapter 3,THEORIES AND METHODOLOGY OF THE STUDY .Firstly, the main load forecasting methods currently used were introduced and analyzed, and a load forecasting model and load forecasting accuracy evaluation model were constructed. A load forecasting method based on the PSO-GRU neural network model was proposed and validated. Secondly, the equipment models of hydrogen energy systems such as photovoltaic Hydrogen station, Hydrogen fuel cell Cogeneration system and hydrogen doped gas turbine are established. Then, the development prediction methods were introduced and analyzed. Finally, an economic and environmental analysis model was constructed to provide a theoretical basis for subsequent chapters.

In Chapter 4, RESEARCH ON THE APPLICATION EFFECT EVALUATION OF PHOTOVOLTAIC-HYDROGEN REFUELING STATION BASED ON HYDROGEN LOAD ANALYSIS.This chapter takes a hydrogen refueling station in Shanghai with a supply capacity of 500kg/day as the research object. Based on the analysis of the all-day hydrogen demand characteristics of the station, the system configuration, operation strategy, and socio-economic benefits of the photovoltaic hydrogen refueling station are studied and analyzed. Compared with conventional hydrogen refueling stations, photovoltaic hydrogen refueling stations have better socio-economic benefits. When the price of hydrogen is not less than $6.23, the photovoltaic hydrogen production and refueling station project has good economic benefits. Compared with traditional fuel vehicles, hydrogen fuel cell vehicles fueled by this refueling station can reduce carbon dioxide emissions by approximately 2737.5 tons per year. Meanwhile, compared to hydrogen refueling stations, photovoltaic hydrogen production and refueling stations can reduce carbon emissions by approximately 1237.28 tons per year, which has good social benefits.

In Chapter 5, RESEARCH ON THE APPLICATION EFFECT EVALUATION OF HYDROGEN FUEL CELL COGENERATION IN AIRPORT TERMINAL BUILDING. This chapter takes an airport terminal in Shanghai as an example, first analyzes the load characteristics and space-time characteristics of the terminal building, forecasts and analyzes the 8760 hour and typical daily load of the terminal in each season, and then focuses on the research and analysis of the equipment configuration scheme, operation optimization strategy, and economic and social benefits of the hydrogen fuel fuel cell cogeneration system when the cost price of hydrogen decreases by 0%, 50%, and 70%. When the price of hydrogen decreases by 50%, compared to the original price of hydrogen, the annual total cost decreases by about 20.8%, which has certain economic benefits. When the hydrogen price drops by 70%, the total annual cost will be reduced by about 46.2% compared with that under the original hydrogen price, the annual carbon emission can be reduced by about 5800000 tons, with good economic and social benefits.

In Chapter 6, RESEARCH ON THE APPLICATION OF NEAR ZERO CARBON ENERGY SYSTEM IN INDUSTRIAL PARKS BASED ON HYDROGEN-FUELED GAS TURBINES. Based on the feasibility study of hydrogen doped gas turbine application, it is known that under the condition that the current carbon emission trading cost is 8.2 \$/t and the hydrogen cost price is 0.432 $\$/m^3$, the higher the hydrogen doping proportion, the higher the carbon reduction amount, but the higher the economic cost, the application of hydrogen doped gas turbine is not economical. Then, under the demand of "Zero carbon" Park construction, taking an industrial park in Shanghai as the research object, the application effect of the combination of hydrogen turbine and photovoltaic system on the construction of "Near zero carbon" Industrial parks and the impact of carbon emission trading prices on the application of gas turbines were studied. The results indicate that the application of hydrogen turbine systems is economically feasible when the carbon emission price is 8.2 \$/t and the cost price of hydrogen is not less than 0.1471 $\$/m^3$. As for gas turbine, its economy will be affected with the increase of carbon emission trading price. Under the condition that the natural gas price is

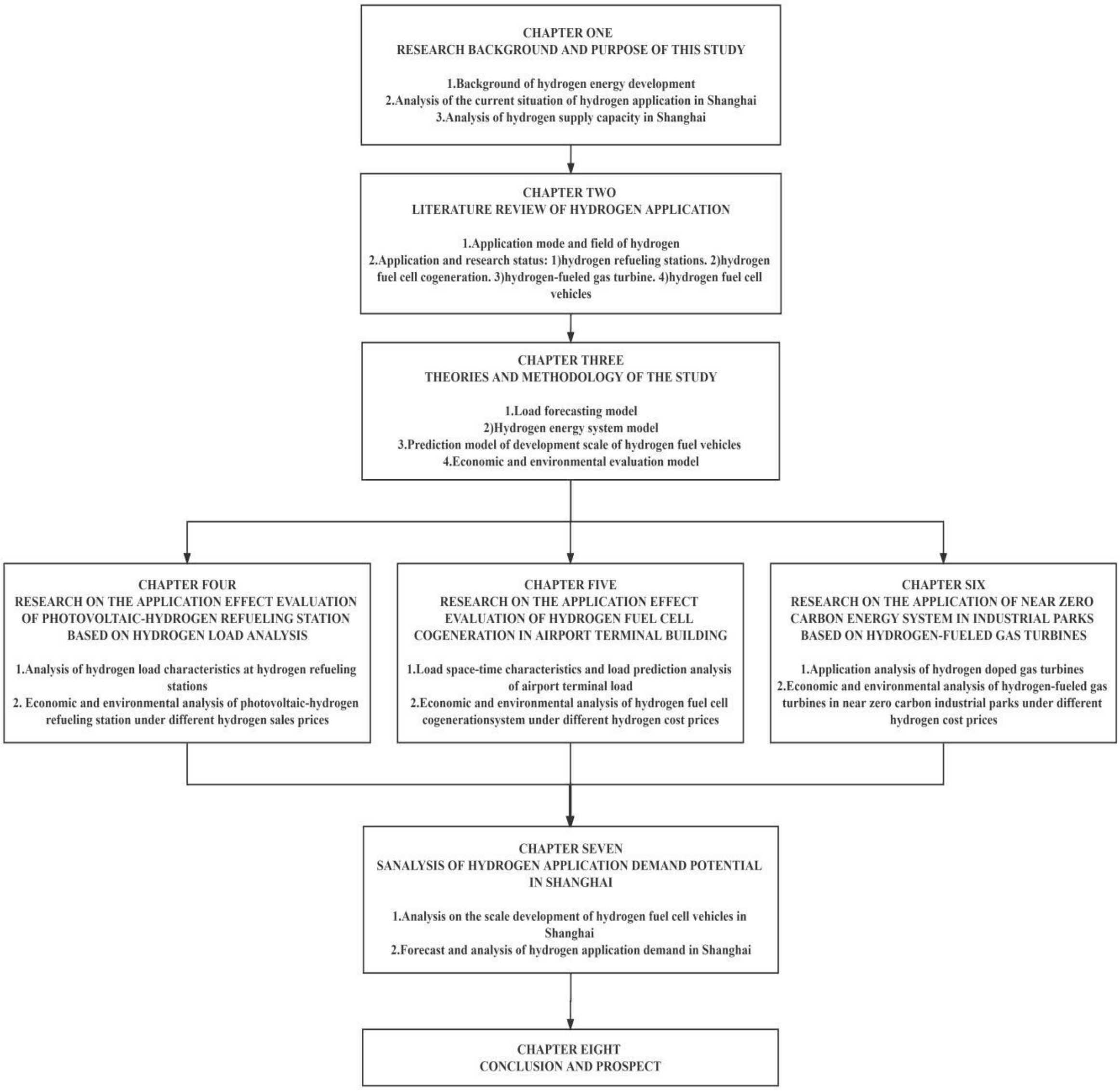
0.42 \$/m3, when the carbon emission trading price is not less than 42.15 \$/t, the gas turbine system will not have economy.

In Chapter 7, ANALYSIS OF HYDROGEN APPLICATION DEMAND POTENTIAL IN SHANGHAI. In view of the fact that hydrogen fuel cell vehicles are the most mature hydrogen use mode for hydrogen energy application in Shanghai, this chapter first carried out in-depth research on their development scale based on SWOT analysis, put forward development goals and recommendations, and defined two scenarios for the development of hydrogen fuel cell vehicles: the baseline scenario and the high scenario. Then, the development scale and hydrogen demand of hydrogen fuel cell vehicles in Shanghai under two scenarios are predicted and analyzed. Finally, based on the feasibility and development trend of hydrogen energy application in different fields, the proportion relationship of hydrogen demand in each field at different stages was clarified, and the total hydrogen energy demand in Shanghai was predicted and analyzed.

In Chapter 8,CONCLUSION AND PROSPECT. The chapter summaries the research of the previous chapters. On this basis, the future development of hydrogen application is prospected.

宋 麗斐 博士論文の構成

ECONOMIC AND ENVIRONMENTAL EVALUATION ON THE APPLICATION OF HYDROGEN IN SHANGHAI



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Chapter 1

RESEARCH BACKGROUND AND PURPOSE OF THIS STUDY

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1.1 Research background

According to the latest released "China Climate Change Blue Book (2021)", global climate change has reached a critical point of 1.2 degrees Celsius in 2020, only 0.3 degrees below the critical point of 1.5 degrees Celsius temperature rise stipulated in the Paris Agreement. The average temperature on the land surface in Asia is 1.06 degrees higher than usual, making it the warmest year since the beginning of the 20th century. Therefore, in the face of the increasingly severe global climate change situation, promoting low-carbon transformation has become a consensus for global sustainable development[1][2]. At the 75th UN General Assembly in September 2020, China clearly put forward the goal of "carbon peak in 2030 and carbon neutralization in 2060", which demonstrated the image of China as a responsible power. As an ideal interconnected medium for promoting the clean and efficient use of traditional fossil energy and supporting the large-scale development of renewable energy, as well as the best energy carrier for large-scale and deep decarbonization in transportation, industry and construction[3][4], hydrogen is a strategic choice to ensure national energy security and achieve high-quality economic and social development.

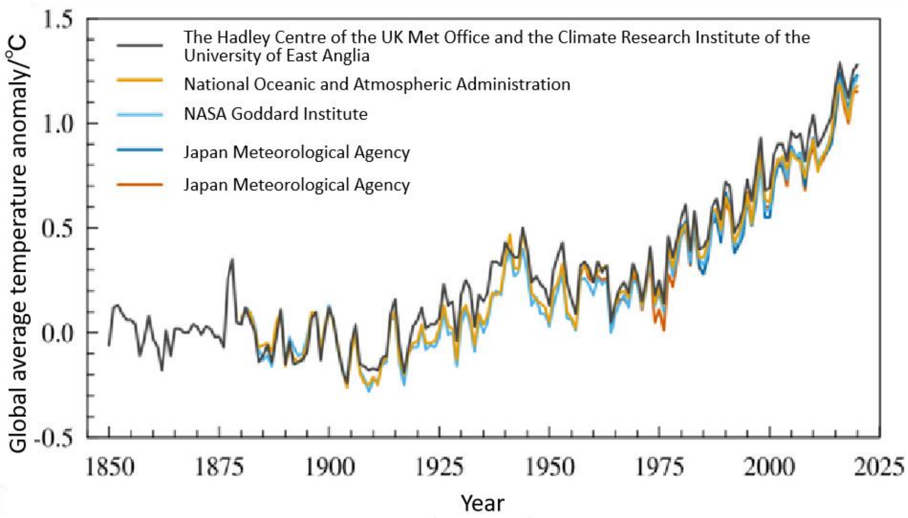

Fig.1-1 Global average temperature rise[5]

The United States hydrogen energy has risen to the national strategic level and issued the Hydrogen Energy Project Plan in 2020, which is committed to the technology research and development of the whole hydrogen energy industry chain, and will increase demonstration and deployment efforts in order to achieve industrial scale[6]. According to the forecast of the US National Laboratory, by 2050, the domestic hydrogen energy demand in the United States will increase to 41 million tons per year, accounting for 14% of the total energy consumption in the future. Over the past 20 years, the U.S. Department of Energy has invested more than $4 billion in hydrogen and related fields, including hydrogen production, transportation, storage, and research and development of technologies such as fuel cells and hydrogen turbines[7].

Table 1-1 Current status and future consumption forecast of hydrogen energy in the united states (million tons/year) [8]

Application area	Consumption status 2020	Consumption forecast 2050
Petroleum refining	6	7
Metal smelting	Negligible	4
Synthetic ammonia	3	4
Biofuels/synthetic fuel	1	9
Transportation (fuel cell vehicles)	Negligible	17
Total hydrogen energy market	10	41

The European Union has been committed to the development of clean energy[9][10]. In recent years, the EU has actively made use of its own advantages to speed up the process of commercialization of hydrogen energy, and has gradually defined the development route of hydrogen energy. In 2020, the European Commission formally issued the policy document "Climate-neutral European hydrogen Energy Strategy", announced the establishment of the EU Clean hydrogen Energy Alliance, and formulated the EU road map for the development of hydrogen energy, promoting the development of hydrogen energy in three stages[11]. The first phase (2020-2024) involved the installation of at least 6 gigawatts of renewable hydrogen cells with a capacity of 1 million tons per year; the second stage (2025-2030), the installation of at least 40 gigawatts of renewable hydrogen cells with a production capacity of 10 million tons per year, has become an integral part of the European energy system; and in the third stage (2030-2050), renewable hydrogen technologies should be mature and deployed on a large scale to cover all industries that are difficult to decarbonize[12]. The European Union regards hydrogen energy as an important guarantee of energy security and energy transformation, and actively makes use of its own advantages to speed up the process of commercialization of hydrogen energy[13]. Based on its own advantages, the European Union has achieved fruitful results in the fields of hydrogen production, hydrogen storage and transportation, hydrogen utilization and fuel cells, and has formed a complete industrial chain[14].

In Japan's strategic path[15], hydrogen energy is not used as an alternative to fossil energy, but is committed to promoting the coupling and coordinated development of hydrogen energy, lignite and other fossil energy and renewable energy. The "hydrogen Energy / fuel Cell Strategic Development Roadmap" was issued in 2019[16][17], which describes in detail the three-step strategy for the use of hydrogen energy technology in Japan[18]. The first phase is to rapidly expand the use of hydrogen energy by 2025, with the aim of increasing the number of household fuel cell devices in Japan to 1.4 million and 5.3 million in 2020 and 2030 respectively, and to 100 fuel cell vehicle hydrogenation stations in 2015. The second stage is from mid-2020 to the end of 2030, the comprehensive introduction of hydrogen power generation and the establishment of a large-scale hydrogen supply system, which aims to reduce the price of hydrogen purchased overseas to 30 yen per cubic meter, expand the circulation network of commercial hydrogen in Japan, make full use of unused overseas energy to produce, transport, store hydrogen, and develop the hydrogen power generation industry in an all-round way. The third stage, starting from 2040, is the establishment of a hydrogen supply system with zero carbon dioxide, which aims to fully realize zero-emission hydrogen production, hydrogen transport and hydrogen storage by collecting and storing carbon dioxide. In 2020, Japan's hydrogen demand is close to 2 million tons, of which oil refining accounts for nearly 90 per cent of the demand, and the rest is ammonia production demand[19][20]. In April 2021, Japan has about 5600 FCEV vehicles, making it the fourth largest market in the world[21].

Committed to creating the world's largest transportation and power hydrogen fuel cell market, South Korea issued the Innovation and Development Strategic Investment Plan in 2018, listing the hydrogen industry as one of the three strategic investment directions. In 2019, the South Korean Ministry of Industry, together with other departments, issued the "Roadmap for hydrogen Economic Development", proposing to enter the hydrogen society in 2030 and take the lead in becoming the world leader in hydrogen economy[22][23][24]. According to the roadmap, the government plans to increase the cumulative production of hydrogen fuel cell vehicles to 6.2 million by 2040, increase the number of hydrogen refueling stations to 1200, expand fuel cell capacity to 15GW, and the price of hydrogen is about 3000 won / kg (about 17.6 yuan / kg). South Korea plans to invest 26 trillion yuan (about 15.2 billion yuan) to increase the promotion and popularization of hydrogen fuel cell vehicles within five years. In 2021, South Korea released its first basic Plan for hydrogen Economic Development, proposing that by 2050, hydrogen energy in South Korea will account for 33% of the final energy consumption and 23.8% of electricity generation, making it the largest source of energy exceeding oil. In 2020, South Korea produced and used more than 1.8 million tons of hydrogen, and almost all of its demand came from oil refining and petrochemical processes, making it one of the most active countries using hydrogen technology[25][26].

Since China entered the 13th five-year Plan, the position and route of hydrogen energy development policy has become clearer, rising to energy strategy and national innovation strategy[27]. In April 2016, the National Development and Reform Commission and the Energy Administration issued the Energy Technology Revolution and Innovation Action Plan (2016-2030), which raised the development of hydrogen energy to the national energy strategy for the first time. According to the White Paper on China hydrogen Energy and fuel Cell Industry (2019 Edition) issued by China hydrogen Energy Alliance in June 2019[28], it is proposed that by 2050, hydrogen energy will be widely used in transportation, energy storage, industry, construction and other fields. the demand for hydrogen has increased to about 60 million tons, and the output value of the hydrogen industry chain will expand the industrial output value of more than 10 trillion yuan. In 2050, the terminal sales price of hydrogen will drop to 20 yuan / kg, the number of hydrogenation stations will reach 12000, the number of hydrogen fuel cell vehicles will reach 30 million, the number of fixed power generation devices will be 20, 000 sets per year, and the production capacity of fuel application pool system will be 5.5 million sets per year. At the same time, it is pointed out that in the aspect of hydrogen energy application system, the field of transportation will serve as a breakthrough in the development of hydrogen energy downstream application market, and gradually expand to the fields of energy storage, industry and construction. Among them, hydrogen fuel cell commercial vehicles will take the lead in realizing the application and operation of industrialization. in addition to the incentive effect of the policy, hydrogen fuel cell passenger cars, logistics vehicles, heavy trucks and other models will achieve full life cycle economy equivalent to pure electric models by 2030 and win the purchase of market consumers. On March 23, 2022, the National Development and Reform Commission and the National Energy Administration jointly issued the medium-and long-term plan for the development of hydrogen energy industry (2021-2035)[29], which put forward the goals for all stages of the development of hydrogen energy industry: by 2025, basically master the core technology and manufacturing technology, the number of fuel cell vehicles is about 50, 000, a number of hydrogen refueling stations are deployed, and the hydrogen production capacity of renewable energy reaches 10-200000 tons / year. To reduce carbon dioxide emissions by 10-2 million tons per year. By 2030, a relatively complete technological innovation system and clean energy hydrogen production and supply system for the hydrogen industry will be formed, which will effectively support the realization of the carbon peak goal. By 2035, the multi-application ecology of hydrogen will be formed, and the proportion of hydrogen production from renewable energy in terminal energy consumption will be significantly increased.

It can be seen that countries around the world have launched policies to support the development of hydrogen energy, and the more economically and technologically leading countries such as the United States, Japan, South Korea and China have planned clear development goals[30]. At present, four regional hydrogen energy industry clusters have been formed in China, namely, Beijing-Tianjin-Hebei, East China, South China and Central China, in which the downstream application market of hydrogen energy is mainly in East China, South China and other developed cities.

Shanghai, as the largest city in China, is the forerunner of hydrogen energy development and attaches great importance to hydrogen energy development[31][32]. On June 20, 2022, in order to speed up the occupation of the new green and low-carbon track, vigorously promote the high-quality development of the hydrogen energy industry in Shanghai, and help achieve the goal of "carbon peak and carbon neutralization". The Shanghai Development and Reform Commission, the Municipal Science and Technology Commission, the Municipal Economic Information Commission, the Municipal Planning and Resources Bureau, the Municipal Housing Urban and Rural Construction Management Committee, the Municipal Communications Commission, the Municipal Emergency Bureau and the Municipal Market Regulatory Administration jointly formulated and issued the medium-and long-term plan for the development of Shanghai hydrogen energy industry (2022-2035)[33]. In key tasks (4) to build a diversified application pattern: clearly speed up the commercial application of hydrogen energy in the field of transportation, increase the promotion and application of hydrogen energy in the field of energy, actively promote alternative applications in the industrial field, and give priority to creating a number of world-class demonstration scenarios.

Under this background, this paper will take Shanghai as an example to study the application of hydrogen in transportation, architecture, energy and other fields, in order to provide reference for the promotion and application of hydrogen in other cities.

1.2 Analysis of the current situation of hydrogen application in Shanghai

This chapter will analyze the current situation of hydrogen application in Shanghai from four aspects: policy system, demand application, regional distribution, and industrial energy level.

(1) Policy System

Shanghai's hydrogen energy application policy system is being gradually improved, and it has deployed hydrogen energy industry development with hydrogen fuel cell vehicle industry development as the "front-runner".

1) In fuel cell application areas

In 2010, Shanghai took the World Expo as an opportunity to carry out hydrogen energy demonstration application, and Shanghai became a city that intervened in the field of hydrogen energy fuel cell earlier in China, and the relevant technology development technology is leading in China. By successively issuing policy documents such as "Shanghai fuel cell vehicle development plan", "Shanghai fuel cell vehicle industry innovation and development implementation plan", "Shanghai implementation plan for accelerating the development of new energy vehicle industry (2021-2025)" and "several policies on supporting the development of fuel cell vehicle industry in the city", it is clear that by 2025, the total number of fuel cell vehicle applications will exceed 10,000, and by 2025, the total number of fuel cell vehicle applications will exceed 10,000, more than 70 hydrogen refueling stations of various types will be completed and put into use, full coverage of key application areas will be achieved, and the city will become a global highland for fuel cell vehicle industry development. By 2030, the city will become a city with international influence in fuel cell vehicle applications. Thus, it is clear that hydrogen-fueled vehicles will be an important direction for the development of new energy vehicles in Shanghai, strengthen the brand of "Made in Shanghai", and accelerate the development of hydrogen energy industry[34].

2) Other hydrogen energy industry expansion areas

On June 20, 2022, in order to accelerate the seizure of the new green low-carbon track, vigorously promote the high-quality development of Shanghai's hydrogen energy industry, and help achieve the goal of "carbon peaking and carbon neutral", Shanghai Municipal Development and Reform Commission, Municipal Science and Technology Commission, Municipal Economic Information Commission, Municipal Planning and Resources Bureau, Municipal Housing and Urban-Rural Development Management Commission, Municipal Transportation Commission, Municipal Emergency Bureau and Municipal Market Supervision Bureau jointly formulated and issued the "Shanghai hydrogen industry long-term development planning (2022-2035)", the clear development goal is that by 2025, the number of fuel cell vehicles will exceed 10,000, the industrial scale of hydrogen energy industry chain will exceed 100 billion yuan, and the CO_2 emission reduction in the transportation field will be driven by 50-100,000 tons/year. By 2035, a rich and diversified application ecology will be formed in the fields of transportation, energy and industry, and a world-class highland of hydrogen energy science and technology innovation, industrial development and diversified demonstration application will be basically built[29].

In July 2022, the Shanghai Municipal People's Government issued the "Shanghai Carbon Peak Implementation Plan", proposing to cultivate and grow new energy, new energy vehicles, hydrogen energy and other green low-carbon cycle-related manufacturing and service industries in the in-depth promotion of industrial green low-carbon transformation. In promoting the carbon peak in the steel industry, it will accelerate the research and development of energy-saving and low-carbon technologies such as hydrogen-rich carbon cycle blast furnace, and explore the demonstration pilot of gas-based shaft furnace hydrogen smelting technology[35]. In accelerating the optimization of building energy use structure, promote diversified energy applications such as shallow geothermal energy, hydrogen energy and industrial waste heat. In promoting the low-carbon transformation of transportation equipment, actively expand the application of electricity, hydrogen and other clean energy in the field of transportation; continue to promote the demonstration, pilot and popularization of heavy cargo vehicles such as liquefied natural gas, biomass fuel and hydrogen fuel. By 2025, the total number of fuel cell vehicles in use will exceed 10,000. To explore the application of hydrogen, ammonia and other new energy sources in ocean-going ships.

(2) Demand Applications

The supply side of hydrogen energy in Shanghai has the basic condition of safe supply guarantee, but the demand of hydrogen energy lacks large-scale application.

1) Supply capacity

In terms of the total supply of hydrogen energy, the theoretical capacity of commercial hydrogen (not self-produced, mainly used for export) in Shanghai is about 160,000 tons/year, mainly concentrated in the chemical industrial zone in the southwest and Baosteel in the north. From the perspective of suppliers, there are five major suppliers: Shanghai Chemical Industrial Zone Industrial Gas Co., LTD., Shanghai Hualin Industrial Gas Co., LTD., Shanghai Secco Petrochemical Co., LTD., Shanghai Chlor-alkali Chemical Co., LTD., and China Baowu Group (Shanghai Base), forming an oligopoly supply pattern. From the viewpoint of the clean property of production capacity, although the hydrogen is mainly produced by industrial by-products and there is no hydrogen from green power production yet, in fact, the level of pollutant emission is low. On the one hand, as the final products of hydrogen production process in the city are hydrogen and carbon monoxide, among which carbon monoxide has already completed "carbon sequestration" as the raw material for producing phosgene in the chemical zone; on the other hand, the production of hydrogen by-products from chlor-alkali industry adopts the electrolysis of sodium chloride process, and the purity of hydrogen is generally above 99.99%, and the content of carbon monoxide is low[36]. There are no organic and inorganic sulfur components in fossil energy. In terms of supply price, the current billing price range of hydrogen energy for vehicles at hydrogen refueling stations is 40-60 RMB/kg, and the "Implementation Plan for the Innovation and Development of Shanghai Fuel Cell Vehicle Industry" proposes that the retail price of hydrogen in the city will be lower than 35 RMB/kg by 2023.

2) Demand side

At present, the hydrogen demand in Shanghai is mainly concentrated in the chemical and transportation fields, with a total hydrogen demand of about 140,000 tons/year.

In the chemical industry, the proportion of hydrogen used is more than 96%, and the current commercial hydrogen demand in the city is about 135,500-143,500 tons/year, which is concentrated in the chemical industry and Baosteel area, and Covestro, Henglian, BASF, INVISTA, Sinopec Shanghai Petrochemical, Chlor-alkali Chemical and Baowu (Shanghai base) are the main hydrogen users, mostly used as chemical raw materials such as reductants and oxidizers in various production processes.

In the transportation field, hydrogen is used as a clean energy source, and the amount of hydrogen used accounts for less than 1%. Shanghai actively carries out vehicle demonstration and promotion of various models and scenarios, forming a pattern of commercial vehicles mainly and passenger vehicles in parallel development. 2021, the number of hydrogen fuel cell vehicles promoted is 1483 (21% of the country), including 1006 logistics vehicles, 368 buses, 81 passenger cars and 28 postal vehicles, involving passenger car leasing, bus line operation, commuter/custom According to 81 passenger cars with hydrogen consumption of 1kg per 100km and 1402 commercial vehicles with hydrogen consumption of 5-8kg per 100km, combined with the annual mileage of the vehicles, the demand for hydrogen for vehicles in Shanghai at the current stage is about 300 tons per year.

(3) Regional distribution

Shanghai is located between 120°52 '- 122°12' east longitude and 30°40 '- 31°53' north latitude. It is located in East China, on the west coast of the Pacific Ocean, along the east coast of the Asian continent, and in the front of the Yangtze River Delta. It faces the East China Sea in the east, Hangzhou Bay in the south, Jiangsu and Zhejiang provinces in the west, and the Yangtze River estuary in the north. By June 2020, Shanghai supplies 16 districts, including Huangpu District, Xuhui District, Changning District, Jing 'an District, Minhang District, Baoshan District, Jiading District, Pudong District, Jinshan District, Songjiang District, Qingpu District, Fengxian District, Chongming District, etc.

Based on the "One Ring, Four Creations, Six Zones"[37] layout target of the "Shanghai Fuel Cell Vehicle Industry Innovation Development Implementation Plan", Shanghai has basically formed fuel cell vehicle industry gathering zones in Jiading, Qingpu, Jinshan, Lingang New Area, Pudong and Baoshan. Along with the implementation of "Shanghai Medium and Long-term Plan for Hydrogen Energy Industry Development (2022-2035)", the spatial layout of hydrogen energy industry will be created with "two bases in the north and south and three highlands in the east and west", among which "two bases" are two hydrogen preparation and supply guarantee bases in Jinshan and Baoshan. The "two bases" are two hydrogen preparation and supply guarantee bases in Jinshan and Baoshan; the "three highlands" are three industrial clusters in Lingang, Jiading and Qingpu. Among them, each region of Lingang, Jiading and Qingpu has defined its hydrogen application mode according to its own industrial development orientation and advantages. The new area of Lingang aims to carry out innovation demonstration of high-quality development of hydrogen energy in the whole region based on the advantages of early and pilot implementation, Jiading relies on the existing industrial advantages to strengthen the innovation and leading development of hydrogen energy automobile industry, and Qingpu relies on the geographical space advantages of Yangtze River Delta to build hydrogen energy industrial park.

Fig.1-2 Hydrogen energy industry space layout

Lingang New Area attaches great importance to the development of hydrogen energy industry, releasing the "Implementation Plan for Building a High-Quality Hydrogen Energy Demonstration and Application Scene in Lingang New Area (2021-2025)" in September, October and November 2021, the "14th Five-Year Plan for the Development of Hydrogen Fuel Cell Vehicle Industry in Lingang New Area of China (Shanghai) Pilot Free Trade Zone Plan (2021-2025)", "Several Measures for Accelerating the Development and Demonstration Application of Hydrogen Energy and Fuel Cell Vehicle Industry in Lingang New Area of China (Shanghai) Pilot Free Trade Zone", and other policy documents in July 2022, such as "Notice on the Work Plan of Science and Technology Insurance Innovation Leading Zone in Lingang New Area of China (Shanghai) Pilot Free Trade Zone"[38], and Laying out key projects such as China-Japan Hydrogen Energy Industry Demonstration Park, hydrogen bus demonstration operation in Lingang New Area, hydrogen logistics light truck demonstration operation, hydrogen heavy truck demonstration operation in ports, and fuel cell combined heat and power demonstration in top science and technology parks. The new area will focus on developing the science and innovation industry with fuel cell as the core, relying on the positive advantages of the system to open up the innovation scene and create a special industrial park, with a view to building a practice area for the high-quality development of hydrogen energy in Lingang.

In December 2021, Jiading District released several policy documents such as "Several Policies of Jiading District on Continuously Promoting the Development of the Automotive "New Four" Industry" and "Action Plan for Accelerating the Development of Hydrogen and Fuel Cell Vehicle Industry in Jiading District (2021-2025)", and laid out key projects such as the Volkswagen MEB Plant, Hydrogen Propulsion Technology Fuel Cell Electric Reactor and System Production, Faurecia Red Lake Exhaust System, and Shanghai Intelligent New Energy Vehicle Functional Platform, clear focus on hydrogen fuel cell vehicle operation and vehicle manufacturing, create a "hydrogen energy port" with world influence[39], build a leading area for innovation in the hydrogen energy vehicle industry in Jiading, and strive to exceed 50 billion yuan in annual output value of the whole industrial chain of hydrogen energy and fuel cell vehicles in 2025.

Qingpu District released the "Shanghai Qingpu District Hydrogen Energy and Fuel Cell Industry Development Plan"in October 2020, specifying that by 2025, fuel cell vehicles will account for no less than 30% of the replacement and new vehicles in the field of public transportation and sanitation, and no less than 1,000 demonstration operation vehicles. Fuel cell passenger vehicles will achieve a thousand-vehicle scale of commercial promotion and application. Promote and demonstrate applications in the field of hydrogen medicine and hydrogen agronomy. By 2030, the hydrogen energy industrial park will be built into a comprehensive hydrogen energy park with international first-class influence, and no less than 2,000 demonstration operation vehicles such as hydrogen fuel cell buses, logistics vehicles, long-distance freight and sanitation vehicles for municipal service purposes will be completed. The "5G+hydrogen energy" big data platform has been built, the coverage of the Yangtze River Delta hydrogen energy trading index has been improved, the influence of the index has been strengthened, and the industrial chain is in the leading position in the country. At the same time, the company has laid out a series of key projects, such as the smart hydrogen logistics project for hydrogen fuel cell heavy trucks and intercity logistics vehicles, and the demonstration application of hydrogen fuel cell in the transportation field in the demonstration area for commercial operation of hydrogen fuel cell vehicles, clearly exploring the development route of hydrogen energy in the logistics scene, and taking this as the starting point to plan and build the hydrogen energy industrial park serving the Yangtze River Delta[40], with a view to building the demonstration area for commercial operation of hydrogen energy in Qingpu.

Therefore, each district in Shanghai will form a special industry based on its hydrogen energy development orientation, and a pattern of hydrogen application is gradually forming with interdependence between regions.

(4) Industrial energy level

The whole industrial chain of hydrogen fuel cell in Shanghai has taken initial shape, and the advantages of industrial foundation are obvious. From the viewpoint of key technology, the core membrane electrode of fuel cell reactor technology of some enterprises has been developed independently and is in the leading position in the world; from the viewpoint of the layout of the whole industry chain, the development speed of Shanghai hydrogen fuel cell vehicle industry keeps the leading position in China[41], and the whole industry chain of technology, product and application has been formed initially, and it basically has the capability of research and development of key parts of fuel cell and manufacturing of complete vehicles. From the perspective of application environment, there are more than 1,000 hydrogen-fueled vehicles in Shanghai, and the output value of the fuel cell vehicle industry chain is 10 billion yuan, and 10 hydrogen refueling stations and nearly 30 kilometers of hydrogen pipeline have been built to lay a solid foundation for the further application and promotion of hydrogen fuel cell vehicles. However, authoritative testing and certification institutions have not yet been formed, and there is a lack of innovative and powerful R&D platforms and hydrogen fuel cell vehicle measurement and testing platforms.

Other fields of industry are not yet visible. The application of hydrogen in the industrial field is mainly characterized by chemical materials, while the application in other fields such as construction and energy is mainly based on innovation and demonstration, and the related industries are not yet visible and have not formed large-scale applications.

In summary, under the conditions of gradual improvement of policies and secure supply, hydrogen in Shanghai is mainly applied in chemical industry in the form of chemical raw materials and transportation in the form of hydrogen energy. However, diversified scenarios and large-scale applications have not yet been formed. The spatial layout of "one ring and six belts" has basically formed[42], and the spatial layout of "two bases in the north and south and three highlands in the east and west" will further deepen the development of hydrogen energy industry in Shanghai, guarantee the spatial and geographical landing basis for the innovative development of hydrogen energy applications in multiple scenes, and further release the potential of hydrogen application industry. The development potential of hydrogen application industry will be further released. With hydrogen fuel cell vehicles as the "front-runner" of hydrogen energy industry development, the application field of hydrogen will be developed more widely, in a larger scale and in a more diversified way through the continuous expansion of hydrogen application scenarios, strengthening the "Shanghai brand" and promoting the high-quality development of hydrogen application in Shanghai[43].

1.3 Analysis of hydrogen supply capacity in Shanghai

From the current supply layout, Shanghai's commercial hydrogen production capacity is mainly concentrated in the southwest (Chemical Industry Park) and the north (Baosteel), and there are five major supply entities, including Shanghai Chemical Industry Zone Industrial Gas Company Limited, Shanghai Hualin Industrial Gas Company Limited, Shanghai SECCO Petrochemical Company Limited, Shanghai Chlor-alkali Chemical Company Limited and China Baowu Iron & Steel Group (Shanghai Base), forming an oligopoly supply pattern. Among them, even if hydrogen production but all used for self-use needs of hydrogen production subjects are not included in the statistical scope of this paper.

(1) Hydrogen supply stock analysis

The hydrogen supply stock in Shanghai is mainly distributed in Shanghai Chemical Industrial Zone and Baowu Iron & Steel (Shanghai base).

1) Stock 1: Shanghai Chemical Industry Zone

Shanghai Chemical Industry Zone is located at the southern end of the city, on the north coast of Hangzhou Bay on the East China Sea, with a planning area of 29.4 square kilometers and a management area of 36.1 square kilometers. It has convenient water and land transportation, strong radiation capacity and superior location conditions. Based on the south of Shanghai and the north bank of Hangzhou Bay, it is located at the intersection of the Yangtze River Economic Belt and the coastal economic belt. In the west, it is connected with Jiaxing, Hangzhou and other cities in the Yangtze River Delta, in the east, it extends to the harbor area and Yangshan Port, and in the south, it is directly connected to the scarce chemical wharves and inland waters in the Yangtze River Delta. The northbound traffic is directly connected to the city, and the hydrogen supply market covers Qingpu, Jiading and even Suzhou Industrial Park.

Shanghai Chemical Industry Zone is richly endowed with energy resources. In terms of natural gas, the zone is a large industrial user of direct gas supply, and a stable supply of high calorific value and high pressure grade natural gas resources can be achieved due to its proximity to the city's main gas source, Yangshan LNG receiving station and the landing point of the Shanghai LNG station line expansion project. In terms of wind energy resources, the north coast of Hangzhou Bay has good wind resource conditions and great development potential, and is one of the four bases of offshore wind power in Shanghai. it is expected that the installed scale of Jinshan offshore wind farm will reach 400MW in the medium and long term. in terms of solar energy utilization, the park has been promoting the construction of photovoltaic projects in an orderly manner. As for hydrogen energy supply, the current hydrogen energy supply is about 150,000 tons/year, accounting for 94% of the total supply capacity of Shanghai, of which 68% comes from natural gas hydrogen production and 32% from chemical by-product hydrogen.

Based on the "14th Five-Year Plan for Renewable Energy in Shanghai", the "14th Five-Year Plan for Shanghai Far-reaching Sea Breeze Electricity", the "Research Report on

Zero Carbon Planning for Shanghai Chemical Industrial Park" and other policy support documents as well as natural resource endowment conditions, it is inferred that by 2030, the supply of hydrogen in Shanghai Chemical Industrial Park will maintain the original structure, with a supply capacity of about 250,000 tons. By 2060, combined with the implementation of offshore wind power projects and the orderly promotion of photovoltaic projects, Shanghai Chemical Industrial Zone can explore wind power and photovoltaic hydrogen production, and carry out demonstration of hydrogen production from photohydrolysated water and seawater. The regional supply structure will be hydrogen production from natural gas + chemical by-product hydrogen + green zero-carbon resources (mainly through electrolysis). In addition, the chemical terminal resources can also be fully utilized to output surplus hydrogen and receive and unload external hydrogen resources on the basis of ensuring local supply[44], which can be used as the entrance and exit of hydrogen resources.

2) Stock 2: Baowu Iron & Steel (Shanghai Base)

At the present stage, the hydrogen supply capacity of Baowu Steel (Shanghai Base) is about 10,000 tons/year, accounting for 6% of the total supply capacity of Shanghai, and all of it is industrial by-product hydrogen. Along with the goal of "striving to achieve carbon peak by 2023, carbon reduction by 30% by 2035 and carbon neutrality by 2050" put forward by Baowu Iron & Steel (Shanghai Base) in 2021, and the release of "Baosteel's Carbon Reduction Action Plan" and low carbon metallurgy roadmap[45], the electrification of the steel industry and hydrogen metallurgy have been fully launched.

In terms of carbon emissions, it is estimated that if the steel industry adopts a combination of 80% hydrogen and 20% natural gas as reducing agent in 2020, carbon emissions can be reduced to 437 kg; if the steel is made entirely with hydrogen, "zero carbon emissions" can be achieved. In terms of production capacity, Baowu Steel (Shanghai base) plans to build several new groups of PSA purification capacity in Baoshan 10 million tons blast furnace steelmaking base during the 14th Five-Year Plan period, and the first phase of the project is expected to be completed in 2021, releasing 3000 tons/year of hydrogen supply capacity, and will maintain an annual growth rate of 10% until the end of the 14th Five-Year Plan. "By the end of the 14th Five-Year Plan, the supply capacity will reach 15,000 tons/year. On the demand side, Baowu Iron & Steel (Shanghai base) has a steelmaking capacity of 1 million tons/year and adopts blast furnace hydrogen enrichment process, the demand for hydrogen will be about 200-300 thousand tons/year by 2030.

Thus, by 2030, the hydrogen supply of Baowu Iron & Steel (Shanghai base) will be used as raw material for steel production and to protect its own metallurgy as the first use. However, no matter whether the hydrogen metallurgy chooses the hydrogen-rich carbon cycle or the all-hydrogen route, it can only meet the tip of the iceberg in terms of its own hydrogen production capacity, and it may rely more on the supply from outside the city in the medium and long term, and it needs to receive external resources by means of its own LNG receiving station. Therefore, it is inferred that Baowu's hydrogen supply capacity is about 15,000 tons. By 2060, Baosteel Group level has fully achieved carbon neutrality and will basically form a supply structure of local chemical by-product hydrogen, green zero carbon resources (more than 80%, with electrolysis as the main method) to produce hydrogen + external procurement of hydrogen.

(2) Hydrogen Supply Increment Analysis

The expandable increment of hydrogen supply in Shanghai is mainly distributed in the new area of Shanghai Lingang, the northern area of Baoshan, Chongming District, Pudong Laogang, and the large scenery base outside the city.

1) Increment 1: Shanghai Lingang New Area

Shanghai Lingang New Area is located in the southeast of Shanghai, at the intersection of the Yangtze River Estuary and Hangzhou Bay, and is an important area of the two national strategies of Yangtze River Economic Belt and Maritime Silk Road Economic Belt; it is 75 km away from the center of Shanghai, adjacent to Pudong International Airport in the north and Yangshan International Hub Port in the south, and is an important node city of Shanghai's coastal corridor and the direct hinterland for the construction of China (Shanghai) Pilot Free Trade Zone.

Shanghai Lingang New Area attaches great importance to the development of hydrogen energy, and has issued the "14th Five-Year Plan for Renewable Energy in Shanghai", "14th Five-Year Plan for Wind Power in Deep Sea in Shanghai", "Measures for Accelerating the Development and Demonstration Application of Hydrogen Energy and Fuel Cell Vehicle in Lingang New Area of China (Shanghai) Pilot Free Trade Zone", "Implementation Plan for Building a High-Quality Hydrogen Energy Demonstration Application Scene in Lingang New Area (2021-2025)", "Development Plan for Hydrogen Fuel Cell Vehicle Industry in Lingang New Area of China (Shanghai) Pilot Free Trade Zone (2021-2025)" and a series of other policy documents. In terms of mechanism and system, Shanghai Lingang New Area has the advantage of independent legislation and special legislation policy, which allows 4 new establishment of storage and processing integrated hydrogen refueling mother stations on non-chemical land in heavy equipment industrial zone[46], special comprehensive bonded area (Yangshan Island area), comprehensive pilot area and Sino-Japanese cooperation demonstration park; encourages near-zero carbon and low-carbon hydrogen production, and provides fixed asset investment for actively carrying out zero-carbon hydrogen production projects such as offshore wind power and photovoltaic based on The maximum 30% investment incentive of up to 10 million yuan, the maximum 20% investment incentive of up to 8 million yuan for low-carbon hydrogen production projects such as liquid ammonia and methanol, and the maximum 10% investment incentive of up to 5 million yuan for natural gas hydrogen production projects; the incentive standard for the sale of renewable energy near-zero carbon hydrogen production is increased to 25 yuan/kg, and will not be refunded by the end of 2025.

At the same time, Shanghai Lingang new area is rich in energy resources endowment. In terms of natural gas, the landing point of Yangshan LNG receiving Station, the main gas source of Shanghai, is located in this area, and the gas turbine will be built in combination with the LNG station line expansion project. In terms of solar energy, it is expected that

200MW PV will be installed in the new zone in 2022, and BIPV technology will be used. In terms of wind energy, Fengxian offshore wind power has been fully connected to the grid in 2021. It is expected that the installed capacity of Fengxian and Nanhui offshore wind farms will reach 1000MW during the "14th Five-Year Plan" period, and the construction of far-reaching offshore wind power will continue to be promoted in the medium and long term. In addition, clean energy endowment such as seawater energy and geothermal energy is good. Fengxian 800 kV UHV DC converter station is adjacent to the new area, and Southwest Fufeng DC Xiangjiaba hydropower plant is located here. Based on the advantages of energy endowment, the hydrogen supply of Lingang New Area in Shanghai will be no less than 1500 tons/year by 2022. On the basis of the existing industrial by-product hydrogen supply, we will actively explore ways to develop hydrogen production from natural gas, electrolytic water and methanol within the area. By 2025, the hydrogen supply will be no less than 14,000 tons/year, and a hydrogen source guarantee system that organically combines industrial by-product hydrogen and hydrogen production from renewable energy will be established, so as to create a renewable energy and low-price electricity hydrogen production industry with the characteristics of Lingang New area. The annual hydrogen self-sufficiency rate will be no less than 30% of the current demand[47]. To the long term, with the introduction of green electricity outside the city, the port will become the main position of hydrogen production of green electricity in Shanghai. At the same time, it is feasible and necessary to carry out the application of hydrogen energy storage in the consumption of renewable energy and the peak regulation of power grid.

Therefore, it can be inferred that the hydrogen supply capacity of Shanghai Lingang New Area will show a rapid growth under the full release of the system dividend, and it will become an area with large-scale growth potential in the whole city. It is estimated that the supply capacity will reach 30,000 tons by 2030, showing a structure in which zero-carbon electrolysis+methanol and other low-carbon resources+natural gas resources coexist. By 2060, on the basis of the original supply capacity and structure, there will be many new renewable hydrogen production methods such as seawater energy and geothermal energy, and the hydrogen produced by green zero-carbon power will occupy the highest weight in the regional supply pattern. Deep integration with new power system construction, hydrogen energy storage will give full play to the role of promoting renewable energy consumption and peak shaving of power grid. At the same time, relying on the shoreline and wharf resources of Yangshan Port Area, we will establish hydrogen resource entrances and exits facing Shanghai and overseas, and lay out hydrogen-powered ship docking and hydrogen-based fuel filling facilities to open up the domestic and international trade space of green zero-carbon hydrogen.

2) Increment 2: Northern Baoshan area (Shidongkou, Luojing, etc.)

Baoshan District is located in the key traffic and vast hinterland, at the intersection of Yangtze River economic belt and coastal economic belt, with the conditions of river and sea intermodal transportation, the transportation radius radiates Nantong, Zhoushan, Ningbo and other oil and gas hub ports, and the resources and market radiates Yangtze River Delta. Through the "Baoshan District National Economic and Social Development 14th Five-Year

Plan and 2035 Visionary Goals Outline", "Shanghai Baoshan District Master Plan and Land Use Master Plan (2017-2035)", "Shanghai Shidongkou Gas Production Co. By 2035, Baoshan District will have a total of 23.5 square kilometers of planned industrial land, with the northern area carrying strategic emerging industries and high-end manufacturing industries led by science and technology innovation. Among them, Shidongkou area carries the mission of green transformation. The location of Shidongkou Gas Production Plant is a chemical land, which has the constraint condition of hydrogen production from the land nature, and its No.2 storage area, as an old facility, is about 100,000 square meters, which has more space for development, and the stock resources are to be revitalized.

It is deduced that during the opportunity period of green transformation of Baoshan old industrial zone, combined with the revitalization and utilization of inefficient industrial land, the potential of hydrogen supply capacity in Shidongkou area is about 5000 tons/year by 2030, and superimposed on the capacity of Baowu, the overall hydrogen supply in the northern area of Baoshan is about 20,000 tons, mainly industrial by-product hydrogen. By 2060, the feasibility of laying out hydrogen ships docking and hydrogen-based fuel refueling can be explored based on the conditions of Luojing Wharf and Stone-coal Wharf, combined with the shoreline and water depth conditions.

3) Increment 3: Chongming District (Chongming Ecological Island, Changxing Island, Heng Sha Island)

Chongming District of Shanghai is located at the mouth of the Yangtze River. Surrounded by the river on three sides, the sea on one side, the Yangtze River on the west, the east coast of the East Sea, the south and Pudong New Area, Baoshan District and Taicang City of Jiangsu Province across the water, the north and Haimen City, Qidong City, a strip of water, the total area of 1,413 square kilometers. Released in January 2022, Shanghai's chongming island a world-class ecological development plan outline (2021-2035), "clearly put forward by 2035 to chongming island a world-class ecological construction into green ecological" bridgehead ", green production "pilot zone", green Life "demonstration site"[48], leading the national ecological civilization, influence of global business card.

Chongming District in Shanghai has rich energy resources endowment. In terms of non-fossil energy, Chongming's installed renewable energy capacity has exceeded 570 MW, and the proportion of renewable energy power generation in the total electricity consumption of society has exceeded 30%[49]. In terms of wind power, Chongming has gradually formed two major wind power development zones - Chongming Northern Wind Power Development Zone and Changxing Island Northern Wind Power Development Zone and Heng Sha Wind Power Development Zone- by combining the management land of the Haitang Dike and the polder land of the land-making company, with 7 wind farms built and a total installed capacity of 291,000 kilowatts, including 223,000 kilowatts on Chongming Island and 68,000 kilowatts on Changxing Island. Changxing Island 6.8 million kilowatts. In the medium and long term, Chongming offshore wind farm (1700MW), Heng Sha Island offshore wind farm (400MW) and offshore wind farm in deep sea (4000MW) will be developed in the northern part of the Yangtze River estuary, and offshore wind power will be connected to Chongming

Island through submarine cables. On photovoltaic, Chongming is vigorously developing "photovoltaic + agriculture" and "photovoltaic&building" systems. The current installed capacity is 22,000 kW. During the "14th Five-Year Plan" period, the installed capacity of PV will be increased by 600,000 kW. On waste power generation, Chongming has built one waste incineration power generation project, which can process 500 tons of domestic waste per day, with an installed capacity of 0.9 million kilowatts, and the annual output of more than 100,000 tons of domestic waste can be fully consumed. In terms of biogas power generation, among 63 biogas projects in the city, three units generate electricity online, among which Shanghai Chongbao Pig Farm will generate 50,000 kWh of electricity in 2020, with 15,000 kWh of electricity online. In terms of thermal energy resources, Chongming Island has the conditions for development. In terms of fossil energy, the Rudong-Chongming natural gas pipeline project was put into operation in December 2015, with a pipeline capacity of 0.18 billion cubic meters per year and an actual supply of about 0.07 billion cubic meters per year, which can theoretically support a maximum hydrogen energy capacity of 16,000 tons per year. In addition, by the end of the "15th Five-Year Plan", Chongming may land an extra-high voltage DC with 80% clean energy from renewable energy bases outside the city, with a total installed power scale of about 20 million kilowatts on the transmission side.

Compared with Jiading, Shanghai Chemical Industry Zone, Lingang and other regions, Chongming is far from the origin of by-produced hydrogen, and there may be safety risks when hydrogen passes through tunnels or bridges as a hazardous chemical, so the feasibility of using by-produced hydrogen in Chongming is yet to be demonstrated. From the resource endowment, there are three types of hydrogen production routes that can be developed in Chongming - electrolysis of hydrogen, biomass hydrogen production and fossil energy hydrogen production. At present, according to the current renewable energy generation capacity of 47.3 billion kilowatt-hours in Chongming, 1.6 billion kilowatt-hours of new renewable energy generation capacity and 2% of electricity will be used for hydrogen production by the end of the "14th Five-Year Plan", and 100 kilowatt-hours of new renewable energy generation capacity and 3% of electricity will be used for hydrogen production by the end of the "15th Five-Year Plan". At the end of the 15th Five-Year Plan, the new renewable energy generation capacity will be 100 kWh and 3% of electricity will be used for hydrogen production, and the efficiency of hydrogen production will be 4 kWh/standard square, then the supply capacity of renewable energy electrolysis hydrogen production in Chongming area will reach 7000 tons in 2030. If 10% of the natural gas supply of Rudong-Chongming is used for hydrogen production, the maximum supply capacity of this part will be 3000 tons/year.

It is deduced that by 2030, the hydrogen supply capacity of Chongming area (including Chongming Eco-Island, Changxing Island and Hongsha Island) will be about 10,000 tons, showing a hydrogen supply structure with wind, electricity, biomass, geothermal and other renewable energy sources such as electrolysis as the main source, supplemented by pipeline natural gas production. By 2060, with the development of renewable energy and the construction of efficient low-carbon energy system, the green zero-carbon hydrogen supply will become another business card of Chongming Eco-Island to the whole country and the world.

4) Increment 4: Pudong Laogang

The potential of biomass natural gas supply, since the implementation of household waste separation in Shanghai on July 1, 2019, the rate of citizens in residential areas consciously and correctly participating in waste separation and disposal has reached more than 95%[50], and the amount of wet waste separated out is 9,200 tons/day, which is expected to generate about 1500 tons of hydrogen production per year based on the average maximum hydrogen supply of 2,000 Nm^3/h, which can theoretically support Shanghai's fuel cell Theoretically, it can support half of the hydrogen demand17 in the first year of the demonstration period of Shanghai fuel cell city cluster. However, under the biogas purification route, assuming a biogas price of RMB 0.665-0.72/m^3, the cost of hydrogen production is as high as RMB 5.15-5.20/m^3, which is not economic and has only demonstration value.

5) Increment 5: Large scenery base outside Shanghai

Continuously promote the optimization of energy structure, increase the proportion of non-fossil energy to total energy consumption, is an important element of Shanghai's low-carbon energy transition[51]. Restricted by the city's renewable energy development resources, and non-fossil energy resource-rich areas to strengthen cooperation, layout of large non-fossil energy base, carrying the heavy responsibility of Shanghai's energy structure adjustment, but also become the construction of "new energy as the main body of the new power system" a key part.

According to the relevant work arrangements, Shanghai strives to start the construction of a large scenic base outside the city during the "14th Five-Year Plan" period, which is expected to build 7 million kilowatts of photovoltaic, 9 million kilowatts of wind power, supporting the regulating capacity, including electrochemical energy storage. The construction of the passageway into Shanghai will strive to be started in the "14th Five-Year Plan" and put into operation in the early and middle period of the "15th Five-Year Plan". By then, this green transmission channel with more than 80% renewable energy consumption ratio will land in Chongming, and then cross the river to the downtown of Shanghai.

Hydrogen production by wind and photoelectrolysis in large scenery bases is an ideal way to consume surplus resources, and also the most economical electrolytic hydrogen production route. It is also an important embodiment of ensuring the safety of hydrogen energy supply in Shanghai with resources outside the market. In terms of supply potential, the supply capacity of hydrogen production by wind and light abandonment will reach up to 5,000 tons/year based on the calculation that wind and light abandonment will be no more than 6% during the "15th Five-Year Plan" period and all wind and light abandonment will be used for hydrogen production. In terms of transmission method, given that the site of renewable energy base outside the city is about 2000 km away from Shanghai Qingpu (west-east gas transmission baihe gate station) and Jiading (auto city), which is far beyond the 1000 km economic radius for liquid hydrogen transportation, the way to utilize and transport this hydrogen resource to Shanghai should be hydrogen pipeline or other economic methods.

In summary, in terms of commercial supply capacity, the total supply of hydrogen in

Shanghai is expected to reach 206,900 tons/year by the end of the 14th Five-Year Plan. The increase comes from three parts: First, the new syngas, propane dehydrogenation, adipononitrile (ADN) projects in the chemical industry zone. Second, several new PSA purification projects of Baowu Group (Shanghai base) will release 3,000 tons of hydrogen per year from 2021, and will maintain an annual growth rate of 10%. Third, 0.69 tons of green zero hydrocarbon gas capacity. By 2030, after the launch of Huayi Energy syngas Project, the annual hydrogen production capacity will be increased by 34,000 tons. When the potential capacity of Lingang and other regions is released, the total amount of hydrogen production from natural gas and industrial by-product hydrogen will be increased to about 294,800 tons, adding 15,100 tons of green zero hydrocarbon gas supply capacity. The city's maximum commercial hydrogen supply capacity will reach 310,000 tons. By 2060, the green zero hydrocarbon gas supply capacity will account for about 50%, the cost price will be about 15-20 yuan/kg, the total hydrogen production from natural gas will account for 20%, the cost price will be about 20 (plus CCUS) -40 yuan/kg (considering carbon tax), and the maximum commercial hydrogen supply capacity of the city will reach 1.08 million tons. In terms of the full caliber supply, the total supply of the whole city is about 914,300 tons and 1,963,300 tons, respectively, based on the calculation that the proportion of green zero hydrocarbon gas supply in 2030 and 2060 is 6% and 55%.

Table 1-2 Shanghai 2020, 2030, 2060 Commercial Hydrogen Supply Sources, Size Forecast (million tons/year)

Year	Chemical Zone	Baowu (Shanghai Base)	Lingang New Area	Baoshan Shidongkou	Chongming District	Laogang	Large scenery base outside Shanghai	Oversea	Total supply capacity
2020	15	1	/	/	/	/	/	/	16
2030	25	1.5	3	0.5	1	/	/	/	31
2060	√	√	√	√	√	√	√	√	107.97

Table 1-3 Medium- and long-term commercial hydrogen supply capacity forecast for Shanghai

Year	Supply capacity (10,000 tons)	Natural gas to hydrogen (10,000 tons)	Percentage (%)	Industrial by-product hydrogen (10,000 tons)	Percentage (%)	Green zero hydrocarbon (10,000 tons)	Percentage (%)
2020	16	10	63	6	37	/	/
2025	20.69	13.00	63	7	34	0.69	3
2030	31	19	61	10.48	34	1.52	5
2060	107.97	21.59	20	32.39	30	53.99	50

Table 1-4 Prediction of Medium and Long Term Hydrogen Supply Capacity in Shanghai

Year	Supply capacity (10,000 tons)	Green zero hydrocarbon (10,000 tons)	Percentage (%)
2020	50.00	/	/
2030	91.43	5.07	6%
2060	196.33	107.98	55%

1.4 Research structure and logical framework

1.4.1 Research purpose and core content

The research objectives and logic of this paper are shown in Fig.1-3. In the face of the increasingly serious global climate change problem, hydrogen energy is standing out as a low-carbon and zero-carbon energy source. However, the large-scale application of hydrogen energy still faces many challenges, among which the high cost is one of the obstacles to the development of hydrogen energy. However, with the emergence of carbon trading market, hydrogen energy has a new development opportunity due to its "zero carbon" property. In this context, this paper will study and evaluate the application effects of hydrogen energy in different forms in different fields from both economic and environmental perspectives, such as the application of photovoltaic-hydrogen refueling stations in the transportation field, the application of hydrogen fuel cell cogeneration systems in the architecture field, the application of hydrogen combustion turbines in the energy field, and the study of hydrogen energy application potential in Shanghai based on the analysis of the development scale of hydrogen fuel cell vehicles. It is hoped that it will help to expand the hydrogen energy application scenarios.

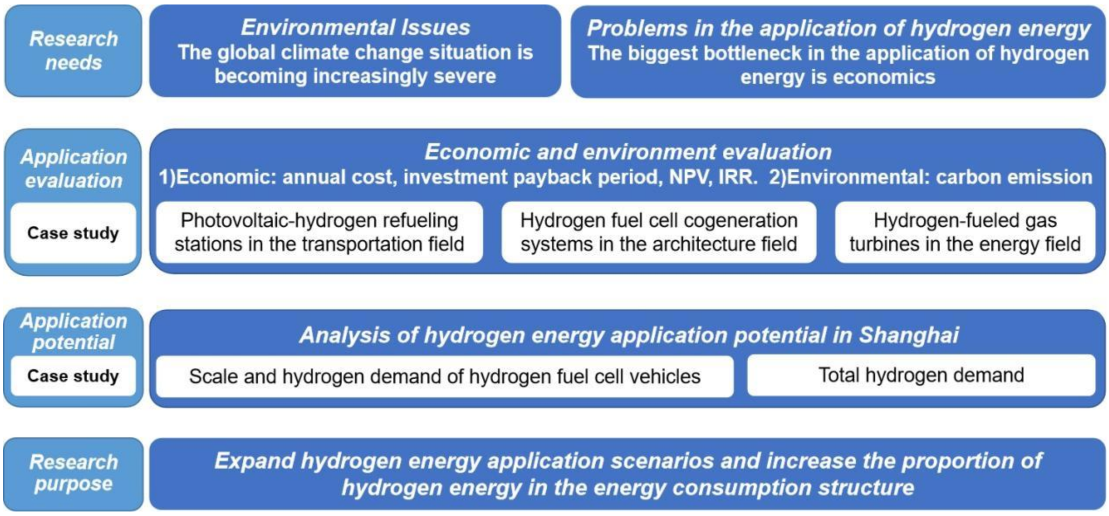

Fig.1-3 Research logic of the article

1.4.2 Chapter content overview and related instructions

The chapter names and basic structure of the article are shown in Fig.1-4. The brief chapters introduction are shown in Fig.1-5.

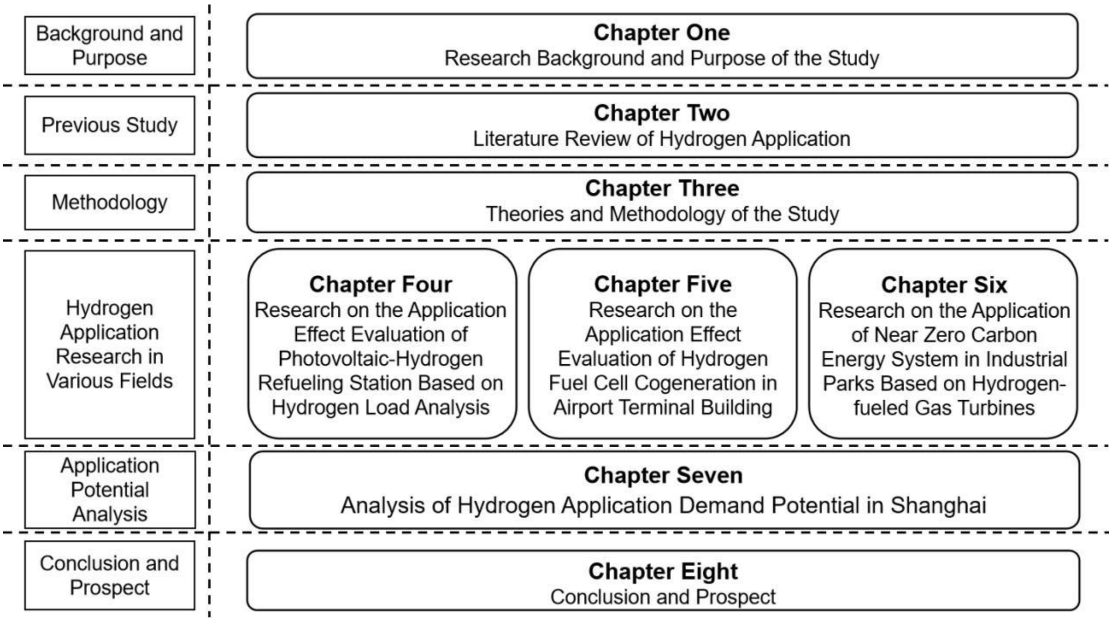

Fig.1-4 Chapter name and basic structure

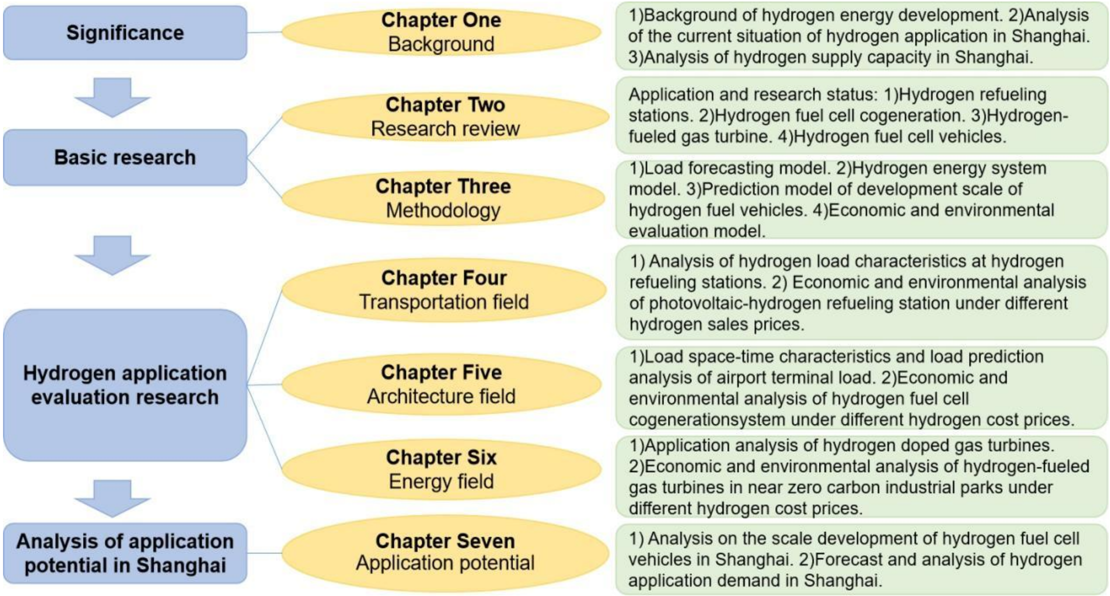

Fig.1-5 Brief chapter introduction

In Chapter 1, research background and purpose of this study：

Facing the increasingly serious global climate change situation, hydrogen, as the best energy carrier that can achieve deep decarbonization on a large scale in transportation, industry and construction, has become a strategic choice to guarantee national energy security, promote energy transformation and realize low-carbon development, so it is of practical significance to carry out research on hydrogen energy application. This chapter firstly analyzes the hydrogen energy development strategies of countries and regions such as the United States, the European Union, Japan, South Korea and China, and then takes Shanghai, which already has the foundation of hydrogen energy development, as the research object, and focuses on the current situation of hydrogen energy application and supply in Shanghai, finally, the research logic and content of the article were expounded .

In Chapter 2,Literature review of hydrogen application：

This chapter first analyzes the main ways of applying hydrogen energy and the forms of its application in the main application fields, and clearly studies the effects of hydrogen applications in the transportation field, the construction field, and the energy field. Then, it focuses on the application and research status of the more maturely developed hydrogen fuel cell vehicles and their infrastructure - hydrogen refueling stations in the transportation field, the application and research status of hydrogen fuel cell cogeneration systems in the building field, and the application and research status of hydrogen-doped internal combustion engines and hydrogen-fired internal combustion engines in the energy field where hydrogen is used as a fuel to replace natural gas. The current status of research on the application of hydrogen as a fuel alternative to natural gas in the energy sector.

In Chapter 3, Theories and methodology of the study：

This part is about methodological research and model building.First, the main load forecasting methods used at this stage are introduced and analyzed, and load forecasting models and load forecasting accuracy evaluation models are constructed.Since load forecasting is the basis of subsequent research, this chapter proposes and validates a load forecasting method based on the PSO-GRU neural network model-based load forecasting method is proposed and verified in this chapter. Secondly, the equipment models of hydrogen energy systems involved in the subsequent chapters of this paper, such as photovoltaic hydrogen refueling station system and equipment model, hydrogen fuel cell cogeneration system and equipment model, and hydrogen doped gas turbine system and equipment model, are established. Then, in order to predict the development scale of hydrogen fuel cell vehicles in Shanghai and the potential of hydrogen energy application in the city, the relevant prediction methods are introduced and analyzed. Finally, the total annual cost of energy model, dynamic cost-benefit analysis model, and carbon emission calculation model of energy system are constructed to provide the research theoretical basis for the environmental and economic assessment in the subsequent chapters.

In Chapter 4, Research on the application effect evaluation of photovoltaic-hydrogen refueling station based on hydrogen load analysis：

As the infrastructure of hydrogen energy application in transportation, hydrogen refueling station is a prerequisite for the popularization of hydrogen fuel cell vehicle application and a key to achieve zero emission at the end of transportation. Therefore, this chapter focuses on the feasibility of the application of photovoltaic hydrogen refueling stations. This chapter takes a hydrogen refueling station in Shanghai as the research object, firstly, it analyzes the characteristics of hydrogen demand of different types of hydrogen fuel cell vehicles and the hydrogen demand of hydrogen refueling station throughout the day; then, it determines the system equipment configuration of PV hydrogen refueling station according to the hydrogen demand load; finally, it studies and analyzes the operation strategy and socio-economic benefits of PV hydrogen refueling station under different hydrogen selling price.

In Chapter 5, Research on the application effect evaluation of hydrogen fuel cell cogeneration in airport terminal building：

As a major energy consumer in airports, energy saving and carbon reduction in terminals is an inevitable trend in the context of achieving the "double carbon" goal. As a common form of hydrogen energy application in the building field, hydrogen fuel cell cogeneration system can not only ensure the security of energy supply, but also help the terminal building to achieve the real "zero carbon" emission, so this chapter focuses on the feasibility of applying hydrogen fuel cell cogeneration system in the airport terminal building. Taking an airport terminal in Shanghai as an example, this chapter first analyzes the building load characteristics and space-time characteristics of the terminal building, and predicts and analyzes the typical daily load of the terminal building for 8760 hours and each season, and then focuses on the equipment configuration, operation optimization strategy and economic and social benefits of the hydrogen fuel cell cogeneration system when the cost of hydrogen drops by 0%, 50% and 70%.

In Chapter 6, Research on the application of near zero carbon energy system in industrial parks based on hydrogen-fueled gas turbines:

By blending hydrogen into natural gas and burning it in a gas turbine to generate electricity, the gas turbine not only becomes the support point of zero-carbon power and achieves flexible regulation of the power grid, but also has great significance in reducing carbon emissions in power generation. In this chapter, we first study the feasibility of hydrogen-doped gas turbine application, and then take an industrial park in Shanghai as the research object under the demand of "zero carbon" park construction, and study the application effect of combining hydrogen turbine and photovoltaic system on the construction of "near zero carbon" industrial park.

In Chapter 7, Analysis of hydrogen application demand potential in shanghai:

As one of the first cities in China to start hydrogen energy industry, the study of its hydrogen energy application potential will provide guidance for future hydrogen energy infrastructure layout and hydrogen energy industry development, so this chapter focuses on the hydrogen energy application potential in Shanghai. Since hydrogen fuel cell vehicles are the most mature hydrogen application method in Shanghai, this chapter first conducts an in-depth study on its development scale based on SWOT analysis, and puts forward development goals and suggestions, and clarifies two scenarios under the development of hydrogen fuel cell vehicles: the baseline scenario and the high scenario. Then, the scale of hydrogen fuel cell vehicle development and hydrogen demand in Shanghai under the two scenarios are predicted and analyzed. Finally, based on the feasibility and development trend of hydrogen energy application in different fields, the proportional relationship of hydrogen demand in each field under different stages is clarified to predict and analyze the total hydrogen energy demand in Shanghai.

In Chapter 8,Conclusion and prospect:

This chapter summarizes the research in the previous chapters. And based on the conclusions, future developments and prospects for further research on hydrogen applications are presented.

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Chapter 2

LITERATURE REVIEW OF HYDROGEN APPLICATION

CHAPTER TWO: LITERATURE REVIEW OF THE DISTRIBUTED ENERGY SYSTEM

LITERATURE REVIEW OF HYDROGEN APPLICATION

2.1 Overview of hydrogen application

Hydrogen mainly appears in the form of chemical combination on the earth, which is the most widely distributed substance in the universe and a secondary energy source. Hydrogen has the characteristics of high combustion calorific value, which is 3 times of gasoline, 3.9 times of alcohol and 4.5 times of coke. Among all gases, hydrogen has the best thermal conductivity, which is 10 times higher than that of most gases[3]. Therefore, hydrogen is a good heat transfer carrier in energy industry. In addition, hydrogen itself is non-toxic, compared with other fuels, it is the cleanest when burned, and the water generated by combustion can continue to produce hydrogen, which can be recycled repeatedly. Therefore, hydrogen energy is emerging as a low-carbon and zero-carbon energy source, and it is recognized as a clean energy source[1].

2.1.1 Application mode of hydrogen

There are three main application ways of hydrogen: direct combustion; Converted into electric energy by a fuel cell[2]; Nucleation. Among them, the safest and most efficient way to use it is to convert hydrogen into electric energy through fuel cells[3].

1) direct combustion

The main applications of direct combustion of hydrogen energy are hydrogen-burning turbine, hydrogen-burning internal combustion engine, metallurgy or chemical synthesis raw material[4][5][6].

Hydrogen turbine refers to the use of hydrogen instead of natural gas as fuel to generate heat energy through combustion, which generates mechanical work in the heat engine and drives the generator to generate electricity. The basic principle of hydrogen-fired internal combustion engine is the same as that of gasoline or diesel internal combustion engine.

Hydrogen internal combustion engine is a slightly modified version of traditional gasoline internal combustion engine. Hydrogen internal combustion burns hydrogen directly, without using other combustion or generating water vapor to be discharged.

Metallurgy or as raw material for other chemical synthesis refers to hydrogen-containing gas produced during coke production (COG), blast furnace (BFG) and basic oxygen furnace (BOFG). Once collected and treated, it can be reused in the process, and can replace other fossil fuels for heating or as reducing agent.

2) Conversion to electricity through fuel cells

The most widely used form of hydrogen energy is mainly fuel cells. The basic principle of hydrogen fuel cell electricity generation is that hydrogen gas first enters the hydrogen electrode of the fuel cell (called the anode), and then the hydrogen gas reacts with the catalyst covering the anode, releasing electrons to form positively charged hydrogen ions, which pass through the electrolyte to the cathode. However, the electrons cannot pass through the electrolyte; instead, they flow into the circuit, forming an electric current and generating electricity. At the cathode, the catalyst causes the hydrogen ions to combine with oxygen in the air to form water, which is the only by-product of the fuel cell reaction[7].

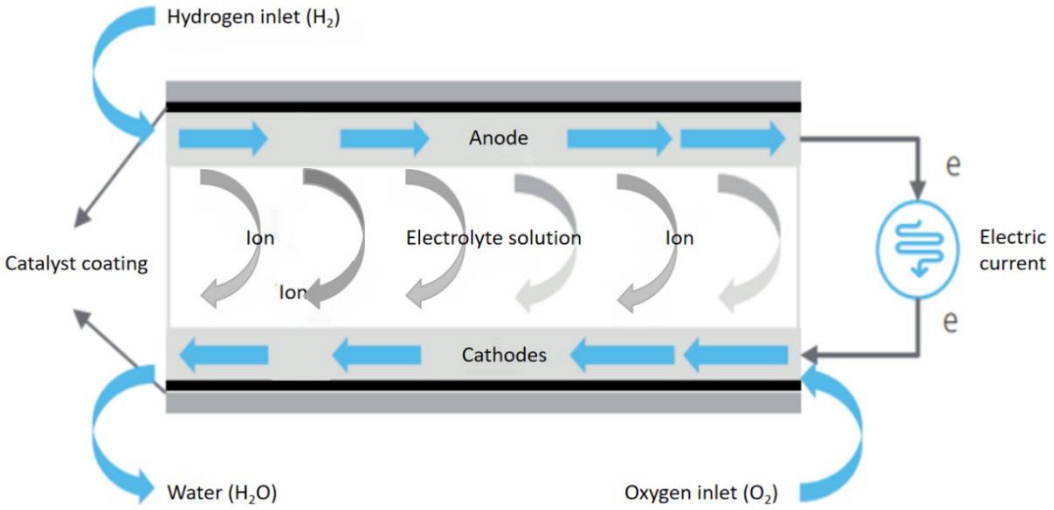

Fig.2-1 Working principle of fuel cell

The main difference between hydrogen battery and ordinary battery is that dry battery and storage battery are energy storage devices[8], which store electric energy and release it when needed; Strictly speaking, hydrogen fuel cell is a kind of power generation device. Like power plants, it is an electrochemical power generation device that directly converts chemical energy into electrical energy. It does not need to be burned, and the energy conversion rate can reach 60% ~ 80%. Moreover, it has less pollution, low noise, large or small devices and is very flexible. Hydrogen fuel cells have no pollution to the environment, and only produce water and heat. If hydrogen is produced by renewable energy sources (photovoltaic panels, wind power generation, etc.), the whole cycle is a complete process without harmful substances. After a hundred years of development, fuel cells have a very wide application prospect and huge market potential in many fields such as national defense, aerospace and civil mobile power stations, discrete power supplies, submarines, electric vehicles, computers and communications[9][11].

Table 2-1 Main application forms of hydrogen fuel cell

Kind	Application
Traffic	Passenger cars
	Trucks
	Forklifts
	Buses
	Logistics vehicles
	Aircraft

	Ships
	Electric bicycles
Fixed power supply	Co-generation system
	Uninterruptible power supply system
	Distributed power generation
Other applications	Portable power
	Unmanned aerial vehicle(UAV)
	……

According to the types of electrolytes, fuel cells can be roughly divided into five categories: alkaline fuel cell (AFC) with alkaline substance as electrolyte, proton exchange membrane fuel cell (PEMFC) with extremely thin plastic film as electrolyte, phosphoric acid fuel cell (PAFC, working temperature can reach 200℃) with phosphoric acid at high temperature as electrolyte, molten carbonic acid fuel cell (MCFC, working temperature can reach 650℃), and solid oxide fuel cell (SOFC, operating temperature up to 1000℃) using solid oxide as electrolyte. Among them, the application of proton exchange membrane fuel cell is at the forefront of commercialization[10][11][12].

The working temperature of proton exchange membrane fuel cell is very low[13], generally around 80℃, and its basic components are membrane electrode assembly (MEA), anode and cathode. Among them, MEA is the core component of the whole single cell, which is composed of proton exchange membrane and catalytic layer (CL) covering both ends of the membrane. MEA is the core component of the single cell, which determines the performance of the cell. The anode mainly includes anode terminal plate and anode current collector plate; The cathode mainly includes cathode terminal plate and cathode current collector plate. In MEA, the main function of proton exchange membrane is to block the gas diffusion between cathode and anode, to prevent the combustion and explosion of hydrogen at anode and oxygen at cathode after mixing, and it can selectively transfer ions, only allowing protons to pass through, thus blocking the electron transfer and forcing electrons to flow through the external circuit to form current. The catalytic layer is the area where electrochemical reaction takes place, and it is mainly composed of carbon-supported platinum and polymer. Several single proton exchange membrane fuel cells are stacked to form a high-power stack, which can meet the needs of different occasions.

Table 2-2 Comparison of Five Types of Fuel Cells

Fuel cell type	Bath solution	Operating temperature/℃	Catalyst	Main advantages	Main disadvantages	Application area
PEM	Proton exchange membrane	50-100	Platinum	● Start up quickly. ● The indoor temperature is low. ● Air can be used as an oxidizer.	● Sensitive to carbon monoxide ● The reactants need to be humidified	● Car ● Portable power
AFC	Alkaline electrolyte	90-100	Silver/ Nickel	● Start up quickly ● The working temperature is low	● Pure oxygen is needed as catalyst.	● Aerospace ● Military Science
PAFC	phosphoric acid	150-200	Platinum	● Insensitive to carbon dioxide	● Sensitive to carbon monoxide ● Start slowly	● Distributed power generation
SOFC	Solid oxide	650-1000	$LaMnO_3$/ $LaCoO_3$	● Air can be used as an oxidizer. ● High energy efficiency	● The operating temperature is high.	● Large-scale distributed generation ● ·portable power
MOFC	Molten carbonate	600-700	Nickel	● Air can be used as an oxidizer. ● High energy efficiency	● The operating temperature is high.	● Large-scale distributed generation

3)Nuclear fusion

Nuclear fusion, that is, when hydrogen nuclei (deuterium and tritium) combine into heavier nuclei (helium), huge energy is released. The fusion reaction caused by the hydrogen nuclei involved in the nuclear reaction, such as hydrogen, deuterium, fluorine and lithium, obtaining the necessary kinetic energy from thermal motion. Nuclear reaction is the basis of hydrogen bomb explosion[14], which can produce a lot of heat energy in an instant, but it can't be used yet. Controlled thermonuclear reaction can be realized if thermonuclear reaction can be controlled in a certain restricted area according to people's intention. Controlled thermonuclear reaction is the foundation of fusion reactor. Once the fusion reactor is successful, it may provide mankind with the cleanest and inexhaustible energy. At present, there are two nuclear fusion experimental devices in China, but the application of nuclear fusion is difficult in both technology and economy, which makes it impossible to form a commercial application mode. Therefore, it is not listed in the scope of this article for the time being[15].

2.1.2 Application field of hydrogen

Under the background of "double carbon" goal, hydrogen energy will become an irreplaceable and important part of energy structure, and it is the key to solve the dilemma of decarbonization of economic development and realize "peak carbon dioxide emissions and carbon neutrality".Hydrogen can be widely used in many fields such as transportation, industrial production, and construction.

In the field of industrial production, hydrogen is mainly used in the chemical industry, electronic industry, steel industry and so on. Among them, in the chemical industry, hydrogen is one of the main raw materials for ammonia synthesis and methanol, etc[16]. In the electronics industry, high purity hydrogen is mainly used as reducing, carrying and protecting gas. In the steel industry, hydrogen is mainly used as a reducing gas instead of carbon reduction for hydrogen metallurgy[17][18][19][20]. Therefore, hydrogen is mainly used in the industrial field in complex processes of industrial production rather than as an energy source, so it is not studied in this paper for the time being.

In the field of transportation, hydrogen powered vehicles are developed by using fuel cell technology to significantly reduce the total consumption of fossil energy in the transportation industry[21][22]. In order to promote the deep decarbonization in the transportation field, the application of "green hydrogen" in hydrogen station needs to be emphatically studied. Therefore, the economic conditions and carbon emissions impact of the application of photovoltaic hydrogen station will be studied in chapter 4.

In the architecture field[23][24], the application of hydrogen technology, such as hydrogen fuel cell cogeneration, can significantly improve energy efficiency and promote the construction of energy-saving and environment-friendly buildings. As a large building with intensive energy consumption and complex energy usage, the airport terminal has enormous potential for energy conservation and emission reduction. Effectively reducing its energy consumption, energy costs, and carbon emissions is of great significance in the context of "dual carbon". Therefore, the chapter 5 will take the airport terminal as the research object to study the application feasibility of hydrogen fuel cell cogeneration system.

In the field of energy and electricity[25], the main application forms of hydrogen energy include: Firstly, replacing other energy sources with hydrogen to provide heat and electricity, such as the application of hydrogen doped gas turbines, which use hydrogen as the connecting hub and can play a good complementary and synergistic role with new energy, resulting in better flexibility and stability of the energy system. Secondly, it is to fully leverage the advantages of hydrogen gas across seasons, regions, and large-scale storage, and support the construction of new power systems through the coupling of electricity and hydrogen to enhance the resilience of the high proportion of new energy power systems. The chapter 6 will study the application feasibility of hydrogen doped gas turbines, as well as the application feasibility of hydrogen turbines in the construction of "near zero carbon" industrial parks.

2.2 Application and research status of hydrogen refueling stations

2.2.1 Application status

A hydrogen refueling station is a gas station that pressurizes and stores hydrogen from different sources in a high-pressure tank inside the station through a compressor, and then fills hydrogen fuel cell vehicles with hydrogen through a gas dispenser. It is an important infrastructure for the industrialization and commercialization of hydrogen fuel cells. According to different classification methods, there are different types of hydrogen refueling stations[26]: According to the different hydrogen refueling pressures, they can be divided into two types, 35 MPa and 70 MPa. According to different construction forms, it can be divided into fixed hydrogen refueling stations and mobile skid-mounted hydrogen refueling stations. According to the different types of construction, it can be divided into single building hydrogen refueling stations, hydrogen refueling joint construction stations, and comprehensive integrated joint construction stations such as refueling, gas, electricity, and hydrogen refueling. According to different purposes, it can be divided into self use stations, commercial stations, and demonstration stations. According to different hydrogen supply methods, it can be divided into external hydrogen supply stations and internal hydrogen production stations.

According to public data[27], there were approximately 860 hydrogen refueling stations worldwide in 2022, and it is expected that the number of hydrogen refueling stations will reach 1700 by 2025. From the global distribution of hydrogen refueling stations, the proportion of hydrogen refueling stations in Asia is about 53%, while the proportion of hydrogen refueling stations in Europe and North America is 33% and 13%, respectively. Other countries or regions account for 1.2%. From the distribution of global hydrogen refueling stations' operation status, the proportion of hydrogen refueling stations open for operation is about 74%; The completed hydrogenation accounts for about 2%; Approximately 9% of hydrogen refueling stations are under construction; The proportion of hydrogen refueling stations under planned construction is about 15%.

The earliest hydrogen refueling stations can be traced back to the 1980s at Los Alamos in the United States. In terms of hydrogen refueling station construction, the United States mainly focuses on the layout of densely populated urban areas such as San Francisco and Los Angeles, emphasizing the combination of hydrogen energy application scenarios to form a unique hydrogen energy industry ecosystem in the local area. According to the data of the United States Department of Energy[28], as of November 2020, 46 commercial hydrogen refueling stations have been built in the United States, 45 of which are located in California. All stations except Newport Beach are in normal operation. In addition, according to the "US Hydrogen Economy Roadmap" released by FCHEA in November 2019, 580 hydrogen refueling stations will be built by 2025; By 2030, there will be 5600 hydrogen refueling stations across the United States.

According to data from H_2 Stations, as of November 2020, a total of 43 commercial and non commercial hydrogen refueling stations have been built in South Korea, and 21 hydrogen refueling stations are under construction or planned, mainly distributed around the urban agglomerations of Seoul and Busan. According to the South Korean announced a hydrogen economy roadmap in 2019[29], South Korea plans to build 1200 hydrogen refueling stations by 2040.

Japan's fuel cell industry is at the forefront of global commerce, and the construction of hydrogen refueling stations as infrastructure is the most complete. According to data from the Japan Fuel Cell Utility Promotion Agreement, as of November 2020, Japan has built a total of 146 commercial hydrogen refueling stations, including 106 fixed stations and 40 skid mounted stations, as well as 23 fixed hydrogen refueling stations under construction and planned. According to the "Hydrogen Energy Utilization Schedule" released by the Japanese government in 2019, the key goal of applying hydrogen energy in Japan is to build 320 hydrogen refueling stations by 2025 and increase them to 900 by 2030. In addition, by 2025, the construction and operation costs of hydrogen refueling stations should significantly decrease, with construction costs dropping to 200 million yen and operating costs dropping to 15 million yen per year.

Fig.2-2 The overall structure of "Yamaguchi Hydrogen Station Gunma Takasaki"(イワタニ水素ステーション群馬高崎)[30]

China attaches great importance to the construction of hydrogen refueling stations. In 2006, China's first hydrogen refueling station was located in the New Energy Transportation Demonstration Park of Yongfeng High tech Industrial Base in Zhongguancun, Beijing. In the same year, the first hydrogen refueling station in Shanghai, Anting Hydrogen refueling Station, began construction and was completed. The hydrogen refueling station covers an area of 880 square meters and has a maximum hydrogen capacity of 800kg. It can provide continuous refueling services for 35MPa fuel cell vehicles (20 sedans and 6 buses), with a maximum daily refueling capacity of approximately 400kg/12h. With the continuous maturity of relevant technologies, the number of hydrogen refueling stations in China is steadily increasing. As of 2023[31], more than 350 hydrogen refueling stations have been built nationwide, accounting for about 40% of the global total, ranking first in the world. According to the "Energy Conservation and New Energy Vehicle Technology Roadmap 2.0"[32], the construction goal of China's hydrogen refueling stations is to have at least 1000 by 2025; The construction target for hydrogen refueling stations by 2035 is at least 5000.

Fig.2-3 Shanghai Anting Hydrogen refueling Station Demonstration Base[33]

In summary, the number of hydrogen refueling stations is constantly increasing, which will accelerate the commercialization of hydrogen fuel cell vehicles and provide important guarantees for hydrogen energy applications.

2.2.2 Research status

At present, the research on hydrogen station mainly focuses on the layout of hydrogen station, the optimization of hydrogen station system, and the combined application of hydrogen station and renewable energy.

In terms of research on hydrogen station site layout. Literature[34] designed and implemented a hydrogen station site selection system considering multiple site selection factors. The system integrates data related to hydrogen station site selection, supports modeling and analysis of site selection areas, analyzes the distribution of regional hydrogen refueling demand and the distribution of hydrogen station candidate sites, and can be evaluated and compared horizontally in combination with other site selection goals. Literature [35] carried out in-depth analysis on the working mode of hydrogen production hydrogen station, and built a hydrogen production hydrogen station layout optimization model considering the coupling effect of distribution network and hydrogen fuel vehicles under the framework of transportation power network. Literature[36], based on the composition of the hydrogen supply chain, combined with the construction demand of the hydrogen energy highway, aimed at minimizing the cost of hydrogen consumption, and by comprehensively considering the constraints such as the distance between hydrogen station, hydrogen source capacity, and geographical location, and taking the location of hydrogen station, hydrogen transportation volume, and hydrogen transportation volume under different transportation modes as decision variables, constructed a mathematical model for the location of hydrogen station considering the optimal hydrogen supply chain.

In terms of research on optimization of system configuration of hydrogen station. Literature[37] studied the optimization of high-pressure hydrogen supply system of hydrogen station from aspects of configuration of hydrogen refueling machine, configuration of compression and gas storage system and design of high-pressure hydrogen precooler, aiming at the core of hydrogen station - high-pressure hydrogen supply system consisting of compression, gas storage, precooling and filling systems. The optimization process proposed in literature[38] has a significant effect on protecting the 45MPa hydrogen compressor, improving the effective hydrogen unloading capacity of long tube trailers, and reducing the cost of hydrogen sales. It can provide reference for actual production and operation. Literature[39] obtained the change rule of key parameters by calculating the filling capacity of an example hydrogen station, discussed the relationship between the changes in compressor power consumption and the filling sequence of each pressure level of the hydrogen storage container under the long tube trailer hydrogen supply method. These rules are helpful to understand and optimize the equipment configuration and operation mode of hydrogen station.

In the research on the application of the combination of hydrogen station and renewable energy. In the literature[40], a transport company Tunis Tunisia is taken as an example,a detailed economic assessment and evaluation of the Levelized Hydrogen Cost (LHC) and the Net Profit(NP) of a Photovoltaic (PV) Hydrogen Refueling Station (HRS) are presented and discussed.In the literature[41], an integrated energy system coupled with wind turbines and an on-site hydrogen refueling station is proposed to simulate the future scenario, which can meet the demands of cooling, heating, power and hydrogen. Literature[42] discusses the feasibility of hydrogen production in grid connected photovoltaic power station and the economic efficiency and the optimization of the PV grid connected system for the production of hydrogen.

In summary, most of the existing studies on hydrogen refueling stations focus on the spatial location layout as transportation infrastructure, system equipment configuration and operation optimization, while most of the studies on photovoltaic hydrogen refueling stations focus on the system configuration of photovoltaic hydrogen refueling stations, but there are fewer studies on the operation strategy of photovoltaic hydrogen refueling stations based on hydrogen demand and its economic environment application.

2.3 Application and research status of hydrogen fuel cell cogeneration

2.3.1 Application status

At present, kW-class equipment of hydrogen fuel cell cogeneration has been demonstrated, but its popularization and application are restricted by economy[43].

Japan is the largest market of micro distributed cogeneration system in the world. The Ene-Farm project for household fuel cells in Japan started in 2009. At present, the comprehensive efficiency of the system is over 95%, and the power of 700W can basically meet 60%~90% of the electricity consumption of ordinary households, with the sales of over 300,000 sets. As of 2018, about 270,000 fuel cell micro cogeneration devices have been installed in Japan[44]. In 2017, Japan announced the Basic Hydrogen Energy Strategy[45], pointing out that it is expected that the household cogeneration fuel cell system will replace the energy system of traditional residents in 2050.

While implementing large-scale fuel cell distributed power stations, South Korea has mainly acquired advanced technology from North America and Europe through acquisition or joint development. In addition to the large fuel cell of 308MW, there are 7MW fuel cells to supply power to 3,167 homes/buildings.In August 2020, the 50MW hydrogen fuel cell power plant located in Dashan Industrial Park, Ruishan City, South Korea was completed and put into operation. The power plant covers an area of 20000 square meters, with a total investment of 212 million US dollars, and is the world's largest by-product hydrogen power plant (25000 tons/year)[46]. The project consists of 144 units of 440 kW fuel cells, which can generate 400000 megawatt hours of electricity annually and meet the electricity needs of 160000 households.

The United States focuses on the development of large-scale distributed fuel cell power plants with power ranging from 100 kW to MW. Bloom Energy provides customers with distributed power solutions ranging from 200kW to 1MW[47]. The initial power generation efficiency of the system is as high as 53%~65%. As of the first half of 2020, Bloom has deployed and operated nearly 500MW power generation systems around the world, generating more than 16 billion kWh in the past 10 years.

There are already relevant application cases for small-scale power generation system of fuel cell distributed power generation system in China, but the relevant development of large-scale electric system is still under exploration[48].

In January 2022, the first 100kW proton exchange membrane fuel cell cogeneration system in Guizhou Province was officially put into operation[49]. The project is located in the new energy industry demonstration base in Guiyang Economic Development Zone, and as an important part of the hydrogen energy industry layout in the zone, it aims to provide part of the heat and electricity in the park with the fuel cell cogeneration system, provide design and construction experience for wide application, provide experience scenarios for future end-users It will provide experience in design and construction for wide application, provide experience scenarios for future end-users, and provide a project model for the industrial drive of the Economic Development Zone. The fuel cell cogeneration equipment has a power generation capacity of 100kW, a maximum waste heat recovery power of 130kW, and a hydrogen consumption of 6.7kg per unit hour, and the generated electricity will be consumed locally in the park in grid-connected operation mode, while the heat energy from the fuel cell will be used to supply domestic hot water to the staff apartments and canteens in the park through the waste heat recovery heat exchanger. The peak power generation efficiency of the system can reach up to 54%, and the total efficiency of cogeneration can reach over 98% (the calorific value of hydrogen is calculated by low calorific value). Compared with other fuel cell cogeneration projects in China, the cogeneration equipment adopted in this project is a special equipment for stationary power generation scenario, and the operating life can reach 40,000 hours, which provides a more practical solution for the development of fuel cell non-transportation field.

In January 2022, the 150kW-class fuel cell cogeneration system of the State Grid, which YuHydro Power won the bid to undertake, was officially shipped and delivered to Taizhou Dachen Island[50], which is the first island hydrogen energy production, energy storage and cogeneration technology demonstration project in China. The fuel cell combined heat and power system built by Henan Yu Hydrogen Power is equipped with self-developed fuel cell reactor, power generation system, waste heat recovery system and other core components, the system power generation efficiency is over 51%, the comprehensive efficiency of low thermal value combined heat and power supply is over 95%, the system AC grid-connected peak power is 150kW. The fuel cell cogeneration system is equipped with local one-key start/stop, automatic detection, remote control and telemetry functions; it is centrally installed in the form of prefabricated pods and supports multiple modules in parallel with expansion functions, which can be easily expanded to MW level; the fuel cell cogeneration system is equipped with multi-level protection functions and can adjust the power output of the system adaptively according to the user's load requirements, and supports grid-connected and off-grid functions.

In November 2021, Danqingyuan, the first demonstration community for hydrogen energy entering Wanjia smart energy in China, was officially put into operation in Danzao, South China Sea[51][52]. The project uses four 440kW fuel cell distributed cogeneration equipment as the foundation of the smart energy system, and a multi energy complementary energy microgrid as the core of the smart energy system to promote renewable energy interconnection and promote the construction of hydrogen residential and building projects. At the same time, each household in the community is equipped with a 0.7kW household fuel cell cogeneration equipment, with a total installed capacity of 275.8kW. Introduce two lithium bromide absorption refrigeration units to convert the heat energy generated by fuel cell equipment into cold water and deliver it to commercial use, achieving refrigeration effects. By using a plate heat exchanger, the heat generated during the fuel cell power generation process is converted into heat energy and adjusted to an appropriate hot water temperature to provide heating for commercial users in the community. The project achieves a power generation efficiency of over 53% of the power generation equipment, a comprehensive energy utilization efficiency of over 90%, and low emissions of pollutants and greenhouse gases, low noise, environmentally friendly system, with carbon emissions approximately 50%

of traditional energy systems.

In June 2021, the 20kW fuel cell cogeneration system organized and produced by Zhejiang Gaocheng Green Energy Technology Co., Ltd. was successfully delivered to the "Zero Carbon" Smart Park in Jiaxing Red Boat Base, Zhejiang Province[53], which is a new type of zero-emission cogeneration power station based on fuel cells, with significant advantages of safety, reliability, efficiency and environmental protection. It can be applied to the energy storage side on a large scale, as a cyclic power source and peak power source. Its rated grid-connected power is 20kW, and the single system includes electrolytic water hydrogen production module, hydrogen storage module, fuel cell power generation module, waste heat recovery module, DC power distribution module and control module. The fuel cell cogeneration power station can firstly provide electrical energy service to customers, and secondly can provide hot water or heating to customers, and the combined efficiency can be up to 90% or more.

Based on the current domestic electricity price level of residents and industry and commerce, small distributed fuel cell power generation system will not have economic advantages in China; For large-scale industrial and commercial distributed fuel cell systems, only by ensuring high utilization hours, especially in the case of high heating hours, can large-scale distributed CHP systems show obvious economic situation. High power generation cost and low electricity price will be the main obstacles for fuel cell cogeneration system to enter China market.

2.3.2 Research status

The research on hydrogen fuel cell cogeneration system mainly includes the analysis of key problems in system application, development trend of core technology, system simulation and optimization, etc. For example：

Literature[54] systematically analyzes key issues in the development of distributed hydrogen energy cogeneration system, such as equipment specification and performance, user preference, selection of integrated components, and its analysis results provide some guidance for the construction of domestic fuel cell cogeneration simulation model and the trial production of the actual physical system.

Literature[55] proposed a cogeneration system combining methane reforming to produce hydrogen and proton-exchange membrane fuel cell, and simulated the integrated system process. The results indicate that the system integration is completely feasible and can solve the application problems of fuel cells in hydrogen free areas, providing a basis and new ideas for the further application and promotion of fuel cells.

Literature[56] introduced the research progress in mathematical modeling, operation strategy, energy management, multidimensional evaluation, system optimization theory and application of cold cogeneration system based on proton-exchange membrane fuel cell, and proposed that future research could be carried out from multi-scale modeling, deep integration of source network load storage, improvement of system evaluation system, system optimization and real-time regulation.

Literature[57] established a 100 kilowatt Proton-exchange membrane fuel cell cogeneration system model based on the Aspen Plus platform, verified the accuracy of key equipment models, and analyzed the impact of equipment operating parameters on system performance under steady-state conditions. Its research results can guide the adjustment of PEMFC cogeneration system operating parameters to achieve the comprehensive ratio of heat and power in buildings and parks in the regulation area, provided reference suggestions for the operation strategy of PEMFC-CHP system.

Literature[58] has built a hydrogen compressor and hydrogen fuel cell model on MATLAB/Simulink simulation platform. Using model predictive control, parameter identification and sub-unit PID control, the hydrogen fuel cell can be used to generate flow and control signals to adjust the hydrogen compressor power and the number of hydrogen fuel cell units working according to the peak regulation demand of the power grid and heat network, so as to realize a good peak regulation control effect of the hydrogen fuel cell combined heat and power supply system.

In summary, the existing literature on hydrogen fuel cell cogeneration mainly focuses on the study of proton exchange membrane fuel cell cogeneration systems, including mathematical model construction studies and system operation optimization studies, but it focuses more on the research of the system itself and related equipment, while fewer studies study the impact of hydrogen cost price on its application.

2.4 Application and research status of hydrogen-fueled gas turbine

2.4.1 Application status

The core equipment of hydrogen turbine/hydrogen-fueled gas turbine still adopts foreign technology, so it is necessary to speed up the research and development of advanced domestic gas turbine.In recent years, major international gas turbine manufacturers such as Mitsubishi Hitachi in Japan, General Electric in the United States, Siemens Energy in Germany, and Ansaldo Energy in Italy have all launched corresponding development plans for hydrogen fueled gas turbines. They have started research, development, and demonstration applications of hydrogen blended or even pure hydrogen fueled gas turbines, laying a technical foundation for deep decarbonization in the power industry.

GE's gas turbines in the United States have been operating on hydrogen and similar low-calorific-value fuels for more than 30 years. As of 2019, GE has installed more than 70 gas turbines with more than 4.5 million cumulative operating hours[59]. Among them is the Long Ridge Energy HA-rated gas-fired power plant in Ohio, USA, which is making a low-carbon transition by blending hydrogen into natural gas fuel. This is not only the first hydrogen-fueled gas-fired plant in the U.S., but also the first HA-rated combined cycle gas-fired plant in the world to achieve hydrogen-blended combustion[60]. The plant is equipped with a GE7HA.02 gas turbine with an installed capacity of 485 MW and is expected to meet the electricity needs of 400,000 local households. The unit is currently 15-20% (by volume) hydrogen doped and is scheduled to have 100% hydrogen combustion capability by 2030.

The Fucina power plant of the Italian State Power Company has been using an 11MW GE-10 gas turbine to burn hydrogen fuel with a hydrogen content of 97.5% since 2010[60]. Hamburg, Germany successfully renovated the world's first megawatt scale gas turbine cogeneration system with 100% hydrogen operation in 2020, using hydrogen as fuel to provide heating and electricity services for local residents and buildings[61]. In 2019, Siemens Energy promised to achieve 100% hydrogen gas turbines by 2030[62], covering all product combinations from small to heavy-duty gas turbines.

The 6B.03 gas turbine in the Korean Dashan refinery has used hydrogen fuel with 70% hydrogen content for more than 20 years, and the maximum hydrogen content exceeds 90%[63]. So far, the unit has used hydrogen rich fuel for more than 105 hours accumulatively. Doosan Hengneng is conducting research and development on a 50% hydrogen mixed combustion environmentally friendly burner for 300MW hydrogen gas turbines with the Korean Institute of Machinery Research[64], and successfully conducted a 30% hydrogen mixed combustion test for a hydrogen gas turbine burner in August 2022; It is expected that a 50% hydrogen mixed combustion test of a hydrogen gas turbine burner will be conducted in 2023, and the development of a large-scale hydrogen gas turbine will be completed in 2027.

Mitsubishi Hitachi Power Systems in Japan has been developing hydrogen fueled gas turbines since 1970. The J series gas turbines launched in 2011 have the ability to blend 30% renewable hydrogen and 100% use renewable hydrogen for development. In 2018, large-scale hydrogen fuel gas turbine testing was conducted. The results of hydrogen fuel testing with a hydrogen content of 30% showed that the newly developed proprietary burner can achieve stable combustion of mixed hydrogen fuel, reduce carbon dioxide emissions by 10% compared to pure natural gas power generation, and improve the efficiency of combined cycle power generation by more than 63%[65]. In June 2021, Japanese gas turbine manufacturer Mitsubishi Heavy Industries announced that it would commercialize high-power hydrogen fueled heavy-duty gas turbines around 2030[66]. Currently, Mitsubishi Heavy Industries is participating in the project to renovate a 1.32 million kilowatt output natural gas turbine combined cycle (GTCC) power plant. The project requires Mitsubishi Heavy Industries to deliver one of the three M701F gas turbines[67] located at the Nuon Magnum power plant in the Netherlands, which will be converted to 100% hydrogen fuel by 2023.

In 2021, Guangdong Energy, a state-owned power company in China, ordered two GE9HA.01 gas turbines for its Guangdong Huizhou Combined Cycle Power Generation Company, which burn mixed natural gas fuels with a volume of up to 10% hydrogen. It is expected to be put into operation in 2023, providing 1.34 gigawatts of electricity to Guangdong Province[68]. In December 2021, China State Power Investment Group Co., Ltd.'s Jingmen Green Power Plant achieved 15% hydrogen blending combustion transformation and commercial operation of its operating gas turbine. This is the first time China has implemented hydrogen blending combustion transformation experiments and scientific research research on heavy-duty gas turbine commercial units. This project has become the world's first combined cycle and cogeneration demonstration project for hydrogen blending combustion in natural gas commercial units[69].

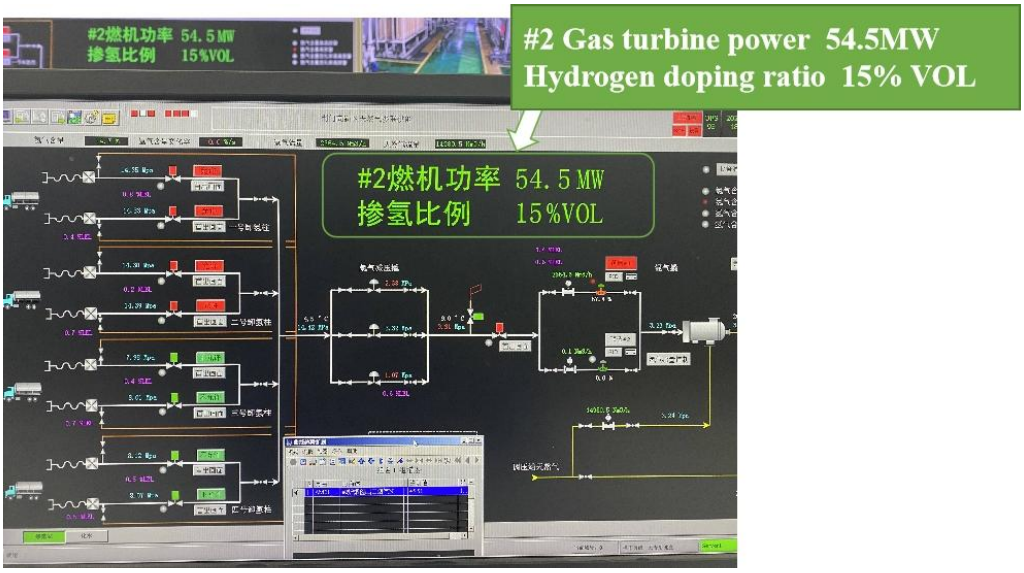

Fig.2-4 Operation status of 15% hydrogen mixed gas turbine in Jingmen Lvdong Power Plant[69]

In summary, hydrogen turbines have developed relatively early, with complete types and advanced technology, and can basically achieve 100% pure hydrogen combustion. However, the core equipment of Chinese projects still adopts foreign technology, and it is necessary to accelerate the research and development of advanced domestic gas turbines. Combined with the development of domestic hydrogen production and storage technology, the research and application of hydrogen fuel gas turbines should keep up with the international pace.

2.4.2 Research status

At this stage, the research on hydrogen-doped gas turbine is mainly focused on the study of combustion characteristics, system operation characteristics, and applications of hydrogen-doped hybrid fuel. For example:

In the terms of combustion characteristics of hydrogen-doped fuel blends.The literature[70] analyzed the changes of combustion characteristics such as adiabatic flame temperature, laminar premixed flame propagation speed and ignition delay time for different ratios of natural gas-doped hybrid fuel by numerical calculation with the PREMIX model of Chemkin software, and the results showed that the change rate of fuel combustion characteristics accelerated with the increase of hydrogen-doping ratio. Literature [71], the combustion and NOx generation characteristics of an 80 kW micro-gas turbine annular low-NOx combustion chamber were studied by numerical simulation with appropriate modifications, and the results showed that increasing the hydrogen doping ratio in the ammonia/hydrogen fuel mixture could improve the flame propagation speed, flame temperature and combustion efficiency.Literature[72] conducted a numerical simulation study of the natural gas hydrogen-doped combustion process in a Siemens SGT-800 gas turbine combustion chamber, and the results showed that hydrogen-doped combustion in the current combustion chamber would lead to an earlier fuel ignition location, higher temperature peak, shorter flame axial length, and larger volume in the high temperature region.

In the terms of system operation characteristics research. In the literature[73], a modular modeling approach was used to establish a prognostic model of the variable operating characteristics of the gas turbine, and the operating parameters, component operating characteristics and unit energy consumption of the gas turbine at different loads with different hydrogen blending ratios were calculated and analyzed. The power, specific work and power generation efficiency of the gas turbine increased with the increase of hydrogen blending ratio with the increase of hydrogen volume fraction.In the literature[74], a mathematical model was developed for the basic operating characteristics of an F-class heavy-duty gas turbine combined cycle unit with hydrogen doping for power generation, and Python calculations were used to predict the unit efficiency, power and gas temperature, and CO_2 emissions at different hydrogen doping ratios. Under the variable air volume approach, increasing the hydrogen doping ratio increases the gas turbine efficiency and power output, and significantly decreases the CO_2 emissions in gas and flue gas.

In the terms of hydrogen-doped gas turbine applications.In the literature [75], a hydrogen storage unit based on a hydrogen-fired gas turbine was established, and the complementary optimal operation mechanism and modeling of the electric-thermal-hydrogen multi-energy system was explored from three aspects: hydrogen production from renewable energy electrolytic water, hydrogen storage technology, and hydrogen-fired gas turbine technology. The results show that the use of hydrogen-fired gas turbine as the power generation link of hydrogen storage unit is a feasible solution and has practical value. In the literature [76], a virtual power plant with P2G-CCS coupling and gas doping was established, and an optimal scheduling strategy for the virtual power plant based on the stepped carbon trading mechanism was proposed. The mathematical models of hydrogen-doped gas turbine, hydrogen-doped gas boiler, two-stage electric-to-gas and carbon capture system are established; the effects of different fixed hydrogen-doping ratios, variable hydrogen-doping ratios and different stepped carbon trading parameters on the low-carbon and economic performance of the virtual power plant are analyzed.

In summary, the research on hydrogen-doped gas turbine systems in the existing literature mainly focuses on the influence of hydrogen doping ratio on the combustion characteristics and operating characteristics of hydrogen-fired turbines, and the research on the application of hydrogen-doped gas turbines mostly focuses on the application of hydrogen-doped gas turbines in electric-thermal-hydrogen multi-energy systems, while the research on the influence of hydrogen cost and price on the application of hydrogen-fired turbines is less.

2.5 Application and research status of hydrogen fuel cell vehicles

2.5.1 Application status

Countries all over the world actively promote the large-scale application of hydrogen fuel cell vehicles[77][78][79][80]. For example, as the country with the largest number of fuel cell vehicles in the world, by the end of 2020, the number of fuel cells in South Korea was 10,906. As the second country in the world with over 10,000 fuel cell vehicles, as of June 2021, the number of fuel cell vehicles in the United States has reached 10,803. From 2003 to 2010, the European fuel cell bus demonstration program demonstrated and operated 30 first-generation Daimler fuel cell buses in 10 cities, running for a total of 1.3 million miles. By the end of 2017, Japan had more than 2,000 hydrogen fuel cell vehicles. It is planned to have 200,000 hydrogen fuel cell vehicles on the road by 2025 and 800,000 by 2030, and 900 hydrogen refueling stations will be built and put into use in China.

Under the strategic goal of "2030 peak carbon dioxide emissions, 2060 Carbon Neutralization" in China, hydrogen energy is facing new development opportunities. As the main application form of hydrogen energy, hydrogen fuel cell vehicle has become an important means to achieve deep decarbonization in the transportation field, so the state strongly supports the development of hydrogen energy. At present, the number of hydrogen fuel cell vehicles in China is increasing in an orderly way. From 2016 to 2020, the number of hydrogen fuel cell vehicles in China increased year by year. Due to the epidemic, the sales volume declined in 2020. By the end of 2020, the number of hydrogen fuel cell vehicles was 7,352[81]. By 2021, China accounted for 18% of the number of hydrogen fuel cell vehicles in major countries in the world, about 8,922[82]. In March 2022, the National Development and Reform Commission of China and the National Energy Administration jointly issued the Medium-and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035)[83], which proposed to promote the diversified application of hydrogen energy in an orderly manner, including transportation, industry and other fields, and explore the path of commercial development. It is clear that by 2025, the number of fuel cell vehicles will be about 50,000, and a number of hydrogen refueling stations will be deployed and built. The hydrogen production from renewable energy will reach 100,000-200,000 tons per year, and the carbon dioxide emission will be reduced by 1-2 million tons per year.

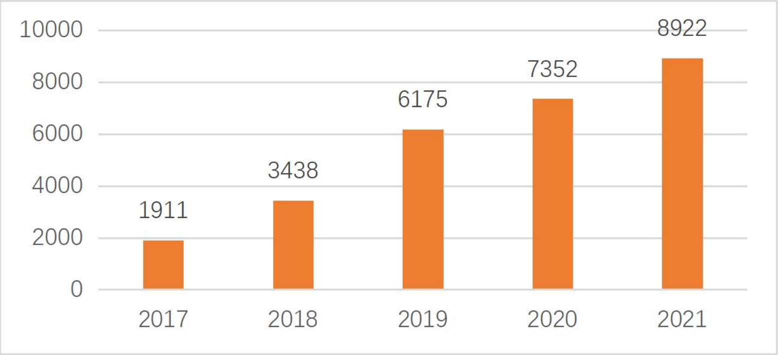

Fig.2-5 2017-2021 number of hydrogen fuel cell vehicles in China

In terms of R&D and production of hydrogen fuel cell vehicles, except for a few achievements, most enterprises in China are in the R&D stage. As the earliest automobile enterprise engaged in the research and development of hydrogen fuel cell technology in China, China SAIC has successively released a number of hydrogen fuel cell automobile models[84]. In 2016, MAXUSFCV80 made its debut at Beijing Auto Show. It is the first commercial fuel cell wide-body light bus in China. It is also the first fuel cell light bus in China and the first fuel cell light bus in the world with new access standards. This car uses dual power sources, mainly fuel cell system and supplemented by power battery, and its cruising range can reach 500km[85]. In 2020, the world's first fuel cell MPV was officially released, and the MAXUSEUNIQ7 of SAIC Chase was put on the market in mass production[86], and announced the first "hydrogen strategy" of China automobile industry. In 2022, SAIC Chase launched the first hydrogen-fueled passenger car G20FC, which can achieve a cold start of minus 30℃. The cruising range of NEDC under comprehensive working conditions is as high as 550 kilometers, and hydrogenation can be completed within 5 minutes.

To sum up, after years of development, fuel cell vehicles have gradually shifted from prototype vehicles to commercial applications. Compared with fuel cell vehicle technology at home and abroad, there is still a big gap in domestic fuel cell vehicle technology, which is restricted by life, cost and performance. The main reason is that the core components of fuel cell system still depend on imports, and the basic research on fuel cell is not sufficient. The research on fuel cell vehicle is still in its infancy.

2.5.2 Research status

The Hydrogen fuel vehicle is mainly composed of fuel cell engine system, motor system, auxiliary power supply system, on-board hydrogen storage system, vehicle control system and other components. Among them, the fuel cell engine system is the core component of fuel cell vehicles, and its performance determines the overall operating efficiency, adaptability to working conditions, safety performance, service life, and development cost of fuel cell vehicles[87]. Therefore, the research on fuel cell engine system is relatively common. For example:

Literature[88] used AMESim simulation software to establish a one-dimensional simulation model for the thermal management system of a hydrogen fuel engine, and carried out simulation analysis on different control schemes, and proposed a thermal management control scheme based on the following of multiple parameters such as stack power, stack inlet and outlet coolant temperature difference, coolant flow, etc, in order to solve the problems of large fluctuation of stack temperature and slow response speed of thermal management subsystem in the process of load change of hydrogen fuel engine system.

In order to fully utilize the power generation performance of PEMFC, literature[89] analyzed the influence of temperature on the output characteristics of the battery, and conducted research on the cooling system model and its control strategy. This has important theoretical significance and practical value for maintaining the normal operation of the battery, improving the reliability of fuel cells, and extending the service life of the battery.

Literature[90] established a simulation model for the output characteristics of a fuel cell stack and a simulation model for the cathode and anode side intake systems based on the design parameters of the stack in MATLAB/Simulink. A fuzzy neural network decoupling control algorithm was proposed, which has important guiding significance for ensuring the stability of the internal pressure and meeting the rapid response of the inlet pressure and flow during changes.

The literature [91]analyzes the integration technology of Hydrogen fuel cells for passenger cars, and discusses the influence factors of Hydrogen fuel cell engine system integration technology and reliability and durability. The integration scheme proposed by the research has good technical indicators of reliability and durability, which is suitable for promotion and application.

In addition, the research on hydrogen fuel cell vehicles at this stage also involves its industrial development forecast, such as:

In order to explore the value transfer relationship among the enterprises in the hydrogen fuel cell vehicle industry chain, literature[92] constructed a GERT network model of hydrogen fuel cell vehicle industry based on the resource-value transfer relationship based on research data, so as to provide effective quantitative support for the macro regulation of relevant government departments.

In the literature[93], the Nash equilibrium principle was used to analyze the coordination of interests among various interest subjects in the industry cultivation period, and the theory of evolutionary game theory was used to discuss the mechanism of industrial strengthening and spatial diffusion between enterprises and the government in the industry maturity period, and rationalized suggestions were put forward to facilitate the coordination among the government, research institutes and enterprises to jointly promote development.

The literature[94] analyzed the advantages and disadvantages, opportunities and threats of the synergistic development of hydrogen fuel cell vehicle industry between Xiong'an New Area and Baoding City based on the SWOT analysis framework, and put forward development suggestions.

The paper[95] constructed a system dynamics causality model and a stock flow model for the hydrogen fuel cell vehicle industry in Jiangsu Province, and analyzed in depth the evolutionary trend of the hydrogen fuel cell vehicle industry in Jiangsu Province, revealed the impact of different financial subsidy policy scenarios on the industry development, and provided reference and reference for the government to formulate a scientific and reasonable hydrogen fuel cell vehicle industry policy.

Taking into consideration the limited rationality of the government, enterprises and consumers, the literature[96] applied a tripartite evolutionary game theory (EGT) model to analyze the impact of government regulation on the development of the HFCV industry, so as to effectively promote the production of HFCV enterprises and the purchase of HFCVs by consumers.

The literature[97] studied the whole life cycle cost of hydrogen fuel cell vehicles by dividing them into three perspectives: enterprise cost, user cost and social cost, established a multi-perspective hydrogen fuel cell vehicle whole life cycle cost model and cost prediction model, and analyzed the whole life cycle cost sensitivity factors for HFCVs from the perspective of vehicle purchase price, hydrogen price and government subsidies.

In summary, the existing literature on hydrogen fuel cell vehicle itself mainly focuses on the fuel cell engine system, including the research on its thermal management system, cooling system, air intake system, and integration technology, etc. The research on the prediction of the development scale of the hydrogen fuel cell vehicle industry mainly focuses on the research on the impact of economic factors such as policy subsidies, life-cycle costs, interest coordination, etc. on its industrial development from the perspective of government control, industry chain, industry cultivation, etc., while the research on the development scale of Hydrogen fuel cell vehicles in a region, its ownership, and the prediction of hydrogen demand is less.

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Chapter 3

THEORIES AND METHODOLOGY OF THE STUDY

CHAPTER THREE: LITERATURE REVIEW OF THE DISTRIBUTED ENERGY SYSTEM

THEORIES AND METHODOLOGY OF THE STUDY

3.1 Motivation

Hydrogen energy, as a clean, efficient, safe and sustainable new energy source, has become an important direction for low-carbon energy development and transformation. With the proposal of China's "carbon peak by 2030 and carbon neutrality by 2060" strategic goal, promoting hydrogen energy to be officially included in China's top-level strategy, the application of hydrogen energy has officially been fully launched, and the hydrogen industry is about to enter a new stage of development. Hydrogen applications will be able to develop rapidly. In addition, in response to the current situation of hydrogen supply exceeding hydrogen application in Shanghai, expanding the feasibility of hydrogen energy application has practical significance.

Therefore, this paper will discuss the feasibility of hydrogen application in different forms in multiple fields, and carry out the feasibility study on the application of photovoltaic Hydrogen station in the transportation field, the feasibility study on the application of Hydrogen fuel cell cogeneration in the construction field, and the feasibility study on the application of hydrogen turbine. Therefore, this chapter will build models of photovoltaic hydrogen station, hydrogen fuel cell cogeneration system and hydrogen turbine system. In addition, as load forecasting methods and related model construction are the foundation of project application, this chapter will introduce and analyze load forecasting methods, construct load forecasting models and load forecasting accuracy evaluation models, and compare and analyze the proposed load forecasting models.

In addition, as a relatively mature application form of technology, the development scale of hydrogen fuel cell vehicles in Shanghai is expected to be further expanded, so this chapter will introduce and analyze the SWOT analysis method to facilitate in-depth analysis of the development status and trend of hydrogen fuel cell vehicles, and introduce and analyze relevant prediction models to analyze the development scale of hydrogen fuel cell vehicles in Shanghai and the hydrogen application potential of the city.

Environmental and economic analysis is an important means to evaluate the feasibility of hydrogen energy application. Therefore, this chapter will construct an environmental and economic benefit evaluation model, such as the annual total cost model of the energy system, cost-benefit analysis model, carbon emission calculation model, etc.

3.2 Load forecasting model

3.2.1 Load forecasting methods and models

Load forecasting is the foundation for ensuring energy supply and demand balance, as well as for formulating energy system equipment configuration and operation strategies. There are various methods for load forecasting, and corresponding models need to be selected according to different needs. At present, load forecasting models include macro indicator method, regression analysis method, unit area indicator method, artificial neural network method, etc.

(1) The macro indicator method

The macro indicator method, also known as the electricity elasticity coefficient method[1], is applied to power load forecasting, which reflects the ratio of the annual average growth rate of electricity consumption to the annual average growth rate of the national economy[2]. The electricity elasticity coefficient is an indicator that reflects the relationship between the growth of electricity consumption and the development of the national economy over a period of time from a macro perspective. However, with the changes in power allocation technology and socio-economic structure, this method is difficult to accurately predict power demand.

(2) Regression analysis method

Regression analysis [3][4] uses statistical principles to perform mathematical reasoning on a large amount of data, fitting the relationship between the independent and dependent variables in the data to a regression equation with good correlation, and then extrapolating to predict future changes in the dependent variables. This method is applicable to the analysis of a large number of years of historical data. The prediction accuracy is directly affected by the type of tropic, the selection of regression variables, regression variable factors, etc.

(3) The unit area indicator method

The unit area indicator method[5][6] divides the predicted area into industrial, commercial, and residential areas. Based on the overall planning and economic conditions of the area, appropriate load density indicators are selected for various buildings to calculate the energy load demand of the entire area. The load density index of this method requires a large amount of historical data for statistical analysis.

$$\mathrm{E} = \sum \mathrm{e_i S_i} \tag{3-1}$$

$$\mathrm{C} = \sum \mathrm{c_i S_i} \tag{3-2}$$

$$\mathrm{H} = \sum \mathrm{h_i S_i} \tag{3-3}$$

Among them, E is the power load, C is the cooling load, H is the heating load, $\mathrm{e_i}$ is the electrical index of functional zone i, $\mathrm{c_i}$ is the cooling index of the building unit area in functional zone i，$\mathrm{h_i}$ is the heating index of the building unit area in functional zone i, and $\mathrm{S_i}$ is the area of functional zone i.

(4) The meta unit method

The meta unit method is mainly used for regional building load forecasting. The area is usually composed of buildings of different types and functions, so the regional building load is affected not only by the factors such as building orientation, building structure, thermal performance of enclosure, outdoor meteorological parameters, indoor thermal disturbance and building operation schedule, but also by many factors such as the spatial layout of buildings in the whole area, regional form, regional microclimate and user behavior, as a result, the regional building load has the characteristics of annual time dynamics and spatial distribution, and the demand for building cooling, heating, electricity, and gas shows seasonal and daytime dynamic characteristics with meteorological conditions, building behavior, and other factors.

The regional building load can be equivalent to the integration of single building load. The research idea is: select a typical single building → establish a model → scenario analysis method→annual dynamic hourly load→probability weighting of different scenarios→expand the single building to the region to forecast the cooling and heating loads of regional buildings. The rationality and accuracy of this method are shown as follows:

1) Using software to establish a typical building model as the basis for load forecasting, the so-called typical building refers to representative buildings that can reflect the architectural form, scale, enclosure structure, internal disturbance, load characteristics, and other characteristics of this type of building in the planning area. To overcome the problem of uncertain specific information for each building during the regional energy planning stage.

2) The scenario analysis method is adopted for the same type of architectural model. Different scenarios are set according to the indoor thermal disturbance intensity, the thermal performance of the envelope, the building use schedule and other parameters. The probability of each scenario is preset according to the regional characteristics, and the annual hourly probability weighted value of each typical building under different scenarios is calculated to avoid the selection of simultaneous use coefficient between similar buildings.

3) When expanding from individual building loads to regional building loads, the annual hourly superimposed loads of different types of buildings are used to avoid the problem of selecting simultaneous usage coefficients between different types of buildings, as the simultaneous usage coefficients obtained based on actual research or design manuals may not represent the future use of buildings in the design area.

(5) The artificial neural network method

The artificial neural network method[7] imitates the intelligent analysis principles of the human brain, exhibiting strong memory and adaptability to the imprecise, unstructured, and nonlinear laws of a large amount of data, and can perform self-learning, data reasoning, and fitting optimization. Among them, recurrent neural network[8][9][10] (RNN) is a powerful type of artificial neural network algorithm, particularly suitable for processing time series data, etc. LSTM and GRU are currently the most widely used variants of the two recurrent neural network models.

1）Short and long term memory network

Long short term (LSTM) is a special form of recurrent neural network (RNN), which can better solve gradient explosion and gradient disappearance. Compared with RNN, LSTM can perform better in longer sequences. Control the transmission state through the gating state, remember the information that needs to be remembered for a long time, and forget the unimportant information; Unlike ordinary RNN, there is only one memory superposition mode. It is especially useful for many tasks requiring "long-term memory", such as predicting time series intervals and events with long delays [11]. Research shows that LSTM network effectively improves the accuracy of short-term load forecasting [12].

LSTM has two transmission states, ct (cell state) and ht (hidden state). Generally, ct output is ct-1 transmitted from the previous state plus some values, while ht is often very different in different nodes. The current input xt of LSTM and the ht-1 splicing training passed down from the previous state get four states. The forgetting gate ft , the input gate it and the output gate ot are multiplied by the weight matrix by the splicing vector, and then converted into a value between 0 and 1 through a sigmoid activation function as a gating state. ct converts the result to a value between -1 and 1 through a tan h activation function. The internal basic units of the LSTM network are shown in the figure below.

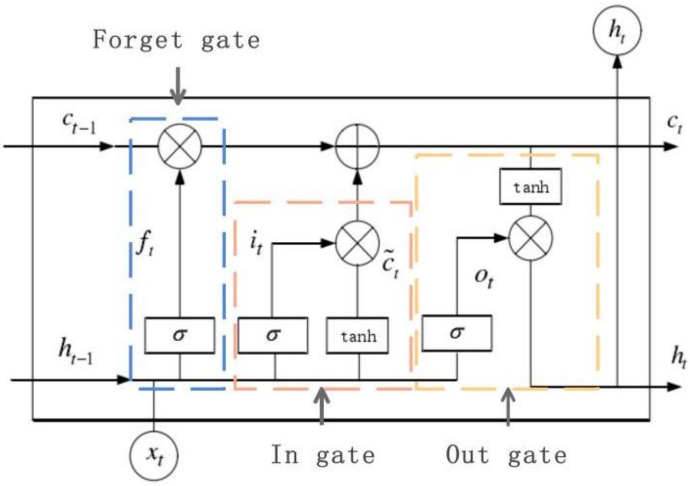


Fig.3-1 LSTM network basic unit

According to the internal structure of forgetting gate, input gate and output gate, the value of LSTM network in the hidden layer depends on the current value and the value within one hour. The three gates are used as control switches to delete the historical information that is not useful for the output characteristics, retain the relevant characteristics and improve the prediction accuracy[13].

2）Gated loop network

Gate recurrent unit (Gru) is a good variant of LSTM network. Like LSTM, it is also proposed to solve the problems of long-term memory and gradient in back propagation. Compared with LSTM network, it has simpler structure, shorter operation time and higher accuracy [14].

In 2014, Chung proposed the Gru network model and improved the LSTM model. By using its specific memory and forgetting blocks, we can better solve the problems of gradient disappearance and gradient explosion in the training process of load time series [15]. The neural network structure of Gru is similar to that of LSTM, but different from the three gates of LSTM model, there are only two gates in Gru model: update gate and reset gate. The update gate is used to control the extent to which the state information of the previous time is brought into the current state. The larger the value of update gate, the more the state information of the previous time is brought in. Replace the output gate of the LSTM with the reset gate. The smaller the reset gate value is, the less the previous status information is written. The specific structure is shown in the following figure.

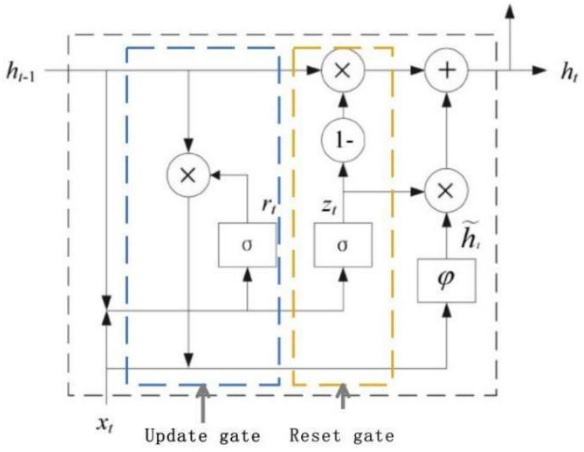


Fig.3-2 GRU network basic unit

Where rt is the update door, zt is the reset door, φ Is the tanh function, ht is the hidden layer at the current time, ht-1 is the hidden layer at the previous time, h t is the candidate hidden state at the current time. The mathematical model of Gru is shown below.

$$r_t = \sigma\left(w_r \cdot \left[h_{t-1}， x_t\right]\right) \tag{3-4}$$

$$z_t = \sigma(w_z \cdot [h_{t-1}, x_t])\# \tag{3-5}$$

$$\hat{h}_t = \tan h\left(w_{\hat{h}} \cdot \left[r_t \times h_{t-1}， x_t\right]\right)\# \tag{3-6}$$

$$h_t = (1 - z_t) \times h_{t-1} + z_t \times \hat{h}_t\# \tag{3-7}$$

$$y_t = \sigma(w_o \cdot h_t)\# \tag{3-8}$$

where, []——two vectors connected; ×——product of matrices; r_t——Update gate state quantity, z_t——reset gate state; w_r、w_z、$w_{\hat{h}}$、w_o——h_{t-1}, x_t Reset gate, weight, candidate set, update gate obtained by multiplying the output vector matrix; $\hat{h}_t$——candidate hidden state; h_t——current state; y_t——output variable; σ——Activate the sigmoid function.

The historical cooling load of the airport terminal will have a long-term impact on the current state[16]. The larger the updated gate value is, the greater the historical cooling load characteristic factors of the airport terminal will have an impact on the current state. The more the reset gate value is, the more the historical characteristic state information will be discarded. Through iterative operation, the historical load characteristic data of the airport terminal will be memorized and updated, and different weight values will be given, The cooling load of the terminal building in the next few days is predicted by the trained model.

3）Optimization of Gru network model based on particle swarm optimization

Gru neural network is prone to accuracy degradation in the calculation process of gradient descent method [17]. In order to improve the prediction accuracy, particle swarm optimization algorithm is used to optimize the number and iteration times of Gru neural network in each layer, train the neural network weight, optimize the loss function, and obtain the optimal solution through iterative updating.

Particle Swarm Optimization (PSO) aims to solve optimization problems. Through intelligent global search, potential solutions to optimization problems can be found. The proposed algorithm is inspired by the behavior of bird foraging groups. The correspondence between PSO algorithm and bird foraging concept is shown in the figure below.

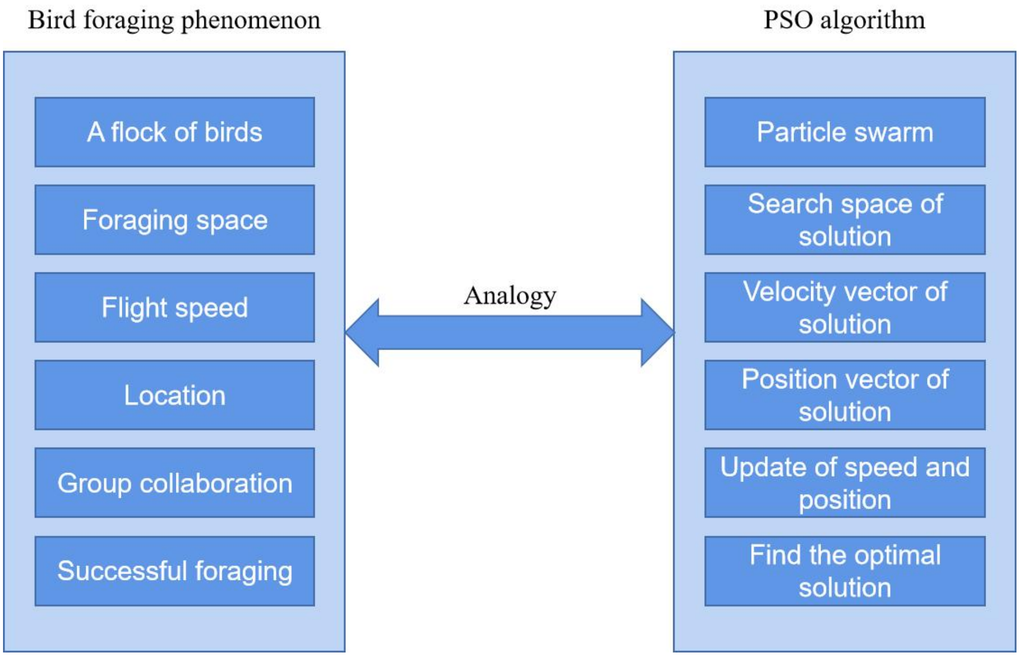


Fig.3-3 Correspondence between PSO algorithm and bird foraging concept [58]

PSO is initialized as a group of random solutions, and then the optimal solution is found through iteration. In each iteration, particles update themselves by tracking two extreme values; The first is the optimal solution found by the particle itself, which is called the individual extremum; The other extreme value is the optimal solution currently found by the whole population. This extreme value is the global extreme value.

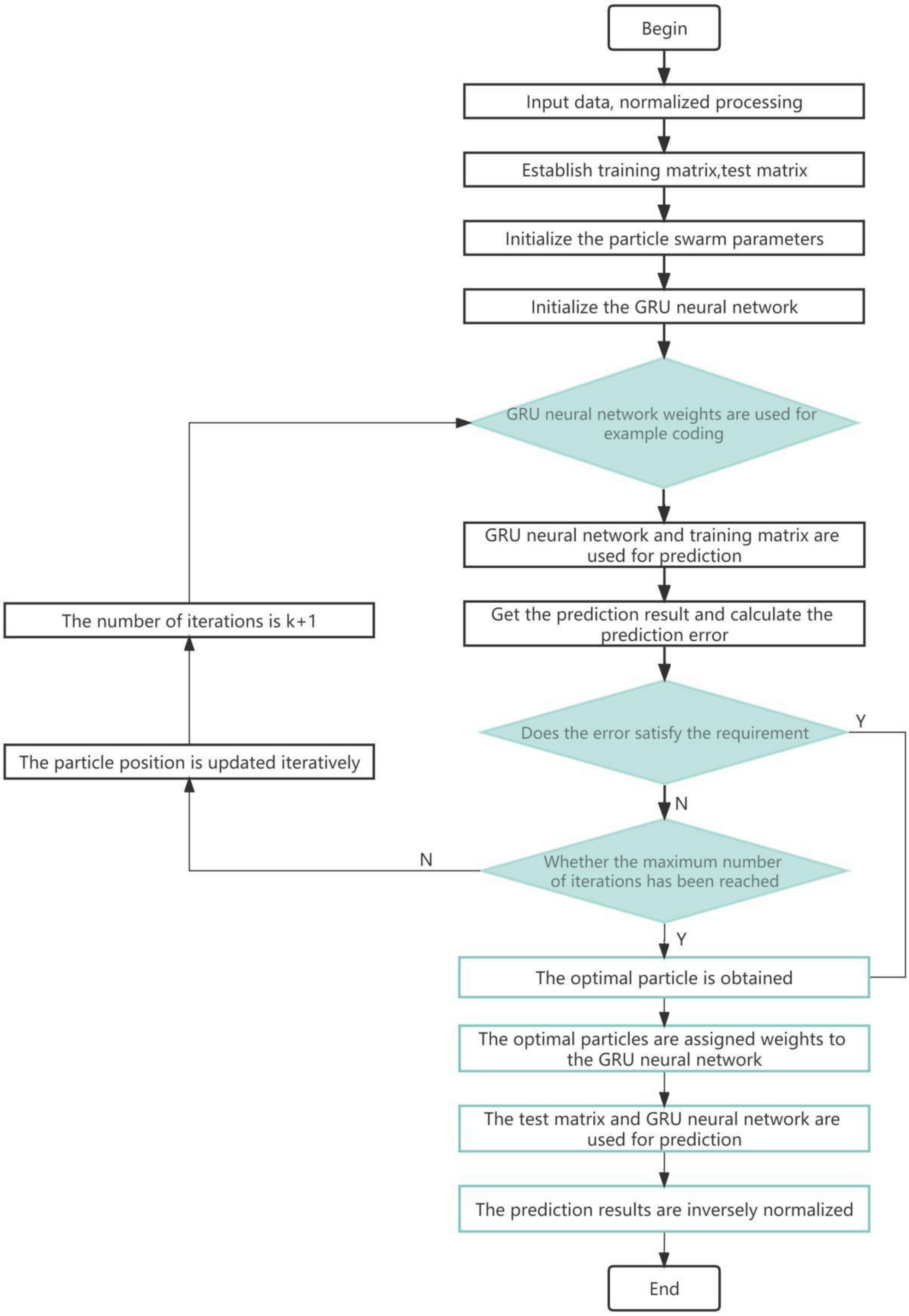


Fig.3-4 Flow chart of short-term load forecasting model of PSO-GRU network

The prediction process of optimizing Gru neural network based on particle swarm optimization (PSO) is as follows:

Step1: perform abnormal value and normalization processing on input data, and establish training matrix and test matrix.

Step2: randomly generate the primary population, and set the upper and lower limits of the parameters contained in each particle in the population.

Step3: Gru network initialization, build Gru multi load short-term forecasting model.

Step4: particle code Gru network weights.

Step5: use Gru neural network and training matrix to predict, calculate the error of output results, compare whether the error meets the requirements, and whether the number of iterations reaches the maximum.

Step6: repeat steps 4 and 5 to get the optimal particle.

Step7: the optimized optimal particle is used for Gru network weight, the test matrix and Gru neural network are used for prediction, and the prediction results are de normalized.

For a more intuitive understanding of the calculation process, the algorithm process is shown in the following figure.

3.2.2 Load forecasting evaluation indicators model

For the evaluation of the effect of load forecast value, appropriate evaluation model is required. In this paper, four indicators are used to evaluate the forecast model: root mean square error (RMSE), mean square error (MSE), mean absolute error (MAE), and mean absolute percentage error (MAPE), these indicators are used to evaluate the error between the measured value and the true value. The smaller the error, the higher the accurate value. The calculation formula is as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2}\# \tag{3-9}$$

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 = \frac{1}{n}\sum_{i=1}^{n} e_i^2 \# \tag{3-10}$$

$$\mathrm{MAE} = \frac{1}{n}\sum |y_i - \hat{y}_i| = \frac{1}{n}\sum |e_i| \# \tag{3-11}$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n} \frac{|y_i - \hat{y}_i|}{y_i} \# \tag{3-12}$$

Where, n——verify the number of samples; i——i-th sample; y_i——predictive value; $\hat{y}_i$——actual value.

3.2.3 Comparative analysis of load forecasting models

The research approach for comparative analysis of load forecasting models is to first screen highly correlated factors through correlation analysis, and then combine historical load related feature data to train and test neural network models using MATLAB software to compare and select the best.

(1) Correlation analysis of influencing factors

According to the characteristics of the envelope structure and energy consumption of the building, the cooling load of the airport terminal is mainly composed of five parts [18]. The cooling load caused by heat gain of the envelope structure, the cooling load caused by outdoor fresh air organization or infiltration wind, the cooling load caused by solar radiation projected by large-area glass curtain walls and external windows, the cooling load caused by heat dissipation of passengers and staff of the terminal, and the cooling load caused by indoor lighting equipment and electrical appliances, The load formula of each part is as follows. Based on the five cooling loads, the main influencing factors are outdoor temperature and humidity, indoor temperature and humidity, outdoor solar radiation intensity, indoor personnel density fluctuation, heat dissipation of personnel sensible and latent heat, outdoor average wind speed, equipment calorific value. At the same time, historical load and weather parameters over 1-2 hours should be considered.

$$Q_\tau = KF(t_{out} - t_n) + FX_g J_{w\tau} + 1000N\left(H_\tau - H_n\right) + n(q_s + q_l) + W_\tau \tag{3-13}$$

where, K——heat transfer coefficient of building envelope, $W/(m^2 \cdot k)$; F——enclosure area, m^2; $t_{out} - t_n$——indoor and outdoor temperature difference,°C; N——number of fresh air units; N——number of people in the room; q_s——personnel sensible heat,W; q_l——personnel latent heat,W; W_τ——equipment heat,W.

In order to avoid the influence of irrelevant factors or parameters with little correlation on the accuracy of prediction, Pearson correlation coefficient method is used to analyze the correlation between cooling load and input parameters. Pearson correlation coefficient is a measure of the correlation between input and output. The calculation formula of Pearson correlation coefficient method is shown in the formula.

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\left(\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\right)\left(\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}\right)} \tag{3-14}$$

where, R_{xy}——The correlation coefficient between the two variables, a positive value indicates a positive correlation, a negative value indicates a negative correlation; x_i——A sequence of factors such as the value of outdoor temperature at point i; $\bar{x}$——the mean of the factor; y_i——Another sequence of factors such as the value of cooling load at point i; $\bar{y}$——The mean value of this correlation factor; n——The mean value of this correlation factor，R_{xy}——The degree of correlation is as follows.

Table 3-1 Correlation table

$\lvert R_{xy}\rvert$scope	Relevance
$\lvert R_{xy}\rvert = 0$	irrelevant
$0 < \lvert R_{xy}\rvert < 0.19$	very low

$0.2 < \lvert R_{xy} \rvert < 0.39$	low
$0.4 < \lvert R_{xy} \rvert < 0.69$	moderate
$0.7 < \lvert R_{xy} \rvert < 0.89$	high
$0.9 < \lvert R_{xy} \rvert < 1$	extremely high
$\lvert R_{xy} \rvert = 1$	completely relevant

Calculate the correlation coefficient Rxy , we need to test whether it is statistically significant, that is, whether it is significant as we often say.

Here we check the calculation formula as follows:

$$s = \frac{R_{xy}\sqrt{n-2}}{\sqrt{1-R_{xy}{}^2}} \tag{3-15}$$

where, n——number of cases;R_{xy} ——correlation coefficient.

It should be noted that the value of s does not represent the strength of the correlation between the two variables, the size of Rxy is the statistic to measure the correlation.

(2) Example verification and result analysis

1) Research object

Taking the a building in Shanghai as the research object, with a total area of 14490m^2, this study selects the time period from 6:00 a.m. to 22:00 p.m. from July 1 to August 20 as the research time. The research data are collected from the real data of the building (historical cooling load, indoor number of personnel), and the outdoor meteorological data (indoor temperature, solar radiation intensity, outdoor wind speed, relative humidity) are derived from the hourly data of China's Meteorological websites, The training data is from July 1 to August 15, 2021, and the forecast data is from August 16 to August 19.

2) Correlation analysis

This paper uses SPSS26.0 platform to analyze Pearson correlation coefficient, and selects input variables with strong correlation with the predicted cooling load. The number of cases is 785, and the correlation is Rxy and significance test values are shown in the table below:

Table 3-2 Pearson correlation analysis between cooling load and input variable

Cooling load at time t_i	Correlation coefficient	Salience
The outdoor temperature at time t_i	0.281*	0.046

Outdoor temperature at time t_{i-1}	0.257*	0.069
Solar radiation intensity at time t_i	0.324*	0.021
Solar radiation intensity at time t_{i-1}	0.332*	0.017
Relative humidity at time t_i	-0.285*	0.043
Outdoor wind speed at time t_i	0.025	0.844
Cooling load at time t_{i-1}	0.229*	0.106
Cooling load at time t_{i-2}	0.06	0.673
Indoor temperature at time t_i	-0.085	0.553
Number of people in the room	1.00**	0

Note: *at the 0.05 level, the correlation is significant; ** at the 0.01 level, the correlation is significant.

When the correlation value is less than 0.2, but still significant, it indicates that the correlation is weak but still relevant. The point graph of cooling load correlation and significance at time t_i is as follows. The abscissa in the graph represents the input variable, and the ordinate represents the correlation value of input variable and cooling load at time t_i.

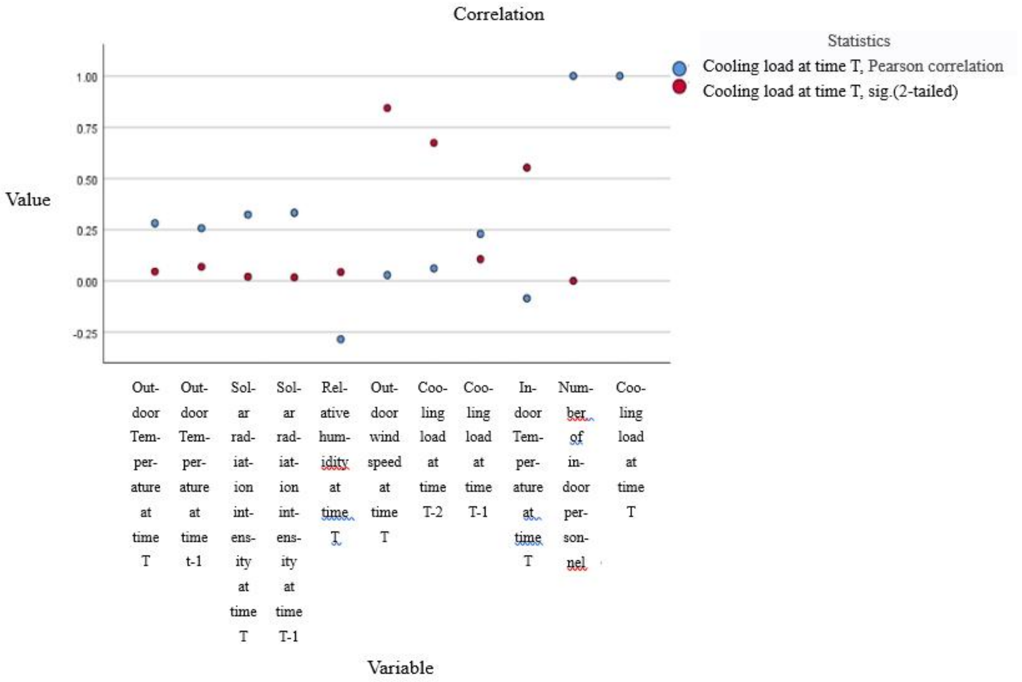


Fig.3-5 Correlation and significance point diagram of cooling load and input variables at time t_i

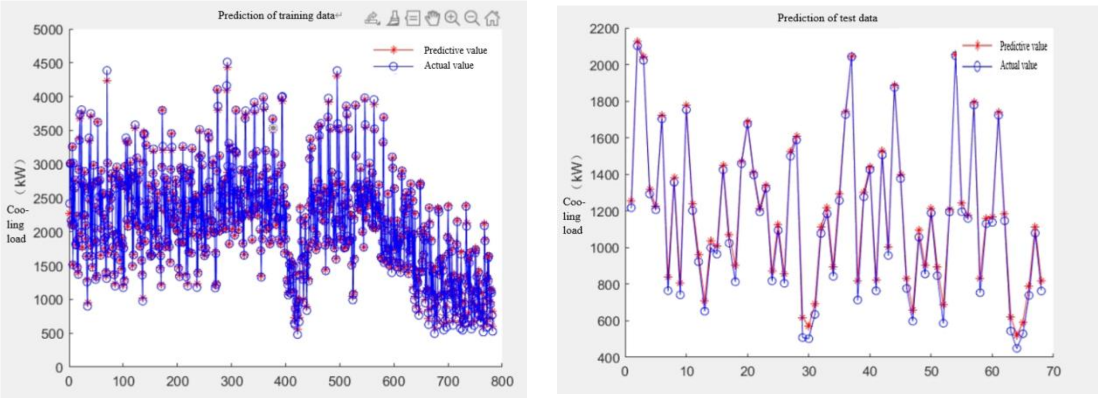
According to the above chart, it can be clearly found that the correlation of outdoor wind speed at time t_i is 0.025. In summer, the unorganized infiltration caused by wind pressure has little impact on indoor temperature and has very little impact on indoor cooling load prediction. Therefore, the correlation is poor. The correlation of cooling load at time t_{i-2} is 0.06, and the correlation is very weak, mainly because the historical cooling load in the past two hours has a low cooling effect with the flow of people, compared with other inputs, The influence of cooling load at time t_{i-2} is very small. The indoor temperature of the building at time t_i is negatively correlated, with a correlation value of 0.085. The correlation is very weak. The results show that the relationship between cooling load prediction and indoor temperature change is weak. To sum up, the input variables X1, X2, X3, X4, X5, X7 and X10 with very weak correlation are discarded in this paper. The correlation coefficient between the number of indoor personnel and the cooling load at time t_i is 1. It can be seen that the impact of personnel flow in the terminal is very large among the factors affecting the indoor cooling load, as shown in the table below.

Table 3-3 Selected variables

Before correlation Analysis			After Correlation Analysis		
	Variable	Variable Explanation		Variable	Variable Explanation
Correlation variable	X1	The outdoor temperature at time t_i	input variable	X1	The outdoor temperature at time t_i
	X2	The outdoor temperature at time t_{i-1}		X2	The utdoor temperature at time t_{i-1}
	X3	Solar radiation intensity at time t_i		X3	Solar radiation intensity at time t_i
	X4	Solar radiation intensity at time t_{i-1}		X4	Solar radiation intensity at time t_{i-1}
	X5	Relative humidity at time t_i		X5	Relative humidity at time t_i
	X6	Outdoor wind speed at time t_i		X7	Cooling load at time t_{i-1}
	X7	Cooling load at time t_{i-1}		X10	Number of people in the room at time t_i
	X8	Cooling load at time t_{i-2}	output variable	Y	Cooling load at time t_i
	X9	Indoor temperature at time t_i			
	X10	Number of people in the room at time t_i			

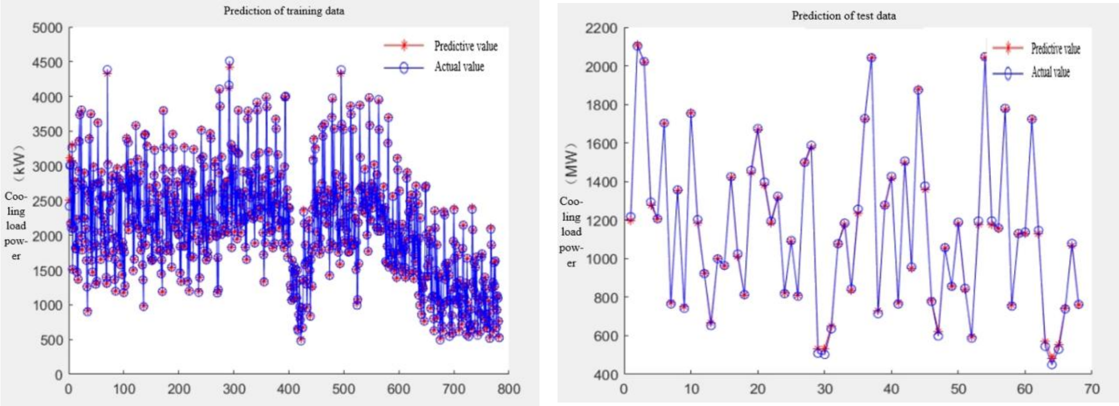
3) Discussion

On the basis of Pearson correlation analysis, this paper uses MATLAB software programming and pso-gru model for prediction. In order to verify the accuracy of the model, LSTM, PSO-LSTM, CNN-LSTM, PSO-CNN-LSTM and Gru prediction models are used for comparison. Convolutional neural network (CNN) and LSTM network can complement each other's characteristics. CNN is used to extract the potential relationship between continuous and discontinuous data in the input historical data, and LSTM network model is used for short-term prediction. The accuracy of power load prediction is higher than that of single LSTM network[19]. The maximum number of iterations of neural network is 500, and the learning rate is 0.005. As shown in the figure, the hourly training data and test data of LSTM model, Gru model and CNN-LSTM model during the research period.



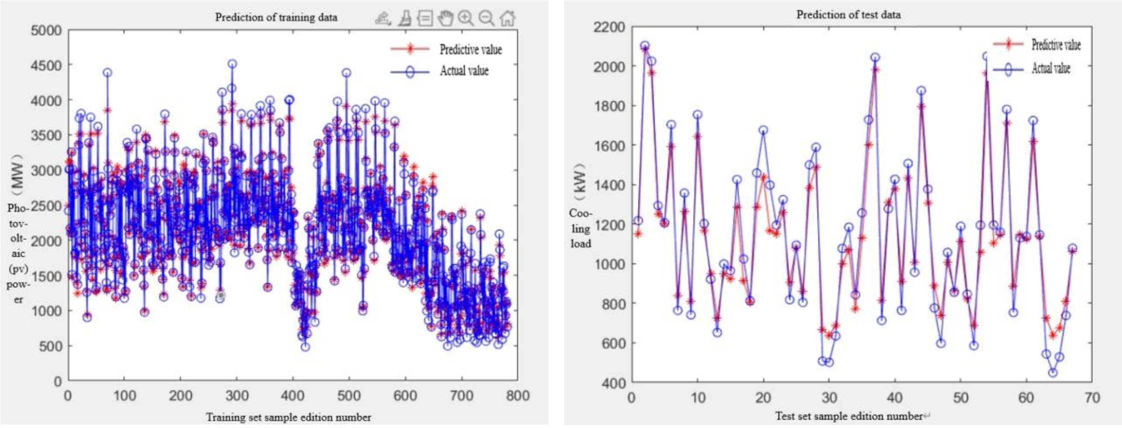
(a) (b)

Fig.3-6 LSTM data prediction diagram (a,b)



(a) (b)

Fig.3-7 GRU data prediction diagram（a,b）

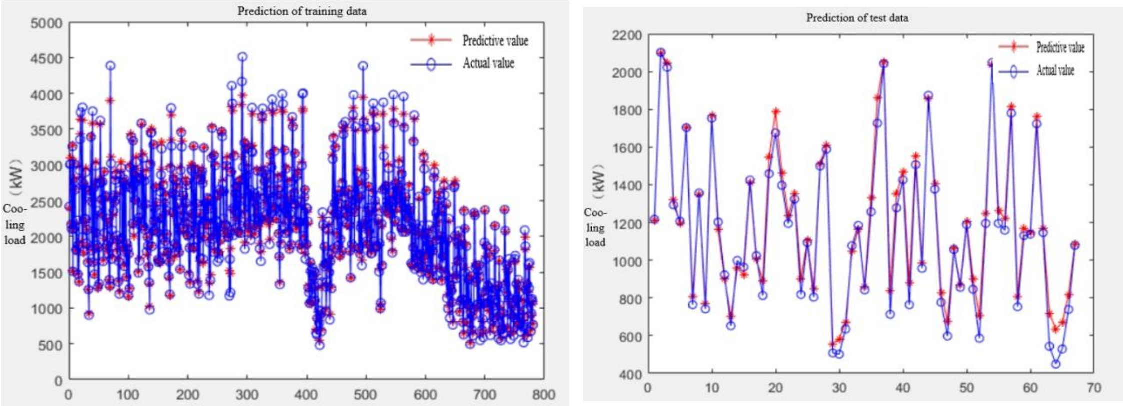


(a) (b)

Fig.3-8 CNN-LSTM data prediction diagram（a,b）

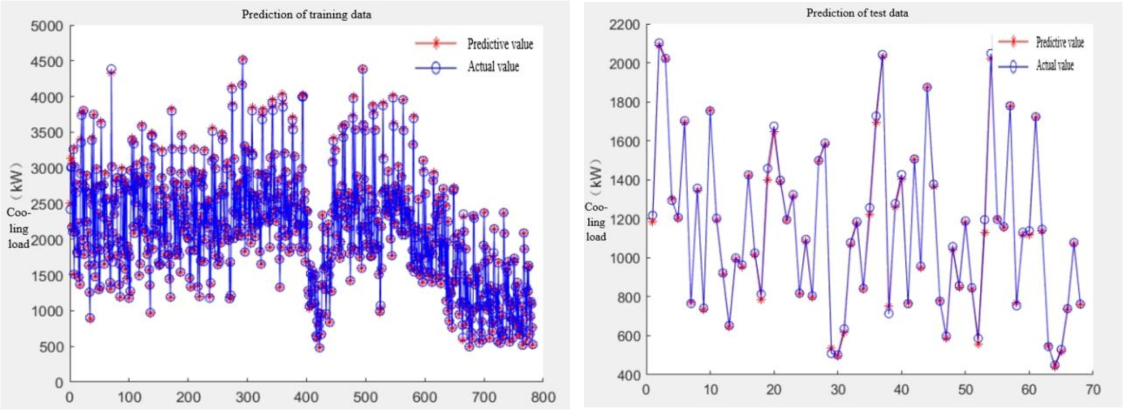
By comparing the training data and test data prediction charts of the three models, it can be found that the fitting degree of LSTM and Gru models is high, and the fitting degree of CNN-LSTM model is the worst. For the cooling load of the airport terminal, CNN extracts the local characteristic parameters of historical load with half the accuracy. Among them, compared with other models, Gru model is obviously more accurate in details, especially at sampling point 30, the fitting of Gru model is significantly higher than that of LSTM model. In general, compared with other models, Gru model is more accurate and feasible for airport terminal cooling load forecasting, but there are fluctuations in details, which can be optimized.

In this paper, particle swarm optimization algorithm is selected to optimize the number of neurons m and time step t in Gru network model. The number of neurons and time step are taken as the characteristics of particle optimization, and the optimal solution is calculated by PSO algorithm. In this paper, RMSE, MSE, Mae and MAPE are selected as the reference for error analysis. In the experiment, the PSO algorithm c1=1.5, c2=1.5, the population size is 10, the maximum number of iterations is 500, Vmax is 1, and the inertia weight w=0.2. The model prediction diagram optimized by PSO is shown in the following figure.



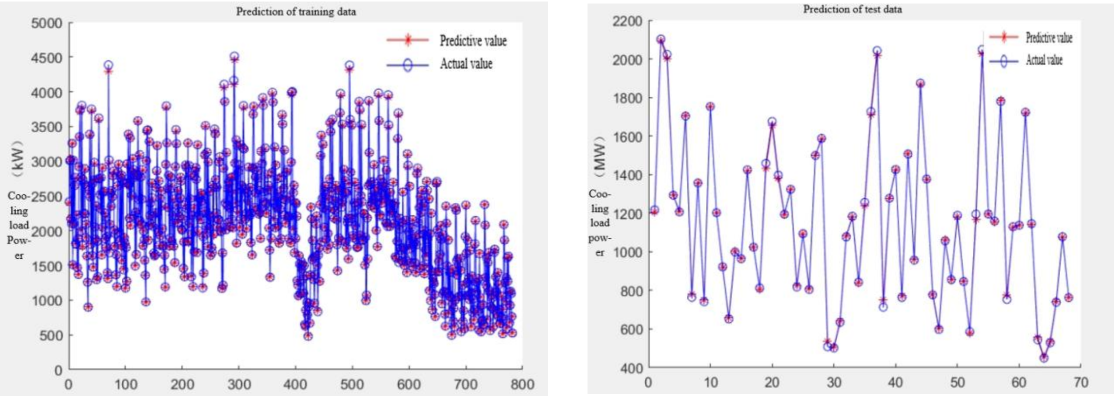
(a) (b)

Fig.3-9 PSO-CNN-LSTM data prediction diagram（a,b）



(a) (b)

Fig.3-10 PSO-LSTM data prediction diagram（a,b）



(a) (b)

Fig.3-11 PSO-GRU data prediction diagram（a,b）

As shown in the figure above, the PSO-optimized model has less fluctuation than a single model. Comparing the three prediction models of PSO-CNN-LSTM, PSO-LSTM, and PSO-GRU, the latter two actual and predicted values fit better, especially At the sampling point 30, the PSO-CNN-LSTM fluctuates significantly, and the PSO-LSTM and PSO-GRU models have high prediction accuracy, but in the details, the PSO-GRU model fluctuates very little, which is more accurate than the other two models. One point can be intuitively reflected by the error evaluation index. The error comparison of different models is shown in the following table.

It can be seen from the above table that the error of the model optimized by PSO algorithm is significantly smaller than that of the model not optimized. Taking the average absolute percentage error (MAPE) as an example, the absolute error of Gru not optimized by PSO is 1.1%, which is 0.1% lower than that of LSTM model optimized by PSO, while the error of cnn-lstm model is the largest, which is 8%. Even after optimization, the error is 2% higher than that of LSTM model. The prediction effect of pso-gru model is the best, and the error is only 0.7%, Gru neural network model based on PSO algorithm is selected for airport terminal cooling load forecasting, which has the best effect and the highest prediction accuracy.

Table 3-4 Error comparison of different prediction models

Predictive model	RMSE	MSE	MAE	MAPE
LSTM	40.1703	1613.6566	34.7746	0.038122
PSO-LSTM	17.8768	319.5788	12.843	0.012873
CNN-LSTM	99.1324	9827.2383	83.3895	0.0830
PSO-CNN-LSTM	63.2905	4005.6861	48.1674	0.051107
GRU	12.227	149.4997	9.8208	0.011321
PSO-GRU	11.1881	125.1739	7.7116	0.0079067

(5) Conclusion

This chapter presents a Gru neural network prediction model based on particle swarm optimization algorithm for the building cooling load, analyzes the correlation of influencing factors through Pearson correlation analysis method, compares the prediction effects of different neural network models, uses particle swarm optimization algorithm to optimize the neural network super parameters and structure, and finds the optimal model.

3.3 The model of hydrogen energy systems

3.3.1 The model of photovoltaic-hydrogen refueling station

The photovoltaic hydrogen production and refueling station mainly consists[20] of a photovoltaic power generation system, hydrogen production electrolysis tank, compressor, hydrogen storage tank, hydrogen refueling station, etc. The hydrogen production electrolysis cell is connected to the photovoltaic power generation system through a step-down converter with a current controller. Hydrogen is generated at constant pressure and different temperatures, and the generated hydrogen is compressed by a compressor under high pressure and stored in a hydrogen storage tank for use at the hydrogen refueling station. The hydrogen in the hydrogen refueling station is mainly supplied to various types of hydrogen fuel cell vehicles. The system structure is shown in Fig.3-12.

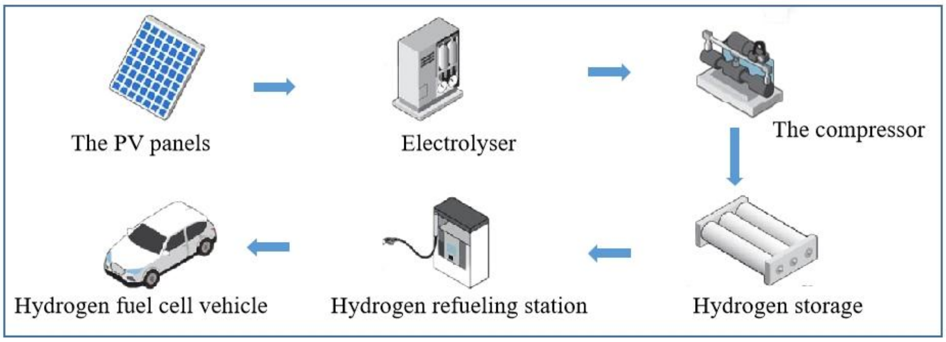


Fig.3-12 Composition of Photovoltaic Hydrogen Production and Hydrogenation System

(1) The model of electrolytic cell

The electrolytic cell is the core device of the hydrogen production system by electrolysis of water, and its main function is to use electricity to drive the oxidation-reduction reaction to decompose chemical substances. Currently, the main electrolytic cells on the market include proton exchange membrane (PEM), alkaline electrolytic cell (AE), solid oxide electrolytic cell (SOE), etc. Due to the uncertainty and volatility of renewable energy, the electrolysis equipment in the wind/light/water waste hydrogen production system should have the ability to safely produce hydrogen under unstable conditions. Alkaline electrolyzers can operate stably under low voltage, high current density, and intermittent power conditions, making them suitable for renewable energy hydrogen production. Fig.3-13 is a schematic diagram of the working principle of an alkaline electrolytic cell.

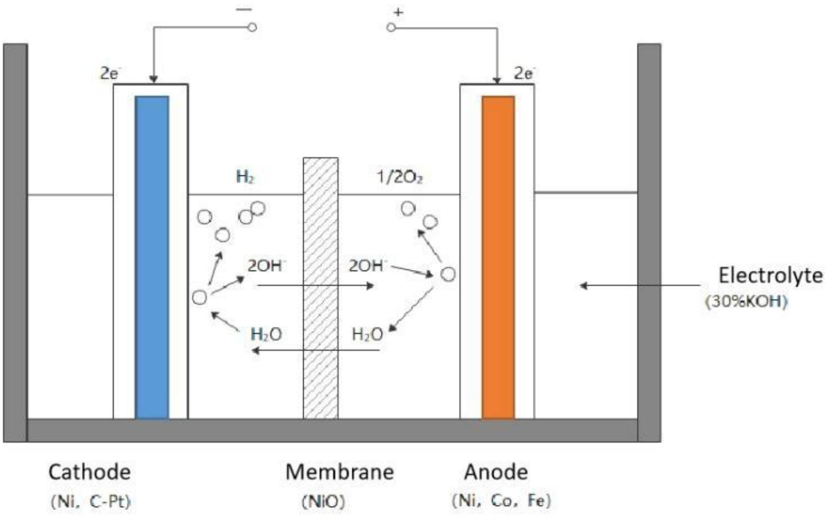


Fig.3-13 Schematic diagram of electrolytic cell device mechanism

The working principle of an alkaline electrolytic cell:

Anode: OH^- ions are oxidized under the action of current, producing O^2 and H_2O and releasing electrons, which pass through an external circuit to the cathode. The reaction equation is as follows:

$$2OH^- \rightarrow \frac{1}{2}O^2 + H_2O + 2e^-$$

Cathode: Electrons cannot reduce K^+ ions in the solution, so what happens on the cathode is a reduction reaction of water itself. The reaction equation is as follows:

$$H_2O + 2e^- = H^2 + 2OH^-$$

The voltage and current equations of the electrolytic cell are:

$$U_{el} = N_{el}\left(U_{re} + \frac{r_1 + r_2 T_{el}}{A_{el}} I_{el} + \left(s_1 + s_2 T_{el} + s_3 T_{el}^2\right)\log\left(\frac{t_1 + {}^{t_2}/_{T_{el}} + {}^{t_3}/_{T_{el}^2}}{A_{el}} + 1\right)\right) \tag{3-16}$$

Among them, U_{el} is the voltage of the electrolytic cell, N_{el} is the number of batteries connected in series in the electrolytic cell, and U_{re} is the reversible battery voltage; I_{el} is the current of the electrolytic cell, r_1、r_2 is the ohmic parameter of the electrolyte, A_{el} is the reaction area of the battery, T_{el} is the electrolyte temperature, and s_1、s_2、s_3、t_1、t_2、t_3 is the electrode overvoltage parameter.

According to Faraday's law, the hydrogen production flow rate of an electrolytic cell is proportional to the external circuit current:

$$V_{H2} = \eta(T，J)\frac{N_{el}}{2F} \tag{3-17}$$

Among them, V_{H2} is the hydrogen production rate; T is the ambient temperature ; J is the current density during the reaction; F is the Faraday constant; η is the relationship function between T and J:

$$\eta = a_1 exp\left(\frac{a_2+a_3T_{el}}{I_{el}/A_{el}} + \frac{a_4+a_5T_{el}}{\left(I_{el}/A_{el}\right)^2}\right) \tag{3-18}$$

In the formula, a_i is the relative coefficient of Faraday efficiency (i=1,2,3,4,5).

(2) The model of compressor

The hydrogen generated through the electrolytic cell is at room temperature and normal pressure, which usually cannot meet the pressure requirements of the system and requires compression treatment. The hydrogen storage requirements for hydrogen refueling stations are usually 20MPa, 45MPa, or 35MPa, 70MPa. According to the requirements for compressing hydrogen gas pressure, different stages of compression are selected, usually consisting of three stages. The equation for the compression system is as follows[21]:

$$E_{co} = m_{H_2} \times \frac{n}{n-1} \times R \times T\left(\left(\frac{P_{co}}{P_{in}}\right)^{\frac{n-1}{n}} - 1\right) \tag{3-19}$$

In the equation, E_{co} is the power consumption of the compressor. m_{H_2} is the mass flow rate of hydrogen gas. n is the heat capacity ratio, and the value is 1.4. R is the gas constant of air, which is 4124J/(kg * K). T is the temperature of the compressed gas. P_{co} is the gas compression pressure , P_{in} is the compressor inlet pressure.

(3) The model of photovoltaic power generation system

The composition of the photovoltaic power generation system is shown in Fig.3-14, where the photovoltaic array has a large number of photovoltaic cells in series and parallel. It utilizes the principle that semiconductor materials generate voltage at both ends after being illuminated, converting light energy into electrical energy. The current generated by the photovoltaic array is direct current, which needs to be converted into alternating current through an inverter, and then boosted by a transformer before being connected to the power grid.

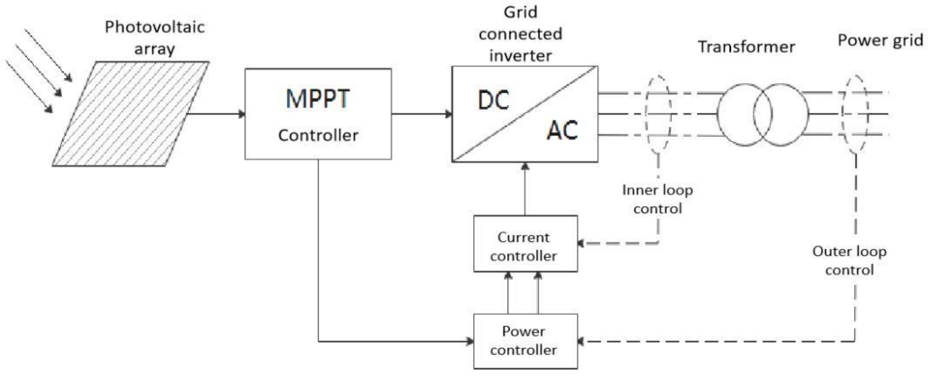


Fig.3-14 Schematic diagram of photovoltaic power generation system group

The photovoltaic current equation based on the influence of solar radiant intensity intensity and actual temperature is:

$$\mathrm{I} = N_P^{PV} I_{sc} \cdot \left\{1 - C_1 \left[exp\left(\frac{U - dU}{C_2 N_S^{PV} U_{oc}}\right) - 1\right]\right\} + dI \tag{3-20}$$

The calculation formula for the parameters in the equation is as follows :

$$\begin{cases} C_1 = \left(1 - \frac{I_m}{I_{sc}}\right) \cdot exp\left(-\frac{U_m}{C_2 U_{oc}}\right) \\ C_2 = \frac{\frac{U_m}{U_{oc}} - 1}{\ln\left(1 - \frac{I_m}{I_{sc}}\right)} \\ dI =- a \frac{G}{G_{ref}}\left(T_c - T_{ref}\right) + \left(\frac{G}{G_{ref}} - 1\right) \cdot N_P^{PV} I_{sc} \\ dU = bdT - R_s dI \\ T_c = T_a + t_c G \end{cases} \tag{3-21}$$

Among them, U_{oc} is the open circuit voltage; I_{sc} is the short circuit current; U_m is the voltage value at the maximum power point; I_m is the current value at the maximum power point; a and b are the current and voltage temperature change coefficients under the reference radiant intensity respectively; T_a is the ambient temperature; t_c is the temperature change coefficient of the photovoltaic module; T_c is the temperature of the photovoltaic panel; G is the radiant intensity of the sun; R_s is the series resistance of the photovoltaic cell;N_S^{PV} is the serial number of photovoltaic array components ; N_P^{PV} is the parallel number of photovoltaic array components.

Under the conditions of known light intensity and environmental temperature, the photovoltaic output can be calculated using the following formula (3-22):

$$P_{PV} = \alpha_F U_{PV} I_{PV} \tag{3-22}$$

The calculation formula for the parameters in the equation is as follows :

$$\begin{cases} I_{PV} = G[I_{sc} + \alpha(T_c - 25)] \\ U_{PV} = U_{oc} - \beta T_c \\ \alpha_F = \frac{U_m I_m}{U_{oc} I_{sc}} \end{cases} \tag{3-23}$$

Among them, P_{PV} is the active power of the photovoltaic cell; α_F is the fill factor.

A large number of statistical data show that the solar illumination intensity conforms to the beta distribution. Similarly, when the PV installed capacity is unchanged, the annual utilization hours of PV can also be fitted by the beta distribution, and its probability density function can be expressed as:

$$f_{PV}\left(\hbar_{PV}\right) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{\hbar_{PV}}{8760}\right)^{\alpha-1}\left(1 - \frac{\hbar_{PV}}{8760}\right)^{\beta-1} \tag{3-24}$$

Wherein, α and β are distribution parameters of beta function; $\hbar_{PV}$ is the annual utilization hours of photovoltaic ; $\Gamma(\,)$is a gamma function.

(4) The model of hydrogen storage

There are three key technologies for hydrogen storage: high-pressure gas hydrogen technology, low-temperature liquid hydrogen technology, and solid hydrogen storage technology. Among them, high-pressure hydrogen storage technology refers to the storage of gaseous hydrogen in gas tanks through high-pressure compression above the critical temperature of hydrogen. It has the characteristics of low cost, low energy consumption, easy dehydrogenation, and wide working conditions, and is the most mature, engineering oriented, and commonly used hydrogen storage technology.

Table 3-5 Comparison of hydrogen storage technologies[22]

Hydrogen storage technology	Volume specific capacity	The cost	Security	Technical maturity
High pressure gaseous hydrogen storage	Small	Lower	Poor	Mature
Liquid hydrogen storage	Large	High	Poor	Not very mature
Solid hydrogen storage	Large	High	Security	Immature, in the laboratory stage

The hydrogen storage model is shown in equation (3-25)[23]:

$$p_s - p_{si} = z\frac{v_{H_2}RT_s}{M_{H_2}V_s} \tag{3-25}$$

In the formula, p_s and p_{si} are the pressure and initial pressure of the storage tank; M_{H_2} is the molar mass of hydrogen (kg/kmol); v_{H_2} is the rate of hydrogen gas generated by the electrolytic cell and transported to the storage tank (mol/s); T_s is the working temperature of the hydrogen storage tank (K); V_s is the volume of the storage tank (m^3); z is the compression coefficient.

(5) The model of hydrogen consumption of hydrogen fuel cell vehicles

The hydrogen demand of hydrogen fuel cell vehicles is the basis for accurately predicting the hydrogen load required for hydrogen fuel cell vehicles. Based on the principle of vehicle longitudinal dynamics, the energy consumption per trip of the vehicle is estimated, and the average speed, distance traveled, and variance of the average speed of the trip feature data are selected to describe the energy consumption during the vehicle's driving process. Considering the wind resistance, rolling resistance, motor efficiency, and transmission efficiency of the vehicle during driving, the following formula is used to estimate the energy consumption of the vehicle[24]:

$$C_e^{100} \approx \frac{2.8\times10^{-2}\left(K_a\left(\bar{v}^2+3\sigma\right)+K_r\right)}{\eta_t\bar{\eta}_m} \tag{3-26}$$

$$K_a = \frac{1}{2}\rho C_d A \tag{3-27}$$

$$K_r = m_v g F_0 \tag{3-28}$$

Among them, C_e^{100} is the energy consumption per 100 kilometers of the vehicle, in kWh/100km; ρ is density of air; C_d is the air resistance coefficient; A is the windward area of the vehicle; m_v is the equivalent mass of the vehicle considering the rotating parts of the vehicle and the mass of passengers; g is gravity acceleration; F_0 is the rolling resistance coefficient; η_t is efficiency of vehicle transmission; $\bar{\eta}_m$ is vehicle motor efficiency; $\bar{v}$ is the average speed within the travel segment; σ is the standard deviation of the average speed of vehicles within the travel segment.

The formula for hydrogen consumption per 100 kilometers of hydrogen fuel cell vehicles is:

$$m_{H_2} \approx \frac{C_e^{100}}{W_{H_2}\times\eta_{to}} \tag{3-29}$$

Among them, m_{H_2} is the hydrogen consumption per 100 kilometers of hydrogen fuel cell vehicles, in kg/100km; W_{H_2} is the mass energy density of hydrogen, and the calorific value of water vapor generated by the complete combustion of 1kg hydrogen under standard conditions is approximately 33.26kWh/kg; η_{to} is the overall power generation efficiency of hydrogen fuel cell systems is generally between 40% and 60%.

Based on the current research and application level of key technologies for hydrogen fuel cell vehicles, the hydrogen consumption per 100 kilometers of different types of hydrogen fuel cell vehicles is shown in Table 3-6.

Table 3-6 Hydrogen consumption per 100 kilometers for various types of hydrogen fuel cell vehicles

Parameter	Hydrogen consumption per 100 kilometers(kg/100km)
Heavy truck	7.5-14
Logistics vehicle	3
Bus	4.1-4.5
Medium volume traffic	14.4-21.6
Passenger cars	0.65-0.75

3.3.2 The model of hydrogen fuel cell cogeneration system

The hydrogen fuel cell cogeneration system involved in this paper mainly uses Proton Exchange Membrane Fuel Cells (PEMFC) as the main energy output to provide electricity and heat for the room. The reaction gas of the fuel cell is hydrogen and air. Before entering the fuel cell, the gas is pretreated by preheating, humidification, etc. Hydrogen and air respectively enter the anode and cathode of the fuel cell for electrochemical reaction to generate electric energy, while releasing a lot of waste heat. Among the heat energy generated by the fuel cell, except for a small part for the pretreatment of reaction gas, the rest is used to heat hot water to meet the heat load of the room, and the other part is used for the lithium bromide water absorption chiller to provide cooling capacity for the room. On the other hand, the power generated by fuel cells is mainly used to supply indoor electrical equipment.

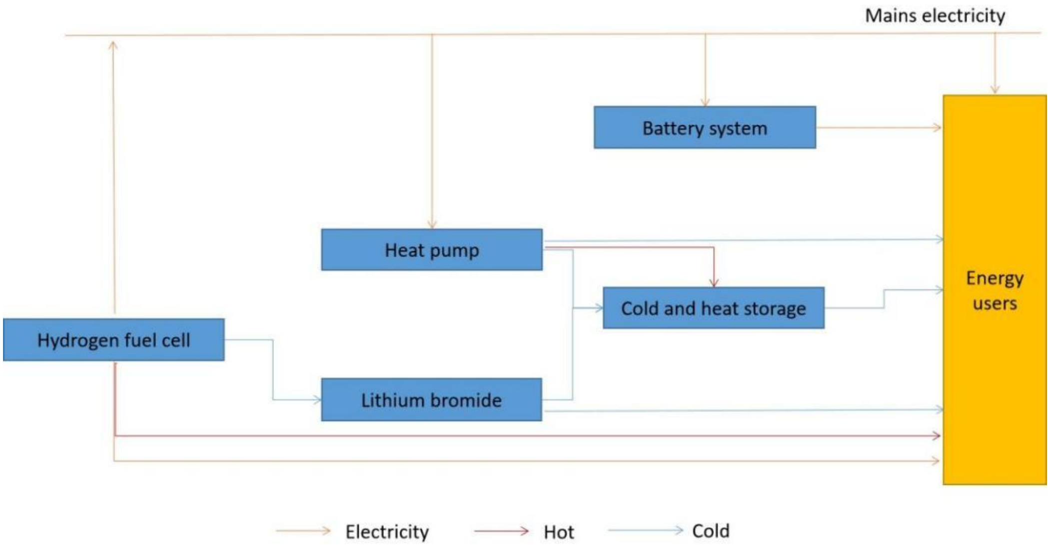


Fig.3-15 Hydrogen fuel cell cogeneration system

(1) The model of hydrogen fuel cell

Fuel cell is an electrochemical device that spontaneously combusts hydrogen and oxygen. It is contrary to the working principle of electrolytic cell and belongs to spontaneous energy conversion. It is based on the electrochemical principle, that is, the working principle of the primary cell. It directly converts the chemical energy stored in the fuel and oxidant into electrical energy isothermal, so the actual process is redox reaction. Fuel cell is mainly composed of four parts, namely anode, cathode, electrolyte and external circuit. Fuel gas and oxidation gas are respectively introduced from the anode and cathode of the fuel cell. The fuel gas emits electrons on the anode, which are transmitted to the cathode through an external circuit and combine with the oxidation gas to generate ions. Under the action of electric field, ions migrate to the anode through electrolyte, react with fuel gas, form a circuit, and generate current. At the same time, due to its own electrochemical reaction and the internal resistance of the cell, the fuel cell will also generate a certain amount of heat.

In this paper, PEMFC is used as the power supply equipment under the energy power system, and the working principle is shown in Fig.3-16.

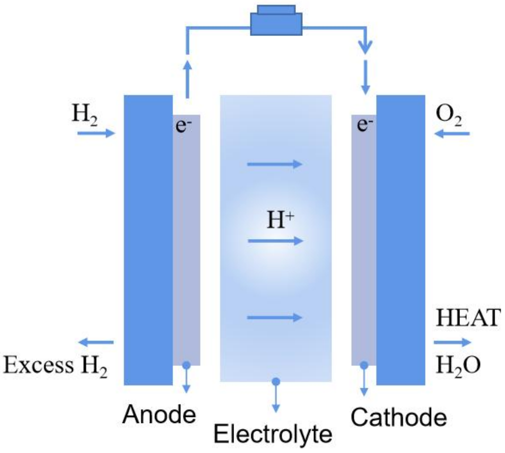


Fig.3-16 Schematic diagram of PEMFC

The electrode reaction in the fuel cell is:

Cathode: $\mathrm{H_2 \rightarrow 2H^+ + 2e^-}$

Anode： $\mathrm{\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O}$

Overall reaction: $\mathrm{H_2 + \frac{1}{2}O_2 \rightarrow H_2O}$

The voltage equation of PEMFC:

$$\mathrm{U_{fc}(t) = N_{fc}[U_{nernst}(t) - U_{act}(t) - U_{\mathit{ohm}}(t) - U_{con}(t)]} \tag{3-30}$$

where, the parameters are calculated as follows:

$$U_{nernst}(t) = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}\left(T_{fc}(t) - T_{fcref}\right) + \frac{RT_{fc}(t)}{2F}\left[\log\left(P_{fcH_2}\right) + \frac{1}{2}\log\left(P_{fcO_2}\right)\right] \tag{3-31}$$

$$U_{act}(t) = \left[b_1 + b_2 T_{fc}(t) + b_3 T_{fc}(t)\log v_{O_2} + b_4 T_{fc}(t)\log\left(I_{fc}(t)\right)\right] \tag{3-32}$$

$$U_{ohm}(t) = I_{fc}(t)\left(\frac{d_{fc}\rho_{fc}}{S_{fc}} + Z_{fc}\right) \tag{3-33}$$

$$U_{con}(t) =- \mathrm{K}\log\left(1 - \frac{I_{fc}(t)}{I_{fc.max}}\right) \tag{3-34}$$

Where, $\mathrm{U_{fc}(t)}$, $\mathrm{U_{nernst}(t)}$, $\mathrm{U_{act}(t)}$, $\mathrm{U_{\mathit{ohm}}(t)}$, $\mathrm{U_{con}(t)}$ represent the fuel cell voltage, thermodynamic electromotive force, activation overvoltage, ohmic overvoltage and concentration difference overvoltage at time t respectively; $\Delta\mathrm{G}$, $\Delta\mathrm{S}$ are gibbs energy variable and entropy variable; $\mathrm{N_{fc}}$ is number of fuel cell units in series; $\mathrm{T_{fc}(t)}$ is the internal temperature of the fuel cell at time t; $\mathrm{T_{fcref}}$ is the reference temperature； $\mathrm{P_{fcH_2}}$、$\mathrm{P_{fcO_2}}$ are respectively the partial pressures of H_2, O_2 on the reaction interface; b_1~b_4 are empirical constants; ν_{O_2} is the cathode oxygen concentration; $I_{fc}(t)$ is Inductive current of fuel cell; $I_{fc.max}$ is Is the maximum current density of fuel cell; d_{fc}, ρ_{fc}, S_{fc} are the thickness, resistivity and area of proton exchange membrane of fuel cell; Z_{fc} is the proton exchange membrane impedance; K is the equation constant.

The electric power p_P and thermal power P_H of PEMFC can be expressed as[25]:

$$P_P = U_{fc} \cdot I \tag{3-35}$$

$$P_H = N_{fc} \cdot I \cdot \left(U_{H_2} - \frac{U_{fc}}{N_{fc}}\right) \tag{3-36}$$

where, I is the total current; U_{H_2} is the equivalent voltage of hydrogen with low calorific value.

The volume flow rate (L/s) of consumed fuel hydrogen can be expressed as:

$$Q_{H_2} = \frac{N_{fc} \cdot I}{2F} \nu_m \tag{3-37}$$

where, F is Faraday constant (96485.33C/mol); ν_m is the molar volume of gas under standard conditions.

In terms of energy conservation and emission reduction, since fuel cells only generate water and do not emit carbon dioxide when generating electricity, compared with traditional fuel cell cogeneration units, the energy savings of hydrogen fuel cell cogeneration can be expressed as:

$$S_{ele} = 0.997 S_{CO_2} = 0.272 S_C \tag{3-38}$$

$$S_{tce} = 2.493 S_{CO_2} = 0.68 S_C \tag{3-39}$$

$$S_{ad} = 1.781 S_{CO_2} = 0.486 S_C \tag{3-40}$$

Where, S_{ele}, S_{tce} and S_{ad} respectively represent electricity saving, standard coal saving and raw coal saving (kg); S_{CO_2} is carbon dioxide emission reduction (kg); S_C is Carbon emission reduction (kg). In addition, the converted standard coal of the above formula is converted by equal value, that is, the coefficient is 1 kWh=0.4 kg standard coal, and 1 kg standard coal=0.7143 kg standard coal.

(2) The model of lithium bromide unit

Absorption refrigeration requires absorbent and refrigerant as working pairs to realize refrigeration cycle. In lithium bromide absorption refrigeration, water is used as refrigerant and lithium bromide is used as absorbent. Since the lithium bromide aqueous solution itself has a high boiling point and is extremely difficult to volatilize, it can be considered that the vapor on the liquid surface of the lithium bromide saturated solution is pure water vapor; At a certain temperature, the saturated partial pressure of water vapor on the liquid surface of lithium bromide aqueous solution is lower than that of pure water; The higher the concentration, the smaller the saturated partial pressure of water vapor on the liquid surface. Therefore, at the same temperature, the greater the concentration of lithium bromide aqueous solution, the stronger its ability to absorb water. This is why lithium bromide is usually used as absorbent and water as refrigerant.

Lithium bromide absorption chiller is mainly composed of generator, condenser, evaporator, absorber, heat exchanger, circulating pump, etc. During the operation of the lithium bromide absorption chiller, when the lithium bromide aqueous solution is heated by the heating steam in the generator, the water in the solution continuously vaporizes; With the continuous vaporization of water, the concentration of lithium bromide aqueous solution in the generator increases continuously and enters the absorber; The water vapor enters the condenser and condenses after being cooled by the cooling water in the condenser to become high-pressure and low-temperature liquid water; When the water in the condenser enters the steam generator through the throttle valve, it expands rapidly and vaporizes, and absorbs a large amount of heat from the refrigerant water in the evaporator during the vaporization process, so as to achieve the purpose of cooling and refrigeration; In this process, the low-temperature water vapor enters the absorber and is absorbed by the lithium bromide aqueous solution in the absorber. The solution concentration gradually decreases, and then it is sent back to the generator by the circulating pump to complete the whole cycle. In this way, the cooling capacity is continuously produced. Since the lithium bromide dilute solution has been cooled in the absorber and the temperature is low, in order to save the heat of heating the dilute solution and improve the thermal efficiency of the whole device, a heat exchanger is added in the system to allow the high temperature concentrated solution from the generator to conduct heat exchange with the low temperature dilute solution from the absorber, so as to increase the temperature of the dilute solution entering the generator.

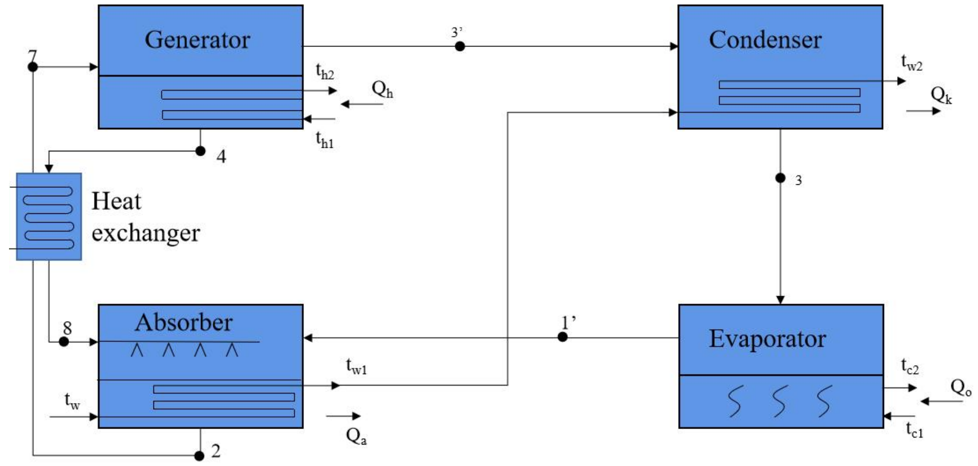


Fig.3-17 Schematic diagram of single effect lithium bromide water absorption refrigeration

In lithium bromide water absorption refrigeration, the energy balance equation is given as follows:

$$Q_h + G_w h_7 = M h_3 + (G_{wx} - M) h_4 \tag{3-41}$$

$$\mathrm{Q_k} + \mathrm{M}h_3 = \mathrm{M}h_3^{'} \tag{3-42}$$

$$\mathrm{Q_o} + \mathrm{M}h_3 = \mathrm{M}h_1^{'} \tag{3-43}$$

$$\mathrm{Q_a} + \mathrm{G_{wx}}h_2 = \mathrm{M}h_1^{'} + (\mathrm{G_w} - \mathrm{M})h_8 \tag{3-44}$$

In the formula, Q_h refers to the heat supplied by the heat source to the generator, namely the heat load (kW); $\mathrm{G_w}$ is the mass flow rate of dilute solution in the generator; M is the steam generation rate (kg/s); h_7 and h_4 are the mass specific enthalpy of the solution at the inlet and outlet of the generator respectively (kJ/kg); $\mathrm{Q_k}$ is the heat absorbed by the cooling water in the condenser (kW); h_3 and $h_3^{'}$ are the mass specific enthalpies (kJ/kg) of liquid and gaseous refrigerant water respectively; $\mathrm{Q_o}$ is the refrigerating capacity of the evaporator; $h_1^{'}$ is the mass specific enthalpy of steam at the outlet of evaporator (kJ/kg); h_8 is the mass specific enthalpy of concentrated solution entering the absorber through the heat exchanger.

The refrigerating capacity of lithium bromide water absorption refrigeration can be calculated by the following equation:

$$\mathrm{Q_o} = (h_1^{'} - h_3)\frac{\mathrm{Q}_h}{\mathrm{q}_h} \tag{3-45}$$

where, q_h is the unit heat load of the generator (kJ/kg).

The refrigeration coefficient (COP) of lithium bromide water absorption refrigeration can be expressed as:

$$\mathrm{COP} = \frac{\mathrm{Q_o}}{\mathrm{Q}_h} = \frac{(h_1^{'} - h_{3})}{\mathrm{q}_h} \tag{3-46}$$

(3) The model of heat pump

The heat pump uses electricity to generate cold or heat using compression refrigeration.

Liquid refrigerant is pumped through an expansion device at the indoor coil, which is functioning as the evaporator. Air from inside the house is blown across the coils, where heat energy is absorbed by the refrigerant. The resulting cool air is blown throughout the homes ducts. The process of absorbing the heat energy has caused the liquid refrigerant to heat up and evaporate into gas form. The gaseous refrigerant now passes through a compressor, which pressurizes the gas. The process of pressurizing the gas causes it to heat up (a physical property of compressed gases). The hot, pressurized refrigerant moves through the system to the coil in the outdoor unit. A fan in the outdoor unit moves outside air across the coils, which are serving as condenser coils in cooling mode. Because the air outside the home is cooler than the hot compressed gas refrigerant in the coil, heat is transferred from the refrigerant to the outside air. During this process, the refrigerant condenses back to a liquid state as it cools. The warm liquid refrigerant is pumped through the system to the expansion valve at the indoor units. The expansion valve reduces the pressure of the warm liquid refrigerant, which cools it significantly. At this point, the refrigerant is in a cool, liquid state and ready to be pumped back to the evaporator coil in the indoor unit to begin the cycle again.

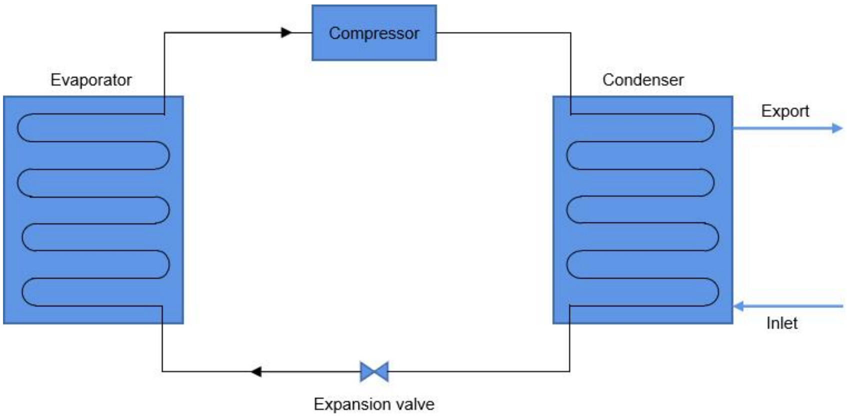


Fig.3-18 Working principle diagram of heat pump

A Heat pump in heating mode operates just like cooling mode, except that the flow of refrigerant is reversed by the aptly named reversing valve. The flow reversal means that the heating source becomes the outside air (even when outdoor temperatures are low) and the heat energy is released inside the home. The outside coil now has the function of an evaporator, and the indoor coil now has the role of the condenser.

The physics of the process are the same. Heat energy is absorbed in the outdoor unit by cool liquid refrigerant, turning it into cold gas. Pressure is then applied to the cold gas, turning it to hot gas. The hot gas is cooled in the indoor unit by passing air, heating the air and condensing the the gas to warm liquid. The warm liquid is relieved of pressure as it enters the outdoor unit, turning it to cool liquid and renewing the cycle.

It has a high COP and high energy efficiency. The cooling and heating capacity of the heat pump is expressed as follows.

$$\mathrm{Q_{HP,cold/heat}} = \mathrm{P_e} \times \mathrm{COP_{HP,cold/heat}} \quad (3\text{-}47)$$

Where, $\mathrm{Q}_{\mathrm{HP,cold}/heat}$ is the cooling capacity of the heat pump, $\mathrm{P_e}$ is the power consumption of the heat pump; $\mathrm{COP}_{\mathrm{HP,cold}/heat}$ is the energy conversion efficiency of the heat pump.

(4) The model of energy storage system

1) The model of Battery

The meaning of the state of charge of the battery SOC (t) is:

$$\mathrm{SOC}(t) = \frac{Q_B(t)}{Q_{B,max}} \quad (3\text{-}48)$$

$$\mathrm{SOC^{min}} \le \mathrm{SOC^t} = \mathrm{SOC^{t-1}} + \eta_{ch} \sum_{\mathrm{t=1}}^{\mathrm{t}} \mathrm{E}_{ch}^{\mathrm{t}} - \eta_{\mathrm{d}ch} \sum_{\mathrm{t=1}}^{\mathrm{t}} \mathrm{E}_{\mathrm{d}ch}^{\mathrm{t}} \le \mathrm{SOC^{max}} \quad (3\text{-}49)$$

Where, $\mathrm{Q_B(t)}$ is the remaining capacity of the battery at time t, and $\mathrm{Q_{B,max}}$ is the maximum capacity of the battery. η_{ch} is the charge efficiency of the battery, %. $\eta_{\mathrm{d}ch}$ is the discharge efficiency of the battery, %. $\mathrm{E}_{ch}^{\mathrm{t}}$ is the charging electricity of the battery at t-time, kWh/h. $\mathrm{E}_{\mathrm{d}ch}^{\mathrm{t}}$ is discharging electricity of battery at t-time, kWh/h. $\mathrm{SOC^{min}}$ is the minimum allowable capacity and $\mathrm{SOC}^{\max}$ is the maximum allowable capacity, kWh.

2) Cold and heat storage

At present, the cold storage technology is mainly divided into water storage and ice storage. The main difference between the two technologies is that the space required by the two technologies is about six times when the cold storage capacity is the same. However, water thermal storage technology does not need to make ice at low temperature, so it can save a lot of power in the process of thermal storage.

The purpose of establishing the peak valley electricity price difference is to encourage the user side to use electricity as much as possible during the period of low electricity load through the price policy, so that the user can obtain the benefit of electricity cost. For example, in the process of industrial production, the production activities with large electricity consumption can be moved to the night. However, the service time of civil buildings cannot be adjusted at will, so the use of cold storage technology can achieve the purpose of storing cold energy in the valley and peak periods.

The ice storage system and water storage system are both kinds of air conditioning cold storage technology. The principle of these two systems is the same. Both systems use a refrigerator to cool during the low power consumption period at night when the power load is low, and use the sensible or latent heat characteristics of the cold storage medium to store the cooling capacity in a certain way. In the daytime when the power load is high, the stored cooling capacity is released to meet the needs of building air conditioning.

The water storage system uses the water chiller for air conditioning as the refrigeration equipment and the thermal insulation tank as the cold storage equipment. The main unit of the air conditioner stores 4~7°C cold water during the low power consumption time, and the stored cold water is pumped out for use during the air conditioning. Water cooling storage is to use the temperature difference of water for cooling storage, which can be directly matched with the conventional air conditioning system without other special equipment. This system can only store the sensible heat of water, not the latent heat, so a large volume of cold storage tank is required.

The ice storage air conditioning system uses electric power at low load at night to make ice and store it in the ice storage device. Ice melting in the day releases the stored cold energy, reducing the power load of the air conditioning system and the installed capacity of the air conditioning system during peak hours of the power grid. The ice storage system consumes more power than the conventional refrigeration system, but because of the full use of valley electricity to make ice, it reduces the power consumption during the peak period of electricity price, and plays a role in shifting the peak and filling the valley.

Ice storage uses 335kJ/kg of latent heat of ice melting to store cold energy. The volume of the ice storage tank depends on the percentage of ice in water. Generally, the volume of the ice storage tank is $0.02\mathrm{m}^3/\mathrm{kWh}\sim0.025\mathrm{m}^3/\mathrm{kWh}$. The ice storage device can provide lower air conditioning water supply temperature, which is conducive to improving the temperature difference between air conditioning water supply and return, so as to reduce the size of piping and power consumption of water pump.

Whether the ice storage system uses partial or full storage, its initial investment is usually higher than that of conventional air-conditioning systems, which requires designers to correctly grasp the time variation characteristics of building air-conditioning load, determine reasonable cold storage equipment and system configuration, formulate system operation strategies, and accurately make economic analysis, So that investors can recover the extra investment in a short time in the form of saving electricity charges. Generally, in a designed cold storage system, the cost of the unit available cold storage capacity can be used to measure the cold storage equipment.

The comparison between ice storage system and water storage system is shown in Table 3-7.

Table 3-7 Comparison of ice storage and water storage systems

Item	Water cool storage	Ice storage
Cold storage temperature (°C)	4~6	-3~-6
Temperature of chilled water (°C)	5~7	1~4
Capacity of cold storage tank (m^3/kWh)	0.089~0.169	0.019~0.023
Storage capacity per unit volume	Small	Large
Refrigerator type	Conventional electric refrigeration	Dual operating condition system
Refrigerant carrier	Water	Ethylene glycol solution
COP of refrigerator	5.2 (Chilled water supply and return temperature 4/12 °C)	4.6 (Air conditioning working condition, supply and return water temperature 4/12 °C) 4.1 (Ice storage condition, supply and return water temperature -2/-6 °C)
Chilled water system	Most of them are open type, with high energy consumption of pumps	Most of them are closed type, and the energy consumption of water pump is low
Other requirement	Special design is required for mixing, layering and storage efficiency of cold and hot water	Special design is required for the ice coil

(5) The model of cogeneration system

The efficiency of the system can be calculated according to the effective energy of the CCHP system and the amount of hydrogen consumed. The efficiency calculated here is the low calorific value efficiency, that is, the low calorific value of hydrogen is used to calculate the energy consumed by the system.

The refrigeration efficiency of the CCHP system can be expressed as:

$$\eta_{co,CCHP}=\frac{\int P_{load,co}dt}{N_{H_2}\times LHV_{H_2}+\int P_{Li}dt}\times 100\% \tag{3-50}$$

The heating efficiency of the CCHP system can be expressed as:

$$\eta_{th,CCHP}=\frac{\int P_{load,th}dt}{N_{H_2}\times LHV_{H_2}+\int P_{Li}dt}\times 100\% \tag{3-51}$$

The generation efficiency of CCHP system can be expressed as:

$$\eta_{el,CCHP}=\frac{\int P_{load,el}dt}{N_{H_2}\times LHV_{H_2}+\int P_{Li}dt}\times 100\% \tag{3-52}$$

Then the total efficiency of the CCHP system is expressed as:

$$\eta_{CCHP}=\frac{\int (P_{load,co}+P_{load,th}+P_{load,el})dt}{N_{H_2}\times LHV_{H_2}+\int P_{Li}dt}\times 100\% \tag{3-53}$$

where, N_{H_2} is the molar amount of hydrogen consumed; LHV_{H_2} is the low calorific value of hydrogen.

3.3.3 The model of hydrogen turbine system

(1) The model of gas turbine

The gas distributed energy system mainly generates power through gas turbines, and the high-temperature flue gas generated is used by waste heat utilization equipment to generate steam or hot water for users to use, meeting their thermal load needs. Compared to the separate production of electricity and heat energy, it effectively avoids heat losses caused by pure heating or power generation, greatly improving energy utilization efficiency. At the same time, the gas distributed energy system is close to users, which can achieve matching of production capacity and energy consumption, reduce transmission losses, reduce customer energy costs, and also reduce pollutant emissions. For cases of insufficient capacity, it can expand the power grid capacity, thus having good social and economic benefits.

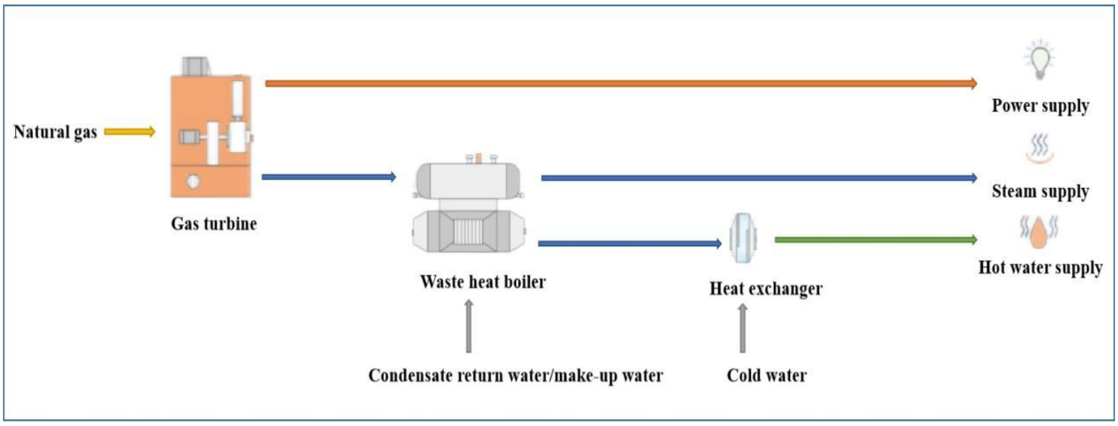


Fig.3-19 Schematic diagram of gas turbine cogeneration

Gas turbines, as energy conversion equipment, use continuously flowing gas as the working fluid to drive the impeller to rotate at high speed, converting the chemical energy of fuel combustion into electrical and thermal energy. A gas turbine is mainly composed of three core components: a compressor, a combustion chamber, and a turbine. The compressor sucks in air from the external atmospheric environment and undergoes stepwise compression to pressurize it, resulting in a corresponding increase in air temperature. Compressed air is compressed into the combustion chamber and mixed with the injected fuel to generate high-temperature and high-pressure gas; Then it enters the turbine to expand and do work, pushing the turbine to drive the compressor and external load rotor to rotate at high speed, achieving partial conversion of chemical energy from gas or liquid fuel into mechanical work and outputting electrical work. The exhaust gas discharged from the turbine is discharged into the atmosphere for natural heat release. From this, the gas turbine converts the chemical energy of the fuel into thermal energy, and also converts some of the thermal energy into mechanical energy.

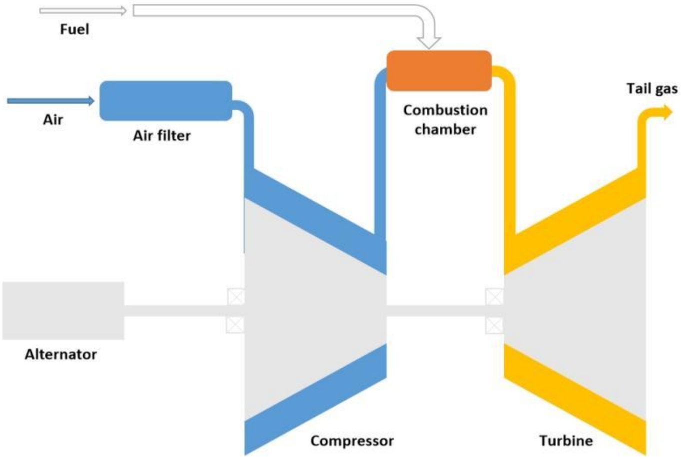


Fig.3-20 Working principle diagram of gas turbine

In order to simplify the calculation, the impact of external conditions on power generation and combustion efficiency is disregarded. The following unified model is adopted for the mathematical model of gas (hydrogen) turbine converting chemical energy in fuel into electrical energy:

$$P_g(t) = H_g(t) \cdot \eta_g \tag{3-54}$$

$$V_g(t) = \frac{H_g(t)}{L_g} \tag{3-55}$$

In the formula: $P_g(t)$ is the power generated by the combustion of gas turbine power generation during time t, kW; $H_g(t)$ is the heat energy generated by the combustion of fuel input to the gas turbine during time t, kW; η_g is the efficiency of natural gas micro gas turbine power generation; $V_g(t)$ is the fuel consumption of the gas turbine at time t, m^3; L_g is the average calorific value of fuel consumed by the gas turbine at any time, KJ/m^3.

(2) The model of hydrogen doped gas turbine

The raw material consumed by gas turbines is natural gas, and its combustion products contain greenhouse gas CO_2, which also increases the carbon emissions of the system. Related studies[26] have shown that the natural gas hydrogen blending ratio of gas turbines ranges from 10% to 20%, and the burner can achieve safe and stable combustion. The mathematical model[27][28] of hydrogen blending gas turbines is as follows:

$$P_{gh}(t) = \left(P_g(t) + P_h(t)\right) \cdot \eta_{gh} \tag{3-56}$$

$$\omega_{\mathrm{h}}(t) = \frac{\frac{P_h(t)}{L_h}}{\frac{P_g(t)}{L_g} + \frac{P_h(t)}{L_h}} \tag{3-57}$$

In the formula, η_{gh} is the electrical efficiency of the hydrogen doped gas turbine; $P_{gh}(t)$ is the power output of the gas turbine at time t; $P_g(t)$ and $P_h(t)$ are the power corresponding to the natural gas and hydrogen consumed by the gas turbine at time t; L_g and L_h are the calorific value of hot gas and hydrogen gas; $\omega_{\mathrm{h}}(t)$ is the hydrogen doping ratio (volume ratio) at time t.

3.4 The forecasting model of development scale of hydrogen fuel vehicles

In this paper, the scenario analysis method and the comparative analogy prediction method are used to carry out the prediction analysis of hydrogen fuel cell vehicles.

3.4.1 SWOT analysis

SWOT analysis[29], that is situation analysis based on the internal and external competitive environment and conditions, it is to list various main internal advantages, disadvantages, external opportunities and challenges closely related to the research object through investigation, and then analyze various factors with the idea of system analysis, and draw a series of corresponding conclusions from them, and the conclusions are usually of a certain decision-making nature.

SWOT analysis uses various investigation and research methods to analyze various environmental factors of the research object, namely external environmental factors and internal capacity factors. External environmental factors include opportunity factors and threat factors, which are the positive and negative factors that the external environment has a direct impact on the development of the research object and belong to objective factors; The internal environmental factors include the advantages and disadvantages. They are the positive and negative factors existing in the development of the research object. They are subjective factors. When investigating and analyzing these factors, we should not only consider the history and current situation, but also consider the future development. The advantage of this method is that it considers the problem comprehensively, is a systematic thinking, and can closely combine the "diagnosis" and "prescription" of the problem, which is clear and easy to test. As a whole, SWOT can be divided into two parts: the first part is SW, which is mainly used to analyze internal conditions; The second part is OT, which is mainly used to analyze external conditions. Using this method, we can find out the positive factors that are beneficial to us and worthy of development, as well as the negative factors that are unfavorable to us and should be avoided, find out the existing problems, find out the solutions, and clarify the future development direction.

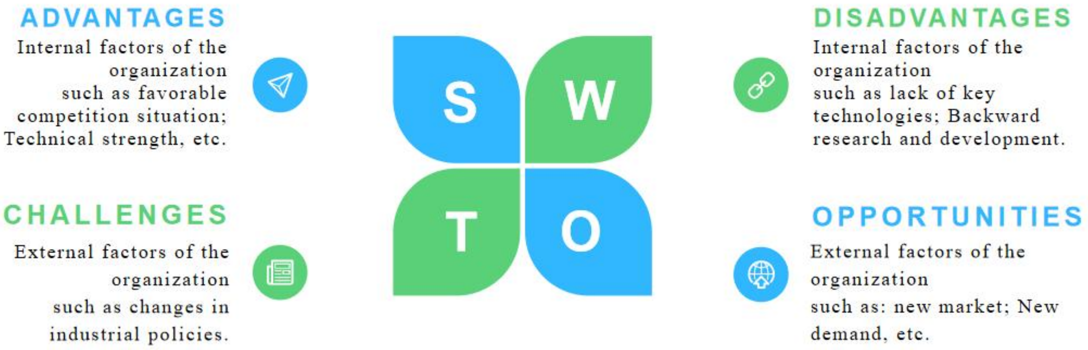
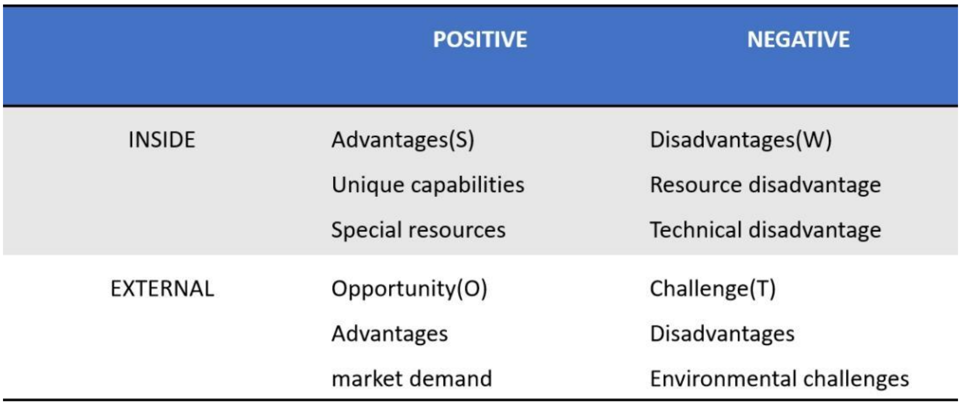


Fig.3-21 Schematic diagram of SWOT analysis



	POSITIVE	NEGATIVE
INSIDE	Advantages(S) Unique capabilities Special resources	Disadvantages(W) Resource disadvantage Technical disadvantage
EXTERNAL	Opportunity(O) Advantages market demand	Challenge(T) Disadvantages Environmental challenges

Fig.3-22 SWOT analysis

The guiding ideology of SWOT analysis is to fully determine the advantages and disadvantages of the research object and the opportunities and threats it faces, vigorously develop the factors favorable to the research object, avoid the factors unfavorable to the research object, find and solve the existing problems, and finally formulate the strategies suitable for the development trend of the research object[30][31], which are widely used in strategic management, policy strategy, planning research, etc.[32][33]. Using this method, we can make a comprehensive, systematic and accurate study on the situation of the research object, so as to formulate corresponding development strategies, plans and countermeasures according to the research results.

3.4.2 Scenario analysis method[34][35][36][37]

Scenario analysis and prediction method refers to the method to predict the possible situations or consequences of the prediction object on the premise that certain phenomena or trends will continue to the future. It is usually used to make various assumptions or predictions about the future development of the prediction object. It is an intuitive qualitative prediction method. According to the classification of scenarios, scenario analysis methods can be divided into historical scenario method, expectation analysis method, factor decomposition method and stress test.

The historical scenario method refers to the analysis method under the premise of assuming that things that have happened in history will repeat. When using historical scenarios, you can not only use your own historical scenarios, but also use others' historical scenarios. In any case, the disadvantage of using historical scenarios is that the generated scenarios are often limited by historical events that have occurred.

Factor decomposition method is to decompose the future impact on the target into several factors, and then generate possible scenarios by assuming the changes of these factors respectively. This method can simplify complex scenarios, clearly see the impact of each factor, and even conduct sensitivity analysis.

The prospective analysis method is to analyze some scenarios of subjective assumptions, and its advantage is that it can not be limited by real historical events. As the expected analysis method is quite subjective and does not take into account other potential risk factors, some difficulties may arise when carefully analyzing the expected scenarios. This method is one of the main methods used in the fourth chapter of this paper to forecast the development demand of hydrogen fuel cell vehicles.

Stress testing refers to the analysis of extreme scenarios. The probability of occurrence of stress testing scenarios is very small, but these scenarios do occur, and once they occur, their sudden impact may be huge. Stress testing can be used as a supplement to the VaR method to make up for the lack of the latter's analysis of extreme events beyond the confidence interval.

3.4.3 Comparison and analogy prediction method[38]

The comparison and analogy prediction method refers to a method that uses the similar characteristics between things to analogy the performance process of the previous things to the subsequent things, so as to predict the future of the subsequent things. The comparative analogy method can be divided into product analogy method, regional analogy method, international analogy method, industry analogy method and upgrading analogy method according to the different objectives of analogy.

The product analogy method refers to the analogy of the life cycle of a product based on the characteristics of similar products or similar products in the domestic market.

The regional analogy method refers to the analogy of the development of the same or similar products in different regions of China in terms of time to the development and change of a certain product in a certain region.

The international analogy method is to compare the development and change laws of the products to be analyzed with those of similar products in foreign developed countries, so as to judge which stage of a domestic product is in the life cycle.

The industry analogy method is based on the time sequence of the same product used in different industries, and uses the characteristics of the industry in which the product was first used to infer the rules of the industry in which the product was later used.

With the development of science and technology and the use of new processes, technologies and materials, the cycle of product upgrading is becoming shorter and shorter. The analogy method of product upgrading is to use the change rule of products before upgrading to infer the change rule of products after upgrading.

Combined with the development history and environment of the research object, this paper adopts product analogy, regional analogy and industry analogy.

3.5 Economic and environmental evaluation model

3.5.1 Annual total cost model of energy system

The annual total cost (C_{AT}) of the energy system proposed in this paper includes the annual investment cost (C_{AI}), annual maintenance cost (C_{AM}), annual operating cost (C_{AO}) and annual carbon emission transaction cost (C_{ACET}) of each equipment in the system, as shown in Formula (3-58).

$$C_{AT} = C_{AI} + C_{AM} + C_{AO} + C_{ACET} \tag{3-58}$$

Annual investment cost (C_{AI}) and annual maintenance cost (C_{AM}) refer to the average amortization of the total investment cost and maintenance cost of equipment in the whole life cycle of the system. The calculation formulas are (3-59) and (3-60).

$$C_{AI} = CRF \cdot \sum_{n=1}^{N} NC_n \cdot C_n \tag{3-59}$$

$$C_{AM} = \beta \cdot \sum_{n=1}^{N} NC_n \cdot C_n \tag{3-60}$$

where, NC_n is the nominal capacity (kW) of the nth equipment in the system. C_n is the initial capital investment cost of the nth equipment (\$). β is the proportion (%) between annual maintenance cost and initial investment cost of each equipment in the system. CRF Capital Recovery Factor. The calculation method is as follows:

$$CRF = \frac{r(1+r)^y}{(1+r)^y - 1} \tag{3-61}$$

Where, r is the interest rate (%). y is the service life (years) of each equipment in the system.

Annual operating cost (C_{AO}) refers to the cost of fuel consumed by system equipment, such as hydrogen consumed by hydrogen fuel cells and the cost of purchasing electricity from external power grids. The calculation equation is:

$$C_{AO} = \sum_{t=1}^{8760} \left(E_{grid}^{t} EC_{e}^{t} + F_{H_2}^{t} EC_{H_2}^{t} \right) \tag{3-62}$$

where, E_{grid}^{t} is the electricity purchased in t hours (kWh); $F_{H_2}^{t}$ is the amount of hydrogen consumed in t hours (kWh); EC_{e}^{t}, $EC_{H_2}^{t}$ are the energy price of electricity and hydrogen in t hours (\$/kWh).

Annual carbon emission cost (C_{ACET}) refers to the cost of carbon emission generated by energy supply of the energy system every year. The trading price of carbon (p_{ct}) is the price paid by users through the purchase and sale of carbon emission rights. It takes carbon emission rights as a commodity and forms carbon emission rights trading, referred to as carbon trading. This is an effective way to reduce carbon emissions and a cost-effective way to guide the economy towards a greener future. The calculation equation is:

$$\mathrm{C_{ACET}} = \mathrm{CE} * p_{ct} \tag{3-63}$$

Among them, $\mathrm{C_{ACET}}$ is the carbon emission cost (\$). CE is carbon emissions (ton). p_{ct} is the carbon trading price (\$/ton), the buying is positive and the selling is negative.

3.5.2 Cost-benefit analysis model of energy system

The economic evaluation indicators for energy system projects are based on the project plan and external data, including detailed statistics of external energy demand, reasonable and comprehensive calculation of various investment costs, calculation of fuel costs, electricity price income, and heat (cold) sales income based on actual prices. On this basis, appropriate evaluation indicators are selected to calculate the profitability of the project. Evaluate the investment return of the project through a 'Cost Benefit Analysis' of the energy system. It is mainly divided into two categories: static analysis and dynamic analysis.

The main analysis objects of static analysis are the investment profit margin, capital profit margin, static investment payback period, etc. of the project.

$$\sum_{t=0}^{T_s} (\mathrm{B_t} - \mathrm{C_t}) = 0 \tag{3-64}$$

Among them, t is the number of years after the project investment;$\mathrm{T_s}$——Static investment payback period;$\mathrm{B_t}$——Cash inflow of energy system projects in year t;$\mathrm{C_t}$——Cash outflow from energy system projects in year t.

The dynamic analysis method is used to calculate the economic benefits of the project, that is, the reciprocal (discount) of compound interest is used to convert the benefits and costs within the project life cycle into the present value, and compare the present value of benefits and costs. The economic evaluation indicators used include: dynamic investment payback period ($\mathrm{T_p}$), financial net present value (NPV) and internal rate of return (IRR).

(1) Calculation of dynamic investment payback period ($\mathrm{T_p}$) indicators

The calculation formula for dynamic investment payback period ($\mathrm{T_p}$):

$$\sum_{\mathrm{t}=0}^{\mathrm{T_p}} \frac{\mathrm{B_t} - \mathrm{C_t}}{(1+\mathrm{i_c})^{\mathrm{t}}} = 0 \tag{3-65}$$

Among them, t - the number of years after the project investment; $\mathrm{T_p}$——Dynamic investment payback period;$\mathrm{B_t}$——Cash inflow of energy system projects in year t;$\mathrm{C_t}$——Cash outflow from energy system projects in year t;$\mathrm{i_c}$——The industry's benchmark Discount rate.

(2) Net present value (NPV) Index Calculation

Net present value (NPV)[39] is the most commonly used dynamic economic evaluation indicator. The calculation method is to discount the net cash flow of each year at a certain interest rate to the sum of the present value at the same time (usually at the beginning). The calculation formula of net present value is:

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+i_c)^t} \tag{3-66}$$

Among them, t - the number of years after the project investment;T - Number of years of project life.

When using the net present value calculation method to measure the project value, there are three situations:

When the NPV (net present value) is 0, it means that the income from the development of the project is greater than the cost. Not only the loan can be repaid, but also the profit can be obtained. It means that there is no risk and the project can be launched;

When NPV (net present value)=0, it means that the development of the project just gets the benefits of the expected rate of return on investment. The income and expenditure are balanced, only the interest can be paid, and there is no profit, which is worth further study;

When the NPV (net present value) is less than 0, it means that the project cannot reach the interest rate of the expected rate of return on investment, there is no profit, there is risk, and the project cannot be launched.

(3) Calculation of internal rate of return (IRR)

Internal rate of return (IRR) refers to the corresponding Discount rate when the net present value is zero. The financial internal rate of return is the Discount rate when the sum of the present values of the financial net cash flows of each year in the whole calculation period of the project is equal to zero. From an economic point of view, at the end of the life of the project, the Discount rate at which the investment is fully recovered is the internal rate of return. In other words, before the end of the project's lifespan, if the interest rate i=IRR is calculated, there will always be uncollected investments in the project, and at the end of the lifespan, all investments will just be recovered. The mathematical formula is:

$$\sum_{i=1}^{t} \frac{B_t - C_t}{(1+\mathrm{IRR})^t} = 0 \tag{3-67}$$

The calculation result of internal rate of return (IRR) has three situations:

When IRR=opportunity cost of capital (a standard investment return rate determined in advance, such as 12%, etc.), it indicates that the profitability of the project is equal to the level of investment profitability determined by us, and the project is acceptable;

When IRR>opportunity cost of funds, it indicates that the profitability of the project is relatively high, that is, higher than the standard return on investment (12%) level specified by us, and the project is desirable;

When IRR<opportunity cost of funds, it means that the profitability of this project cannot reach the profitability level specified by us, and this project is not advisable.

3.5.3 Carbon emission calculation model for energy systems

Carbon emission accounting is a fundamental prerequisite for effectively carrying out various carbon reduction efforts and promoting green economic transformation. Currently, there are three main methods for calculating carbon emissions: emission factor method, quality balance method, and measurement method. Among them, the emission factor method is the most widely applicable and widely used carbon accounting method.

This article will use the emission factor method[40] (i.e. carbon emission coefficient method) to calculate the carbon emissions generated by energy consumption in industrial parks. The carbon emission coefficient refers to the amount of carbon emissions per unit of energy generated during the combustion or use of each type of energy, usually referring to the emission coefficient of carbon dioxide. Other greenhouse gases such as methane and nitrous oxide are generally converted into carbon dioxide before being included in the calculation. According to the assumption of the Intergovernmental Panel on Climate Change (IPCC), it can be assumed that the carbon emission coefficient of a certain energy source is fixed and unchanging.

In the process of carbon emission accounting, carbon emission coefficients will be used to calculate the emissions of each stage. Carbon accounting through carbon emission coefficients can directly quantify data on carbon emissions. The specific calculation formula is:

$$\mathrm{CE} = \sum_{i=1}^{k} \mathrm{E_i} \times \xi_i \times \kappa_i \tag{3-68}$$

In the formula, CE represents the total carbon emissions from energy consumption; i refers to various fuel types, mainly referring to natural gas and electricity in this chapter; $\mathrm{E_i}$ is the consumption of Class i fuel; ξ_i is the conversion coefficient for converting standard coal to Class i fuel; κ_i is the carbon emission coefficient of the i-class fuel.

Table 3-8 Fuel standard coal conversion coefficient and carbon emission coefficient

Fuel type	Natural gas	Power
Standard coal conversion coefficient	1.3300t standard coal/10000 m^3	1.229t standard coal/10000 kWh
Carbon emission coefficient	0.4479t carbon/t standard coal	2.2132t carbon/t standard coal

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Chapter 4

RESEARCH ON THE APPLICATION EFFECT EVALUATION OF PHOTOVOLTAIC-HYDROGEN REFUELING STATION BASED ON HYDROGEN LOAD ANALYSIS

CHAPTER FOUR: RESEARCH ON THE APPLICATION EFFECT EVALUATION OF PHOTOVOLTAIC-HYDROGEN REFUELING STATION BASED ON HYDROGEN LOAD ANALYSIS

RESEARCH ON THE APPLICATION EFFECT EVALUATION OF PHOTOVOLTAIC-HYDROGEN REFUELING STATION BASED ON HYDROGEN LOAD ANALYSIS

4.1 Content

The carbon emissions in the transportation sector account for about a quarter of the total global carbon emissions[1], and are closely related to human production and life, receiving high attention from various countries. The carbon emissions in China's transportation sector account for about 10% of the total carbon emissions[2], with urban road transportation being the main source of carbon emissions. With the steady progress of China's economic development and the gradual improvement of people's living standards, the transportation sector will face carbon emission pressure in the long term. According to data, the total carbon emissions in Shanghai's transportation sector (excluding long-distance aviation and air transportation) in 2019 were 20 million tons, with an average annual growth rate of about 2.0%[3]. In order to effectively promote the achievement of the dual carbon target in the transportation sector of Shanghai, the Shanghai Municipal Transportation Commission and the Shanghai Development and Reform Commission have issued the "Implementation Plan for Carbon Peak in the Transportation Sector of Shanghai"[4], which clearly proposes that by 2030, the proportion of new energy powered motor vehicles added annually will not be less than 50%, and the carbon emission intensity per unit converted turnover of operating transportation tools will decrease by about 9.5% compared to 2020. Under this goal, hydrogen fuel cell vehicles, as the most common and mature application scenario for hydrogen applications, will inevitably experience a rapid growth period in the application of hydrogen energy as a "zero carbon" energy in the transportation field.

The construction of hydrogen refueling stations is a prerequisite for the widespread application of hydrogen fuel cell vehicles and a key factor in achieving zero emissions at the end of the transportation sector. The "Medium and Long Term Plan for the Development of the Hydrogen Energy Industry in Shanghai (2022-2035)"[5] jointly released by the Shanghai Development and Reform Commission and other departments clearly proposes that by 2025, the number of fuel cell vehicles will exceed 10000, and about 70 hydrogen refueling stations will be planned and constructed. At present, Shanghai has built 14 hydrogen refueling stations. In 2020, a total of 55000 hydrogen fuel cell vehicles were refueled, with a total of about 300000 kg of hydrogen being refueled. Some hydrogen refueling stations have accumulated years of safety operation and management experience, laying a solid foundation for the wider construction and operation of hydrogen refueling stations in Shanghai in the future.

Table 4-1 Established hydrogen refueling stations and refueling capacity in Shanghai

Serial Number	Station name	Refueling capacity
1	Baosteel Station (Pure Hydrogen Station)	500 kg/day
2	Jiangqiao Station	500 kg/day
3	Qingwei Station	1000 kg/day
4	Electric drive station	500 kg/day

5	anting	200 kg/day
6	Autocity Station	1600 kg/day
7	Anzhi Station	1000 kg/day
8	Shenli Station	200 kg/day
9	Fengxian Bus Depot	The fixed hydrogen storage capacity of the station reaches 2000 kg
10	Chemical Zone Station	800 kg/day
11	Pujiang Gas Station	Commercial hydrogen refueling station with a hydrogen refueling capacity of 70 megapascals
12	Shanghai Petrochemical Station	500 kg/day
13	Pingxiao Station (Oil Hydrogen Joint Construction Station)	1000kg/12 hours
14	Hongyin Station	500 kg/12 hours

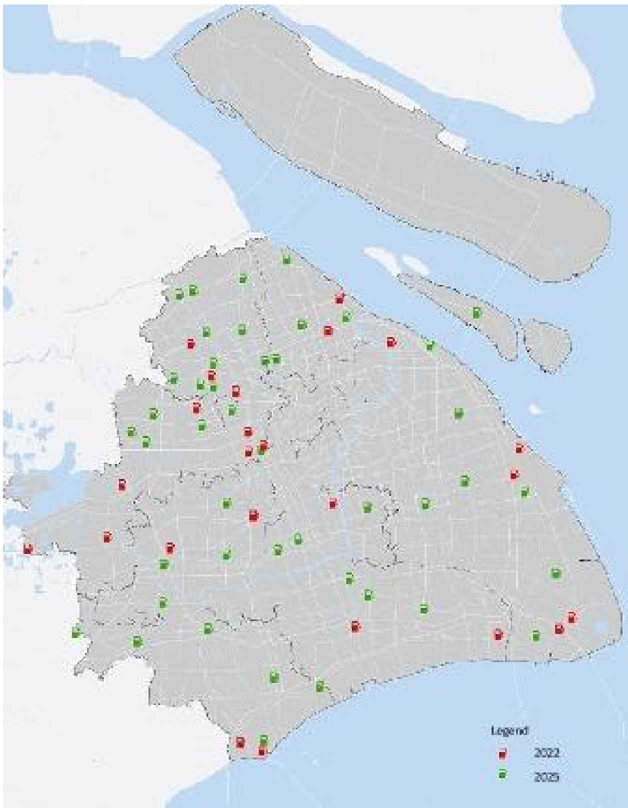


Fig.4-1 Layout Plan of Shanghai Hydrogenation Station

According to different hydrogen supply methods, hydrogen refueling stations can be divided into two forms[6]: external hydrogen refueling stations and internal hydrogen production refueling stations. Among them, the internal hydrogen production refueling station supplies hydrogen through the electrolysis of water in the station. In order to fully utilize regional energy resources, achieve the coupling of renewable energy and hydrogen energy, and promote the true "zero carbon" emissions of hydrogen powered vehicles in the transportation field, this chapter will take a hydrogen refueling station with a scale of 500kg/day in Shanghai as the research object to study and analyze the feasibility and effectiveness of photovoltaic hydrogen production and refueling station application.

4.2 Analysis of hydrogen demand load characteristics of hydrogen station

4.2.1 Analysis of hydrogen demand for different types of hydrogen fuel cell vehicles

At present, hydrogen fuel cell vehicles mainly involve heavy-duty trucks, logistics vehicles, buses, medium capacity buses, passenger cars, and other forms. Among them,

- Heavy trucks mainly include various specialized vehicles (sprinkler trucks, fire trucks, road cleaning vehicles, oil tank trucks, mixer trucks, etc.), dump trucks (bulldozers, all with elevators), trucks (transporting goods, including livestock, etc.), and some rare off-road vehicles (mostly military).
- Logistics vehicle refers to a unit mobile container equipment equipped with four casters for transporting and storing materials, commonly used for logistics distribution in large supermarkets or logistics turnover between factory processes.
- Bus refers to a specialized motor vehicle that usually follows a fixed route and has a dedicated road number to carry passengers for travel. In urban areas, its speed is generally between 25-50 kilometers per hour, and in suburban areas it can reach up to 80 kilometers per hour.
- Medium capacity public transportation refers to buses operating on BRT routes, with dedicated boarding and alighting platforms and dedicated driving lanes. Its passenger capacity is between high volume rail transit and low volume conventional transportation, and its departure interval is significantly shorter than that of regular public transportation, which is close to rail transit.
- Passenger cars refer to cars that are primarily designed and technically designed to carry passengers and their accompanying luggage or temporary items, with a maximum of 9 seats, including the driver's seat.

(1) Analysis of Travel Characteristics and Hydrogenation Behavior

According to the different functions of different types of hydrogen fuel cell vehicles, traffic regulations, and working time constraints of hydrogen refueling stations, their travel characteristics and refueling behavior vary, as shown in Table 4-2.

Table 4-2 Analysis of Travel Characteristics and Hydrogenation Behavior of Various Types of Hydrogen Fuel Cell Vehicles

Different types of vehicles	Travelable range (km)	Daily driving distance (km)	One way duration (hours)	Daily working hours (hours)	Run time	Analysis of hydrogenation behavior
Heavy truck	700	50-100， >300	0.5-1	>8	Suburban: 8:00~17:00 Urban area: 20:00-7:00 the next day	Due to traffic regulations, restrictions on working hours at hydrogen refueling stations, and their commercial attributes, the refueling time is generally during the rest time during its operating period or nearby refueling
Logistics vehicle	260	90-185	0.5-1	3-4.5	24 hours a day	Restricted by working hours of hydrogen refueling stations
Bus	350	70-230	1-1.5	5.5-7， 8.5-9.5	6:50-18:15	Due to the limitations of the working hours of hydrogen refueling stations and their passenger transportation functions, the refueling time is generally during the rotation period during their operating hours Restricted by working hours of hydrogen refueling stations
Medium volume traffic	150	70-230	1-1.5	5.5-7， 8.5-9.5	6:00-22:30	
Passenger cars	440	20-80	0-1.5	0.5-3	24 hours a day, there are two peak hours from 8:00 to 9:00 and from 18:00 to 20:00	Due to traffic regulations, restrictions on the working hours of hydrogen refueling stations, and their commercial attributes, the refueling time is generally around 8 a.m. and 8 p.m

4.2.2 Hydrogen load analysis of hydrogen refueling station

As an infrastructure for providing hydrogen to fuel cell vehicles, hydrogen refueling stations have similar functionality to gas stations as an infrastructure for providing fuel oil to fuel cell vehicles. In addition, hydrogen refueling stations and gas stations also have regional exclusivity characteristics, and the best path for hydrogen refueling station construction at present is to prioritize selecting sites around the original gas station/gas station location, and explore joint construction stations if conditions permit. Based on the multiple similarities between hydrogen refueling stations and gas stations, as well as the limited research on hydrogen loading at refueling stations, this chapter will provide reference for analyzing the refueling demand curve of refueling stations by analyzing the refueling demand curve of refueling stations.

The research report "Analysis Model of H2A Transportation Facilities and Analysis Results of Conventional Transportation Methods"[7] conducted a survey on the temporal distribution characteristics of refueling volume at Chevron gas stations. The results showed that during the year, the demand for refueling in summer was the highest, about 1.1 times the average demand during the year; During the week, fuel demand on Friday is significantly higher than the other days, approximately 1.08 times the weekly average demand. In this report, the refueling station was designed using the Chevron refueling demand curve for summer and Friday (as shown in Fig.4-2, which is a single peak demand curve).

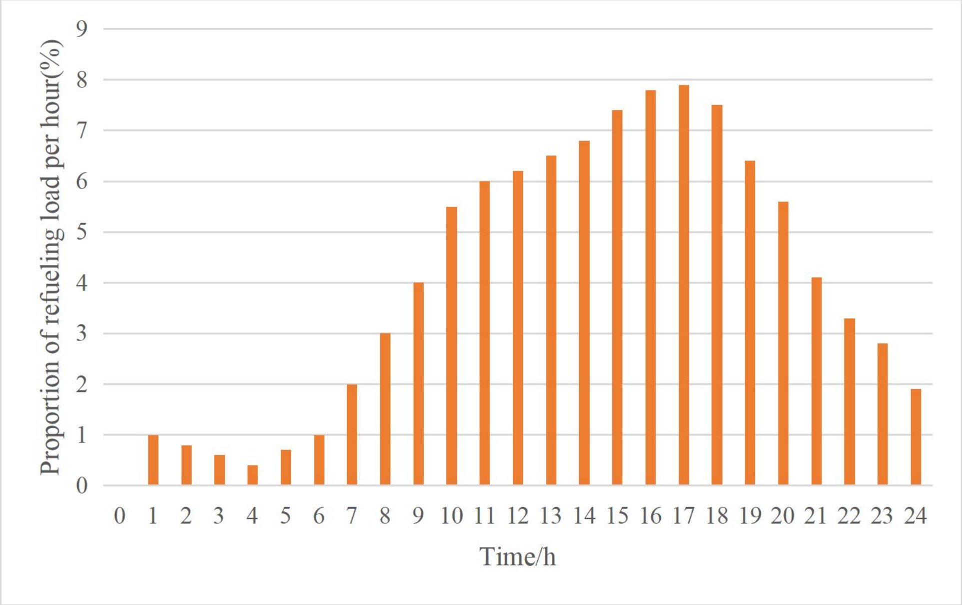
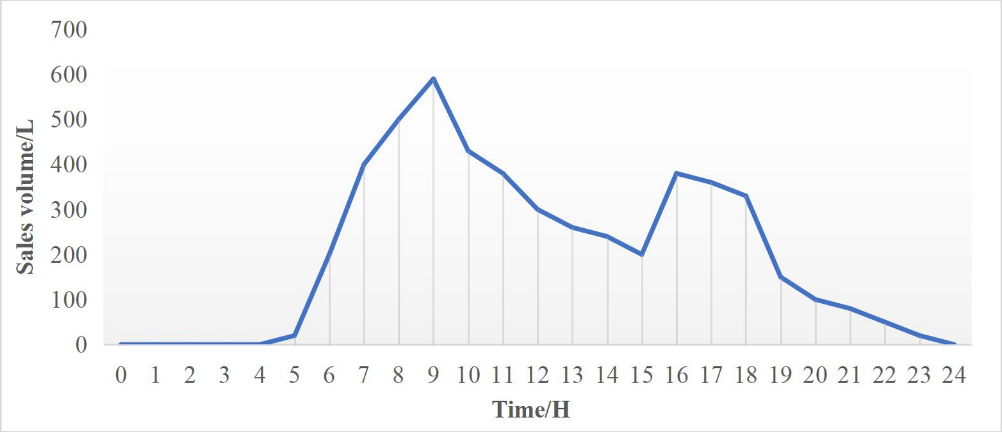


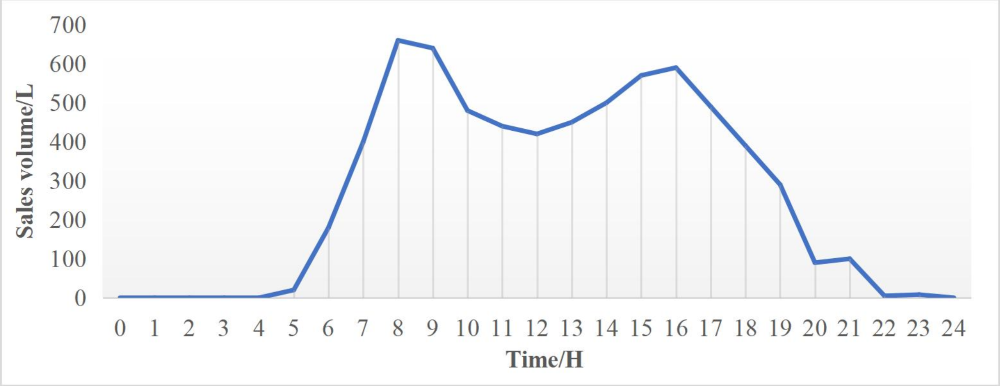
Fig.4-2 Friday hourly variation in refueling station demand[7]

Dalian University of Technology[8] conducted cluster analysis on the daily oil sales curve of No. 92 gasoline for 120 days at a gas station in Dalian, and found that the main oil sales models at the station can be divided into three types (as shown in Fig.4-3): between 7:00 and 16:00, sales model A showed a significant downward trend; Sales mode B maintains a high sales volume every hour; The sales model C exhibits obvious multi peak characteristics.

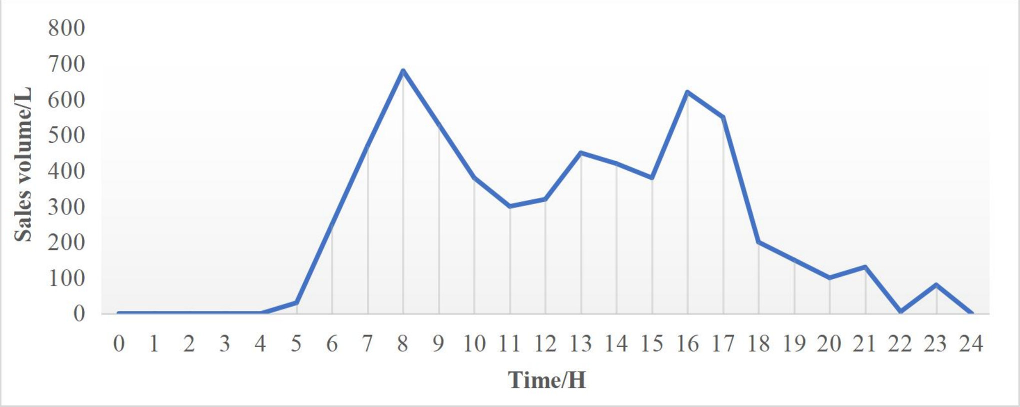
According to the three sales model curves, it can be seen that the fuel demand curve of gas stations in Dalian, China is mainly composed of multi peak demand curves such as double peak and three peak.



(a) Sales mode A



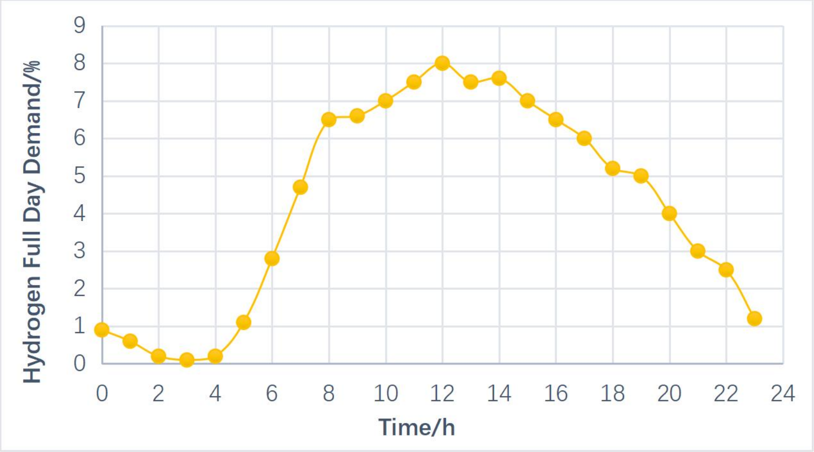
(b) Sales mode B



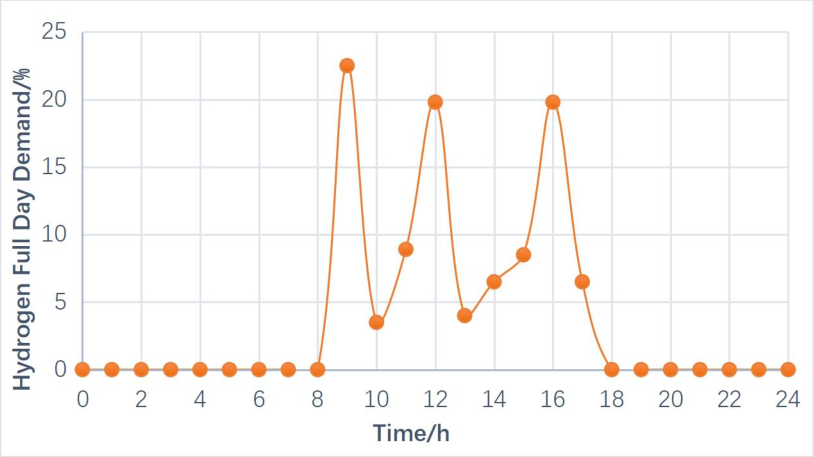
(b) Sales mode C

Fig.4-3 The Clustering Results of the Daily Sales Curves of No.92 Petrol Product in a Gas Station[8]

Shanghai Shunhua New Energy System Co., Ltd.[9] analyzed the distribution of domestic and international hydrogen refueling demand throughout the day (i.e. the proportion of hydrogen refueling demand for fuel cell vehicles per hour of operation to total hydrogen refueling demand throughout the day) curve. Among them, through statistical analysis of the annual average hydrogen refueling demand data of 33 hydrogen refueling stations in California, the United States in 2016, it was found that the distribution curve of hydrogen refueling demand in foreign countries is mainly a single peak distribution, which is basically the same as the distribution curve of refueling demand in foreign countries and gas stations. Through statistical analysis of the hydrogen refueling demand data of Anting hydrogen refueling station in Shanghai, China in 2017, it was found that the distribution curve of China's all-day hydrogen refueling demand showed a three peak distribution. There is a significant difference in the distribution pattern between the three peak demand curve and the single peak demand curve, that is, there are multiple peak refueling demand peaks during the entire day of operation.



(a) Distribution of single peak demand curve



(b) Three peak demand curve distribution

Fig.4-4 Distribution of hydrogen demand for refueling stations throughout the day[9]

In summary, the full day refueling demand curve of foreign hydrogen refueling stations is the same as that of gas stations, which is a single peak demand curve; The full day refueling demand curve of domestic hydrogen refueling stations is the same as that of gas stations, which is a multi peak demand curve. Considering that China's fuel cell vehicle development strategy prioritizes its application in the commercial vehicle field, the main service targets of domestic hydrogen refueling stations will be commercial vehicles operating on fixed routes such as logistics, public transportation, and buses for a long time in the future, with a multi peak demand distribution.

4.3 Case study on the application of photovoltaic-hydrogen refueling station

4.3.1 Research subjects

This chapter will take a hydrogen refueling station in Shanghai as an example to study the economy and feasibility of a photovoltaic hydrogen production and refueling system. The hydrogen refueling capacity of this refueling station is 500kg/day, which can meet the hydrogen demand of 4 heavy-duty trucks, 5 logistics vehicles, 8 buses, 2 medium capacity buses, and 2 passenger cars. The hydrogen gas in the hydrogen refueling station mainly comes from a hydrogen source point 100km away and is transported by a long tube trailer. The hydrogenation process is shown in Fig.4-5. At present, in order to improve the economic and social benefits of the hydrogen refueling station, a deep green transformation will be carried out. Due to the limitation of the available area of the hydrogen refueling station, a portion of the hydrogen in the transformed station still comes from long-distance trailer transportation, and a portion comes from photovoltaic hydrogen production and commercial hydrogen production, which is a combination of photovoltaic hydrogen production and external hydrogen supply[10]. The hydrogenation process is shown in Fig.4-6 .

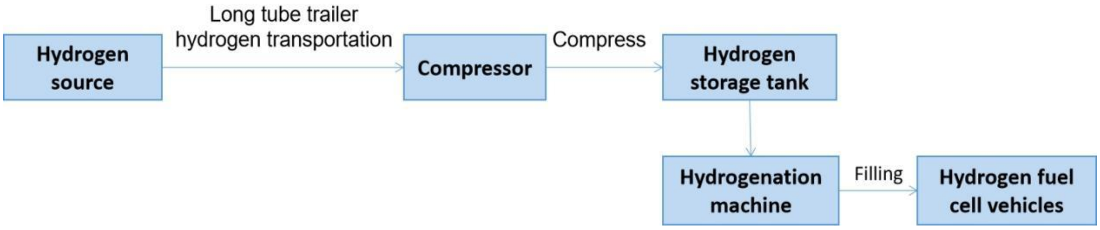


Fig.4-5 Hydrogenation process of external hydrogen refueling station

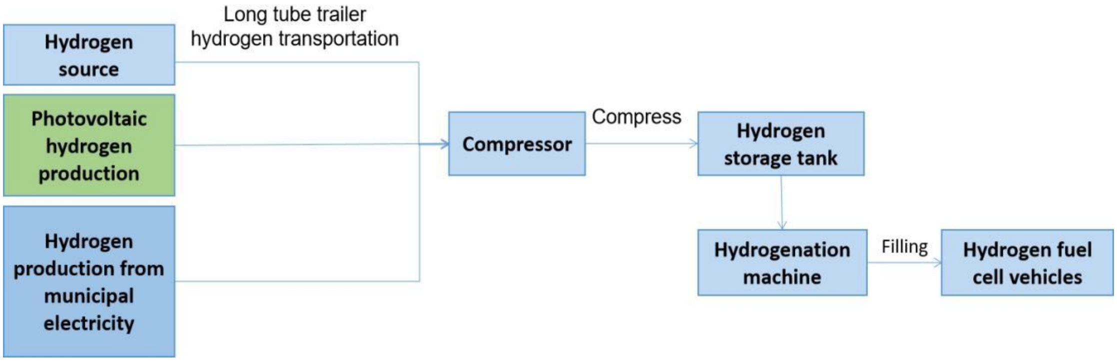


Fig.4-6 Hydrogenation process of hydrogen refueling station combining photovoltaic hydrogen production with external hydrogen supply

4.3.2 Hydrogen load analysis

Based on the gas carrying capacity of long tube trailers and the available area of hydrogen refueling stations, the daily hydrogen source of 500kg is divided into 350kg/day for long tube trailer transportation and 150kg/day for photovoltaic and commercial hydrogen production. Based on the analysis in section 4.2.2, this chapter takes the full day hydrogen refueling demand curve of the Anting hydrogen refueling station in Shanghai as a reference. The full day hydrogen refueling demand curves under each hydrogen source will be shown in Fig.4-7 .

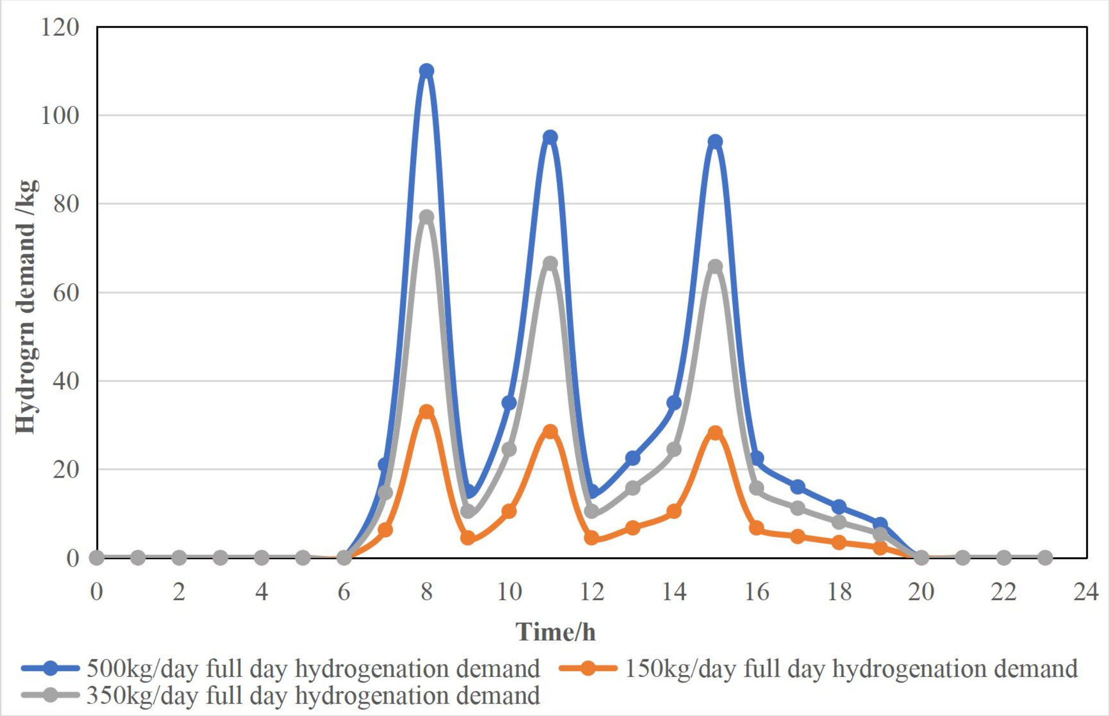


Fig.4-7 Full day and hourly hydrogen demand curve for hydrogen refueling stations

4.3.3 Equipment composition

The photovoltaic hydrogen production and refueling station system includes hydrogen refueling station system, long tube trailer, photovoltaic power generation system, electrolytic cell system, etc. The parameters of each equipment are as follows:

Table 4-3 Hydrogen refueling station system parameters

Parameter	Value
Daily hydrogenation capacity	500kg
Filling pressure	35MPa

Full year operation	365 days
Rated heating power	700kW
Equipment procurement and installation costs	$ 1,660,000
Land and civil engineering costs	$ 420,000
Equipment depreciation	15 years
Land and housing	30 years
Annual management maintenance and labor costs	$ 280,000

Table 4-4 Long tube trailer parameters

Parameter	Value
Full load hydrogen mass	350kg
Residual rate of hydrogen gas in the tube bundle	20%
Average trailer speed per hour	50km/h
Fuel consumption per 100 kilometers	25 liters
Trailer hydrogen charging and unloading time	5h
Annual maintenance costs	$ 58,000
Equipment depreciation	15 years

Table 4-5 Photovoltaic power generation system parameters

Parameter	Value
Installed capacity	1070kW
Unit cost of equipment	0.388 $/W
Civil and installation costs	$ 210,000
Equipment depreciation period	25 years
Depreciation period for civil engineering and installation	30 years
Annual maintenance costs	$ 42,000

Table 4-6 Electrolytic Cell System Parameters

Parameter	Value
Electrolytic cell cost	$ 630,000
Civil engineering and equipment installation	$ 210,000
Equipment depreciation period	10 years
Depreciation period for civil engineering and installation	20 years
Annual labor and maintenance costs	$ 56,000

4.3.4 Economic parameters

The commonly used economic parameters involved in this chapter include electricity prices, water prices, and the price of hydrogen purchased. Among them, the purchased hydrogen mainly comes from industrial by-product hydrogen.

Table 4-7 Economic parameters

Price of purchased hydrogen ($/kg)		1.88
Electricity price（$/kWh）	Valley time	0.04
	Normal time	0.082
	Peak time	0.14
Water Price ($/ton)		0.725
Carbon trading price ($/ton)		8.2

The cost of hydrogen production is one of the decisive factors to determine the market price of hydrogen. According to the fixed and variable cost structures of the hydrogen production process, the cost formula for hydrogen production is:

$$r_m = p_e \times P_e + (A_1 + A_2)/R_t + p_w \times P_w$$

Among them, r_m is the cost of hydrogen production, $/kg; p_e is the electricity price, $/kWh; p_w is the water price, $/t; P_e is the unit power consumption, kWh/kg; P_w is the unit water consumption, t/Nm^3； A_1 is the annual depreciation cost of equipment ; A_2 is the annual operation and maintenance cost, $; R_t is the total amount of hydrogen production per year, kg.

According to the calculation formula for hydrogen production cost, the cost of electrolytic hydrogen production under different electricity prices and photovoltaic hydrogen production is shown in Fig.4-8.

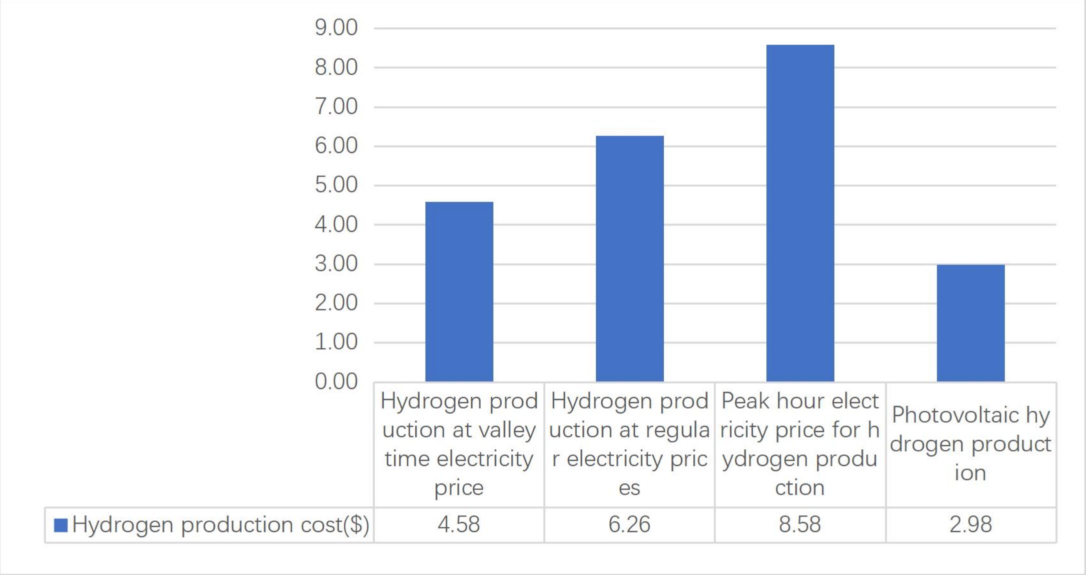


Fig.4-8 Hydrogen production cost

4.4 Results and discussion

4.4.1 Operation strategy analysis

The seasonal variation of solar energy resources in Shanghai is very obvious, as shown in Fig.4-9, the solar irradiance is highest in the summer from May to August, and lowest in the winter from January, November, and December. Therefore, this chapter selects three typical days from the summer, winter, and spring and autumn seasons to analyze and study the photovoltaic system's power generation. Due to the limitation of available area, the installed capacity of the photovoltaic system of the hydrogen refueling station is approximately 1070kW.Panels with a rated power of 585 Wp are proposed in this project. Then, to produce the required amount of electrical power, 1828 PV panels are required to be installed in this project。The power generation curve of the photovoltaic system is shown in Fig.4-10 .

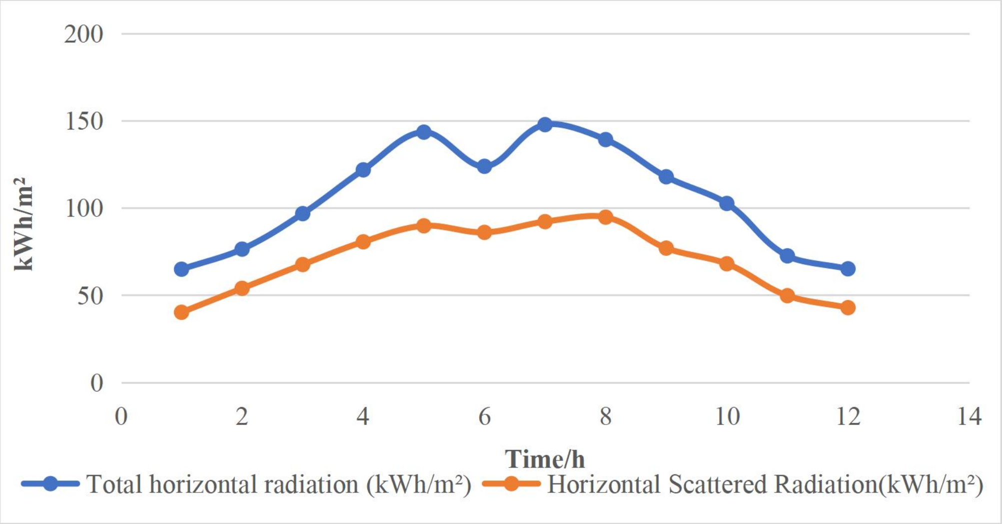


Fig.4-9 Monthly distribution of solar radiant intensity in Shanghai

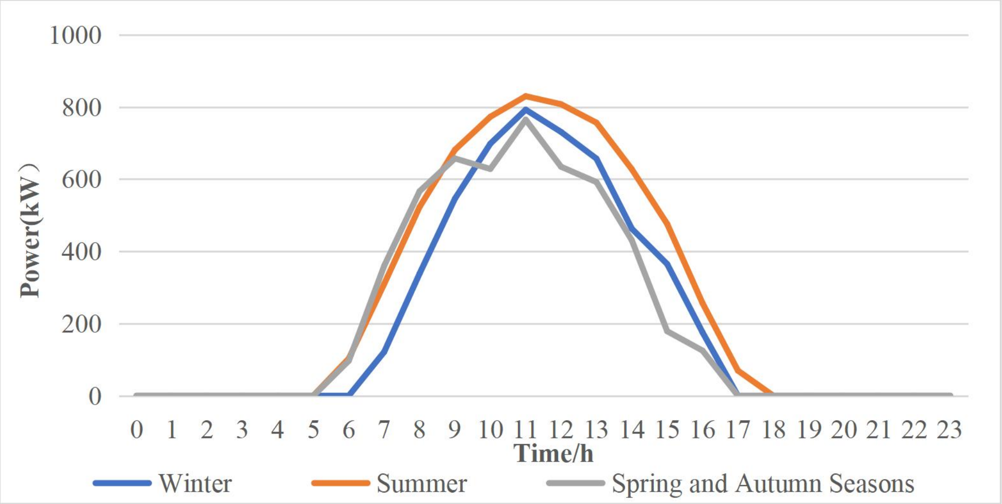


Fig.4-10 Typical solar volt system power generation curve

Based on the principle of transporting hydrogen from hydrogen sources, supplementing and prioritizing the use of electrolytic hydrogen production, during summer, due to strong sunlight, the hydrogen production capacity through photovoltaic power generation can already cover the hydrogen demand, so there is no demand for commercial hydrogen production. The operating curve is shown in Fig.4-11. In winter and spring and autumn, due to the weak sunlight intensity, some hydrogen demand needs to be met through the production of hydrogen from municipal electricity. Considering the economy and working hours, valley time electricity prices can be used to produce hydrogen at 6am. The operating curve is shown in Fig.4-12, Fig.4-13.

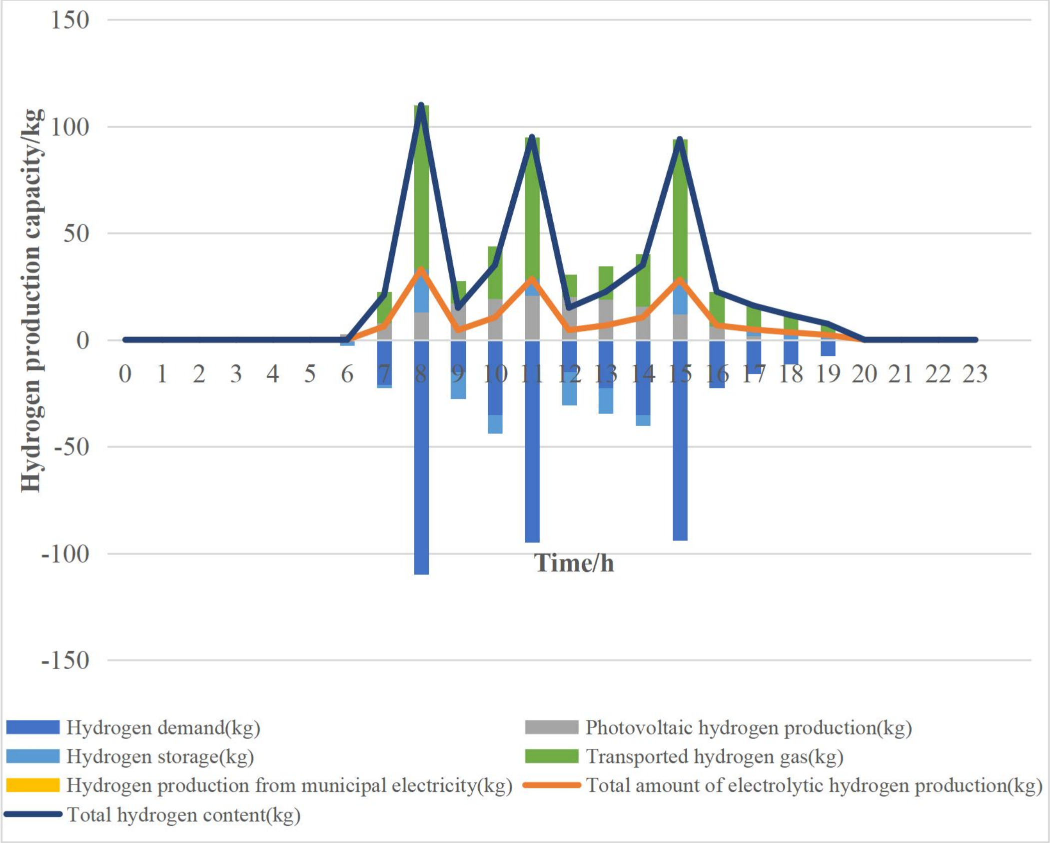


Fig.4-11 Typical Summer Solar Volt Hydrogen Station Hydrogen Production Operation Curve

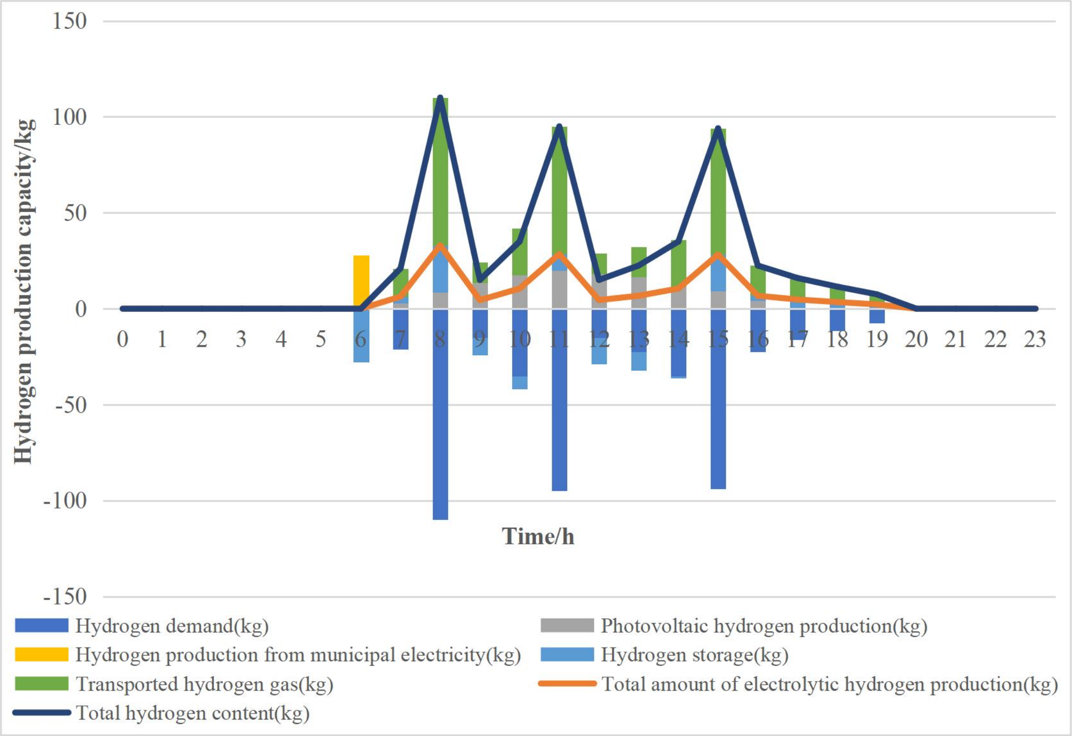


Fig.4-12 Hydrogen production operation curve of typical solar photovoltaic hydrogen refueling stations in winter

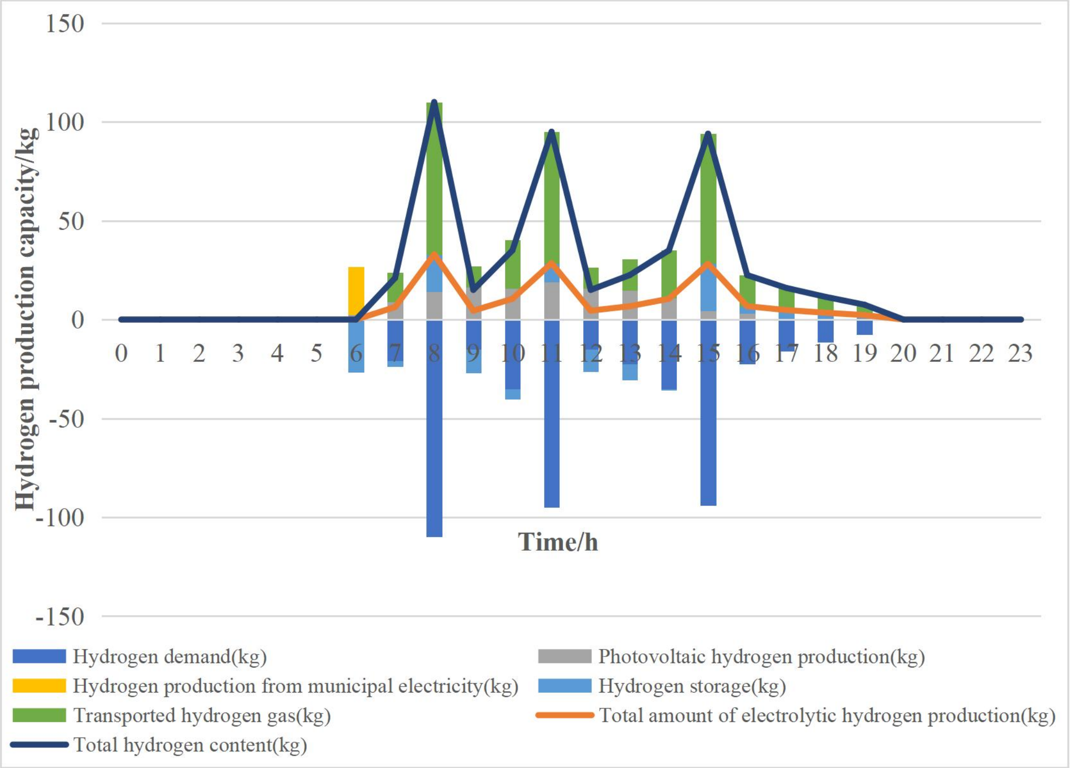


Fig.4-13 Hydrogen production operation curve of typical solar photovoltaic hydrogen refueling stations in spring and autumn

4.4.2 Economic and social benefit analysis

The total annual cost and composition of hydrogen refueling stations and photovoltaic hydrogen refueling stations are shown in Table 4-8, it can be seen that even though the annual investment cost of photovoltaic hydrogen production and refueling stations is higher than that of hydrogen refueling stations, the total annual cost is lower than the total annual cost of hydrogen refueling stations because the hydrogen generated is green hydrogen with no carbon emissions and carbon emission subsidies.

Table 4-8 Composition of total cost for various hydrogen refueling stations

Type of hydrogen refueling station	Annual investment Cost （$）	Annual operating cost （$）	Annual maintenance cost （$）	Annual carbon subsidy cost （$）	Annual total cost （$）
Hydrogen refueling station	130434.78	664511.59	2608.6957	0	797555.07
Photovoltaic-hydrogen refueling station	230391.88	439340.97	4607.84	10145.67	664195.01

To analyze the economic benefits of two hydrogen refueling stations, this chapter calculates the investment payback period, NPV, and IRR of photovoltaic hydrogen production and refueling stations based on the sales prices of different hydrogen, as shown in Fig.4-14 and Fig.4-15. In terms of investment payback period, when the hydrogen price is below $4.37, the hydrogen refueling station is in a loss state, and the investment payback period is negative or infinite years; When the selling price of hydrogen is less than $3.64, the photovoltaic hydrogen production and refueling station is in a loss state, and the investment payback period is negative or infinite years; When the hydrogen price is higher than $5.07, the hydrogen refueling station and investment payback period are within a reasonable range, but due to the NPV value being less than 0, there is a risk in the project. In terms of NPV and IRR, the NPV value of photovoltaic hydrogen production and refueling stations is always higher than the NPV value of the refueling station,that is, the scheme and the investment benefit of the photovoltaic-hydrogen refueling station project are better; When the hydrogen price is equal to or higher than $5.91, the NPV of the refueling station project is >0, and the IRR ≥ 12%, then the project has economic benefits and is feasible; When the price of hydrogen is equal to or higher than $6.23, the NPV of the refueling station project is >0, and the IRR ≥ 12% , then the project has economic benefits and is feasible.

Table 4-9 Cost benefit analysis results .

Hydrogen price ($)	Hydrogen refueling station			Photovoltaic-hydrogen refueling station		
	Investment payback period (year)	NPV	IRR	Investment payback period (year)	NPV	IRR
1.45	/	/	/	/	/	/
2.90	/	/	/	/	/	/
4.64	44.53	-1.35	/	20.90	-0.96	3%
5.07	16.96	-0.42	4%	14.56	-0.03	6%
5.80	8.35	1.13	11%	9.67	1.51	10%
5.91	7.72	1.38	12%	9.17	1.76	10%
6.23	6.40	2.06	15%	8.05	2.44	12%
7.25	4.14	4.22	23%	5.78	4.61	17%
8.70	2.75	7.32	35%	4.13	7.70	24%
10.14	2.06	10.41	46%	3.21	10.80	30%

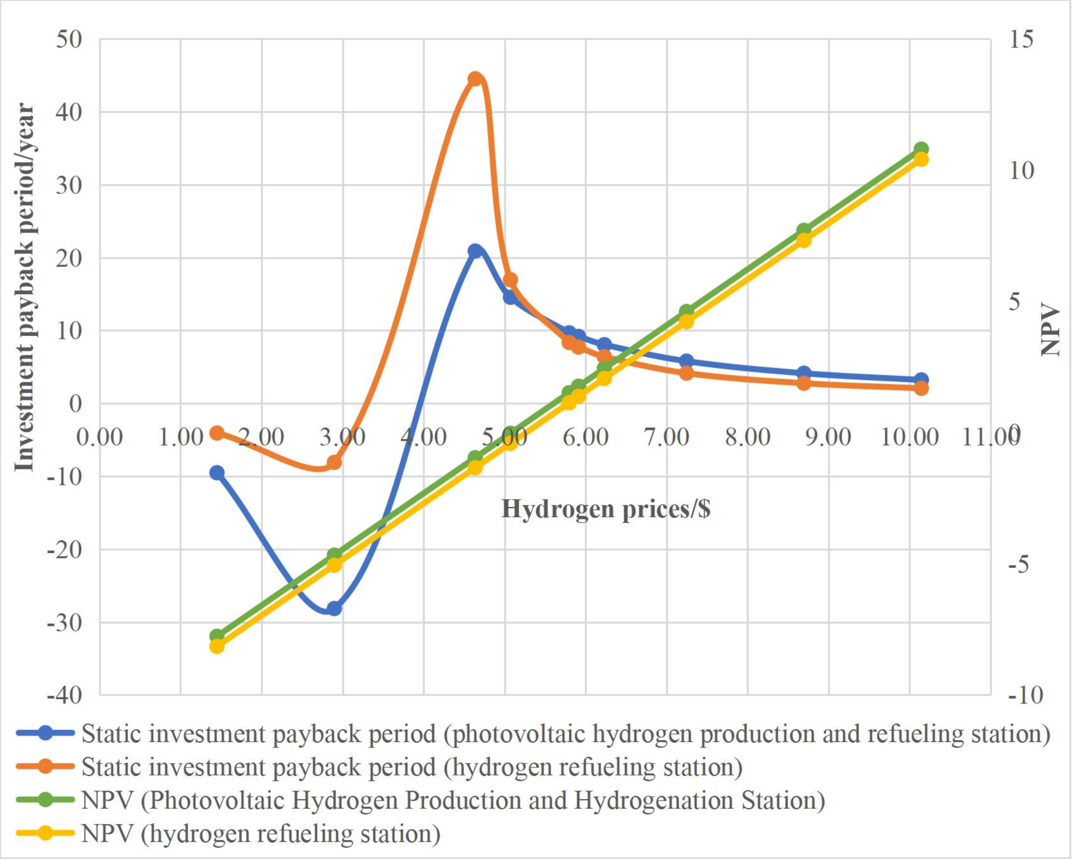


Fig.4-14 Comparison of static investment payback period and NPV between photovoltaic hydrogen production and refueling stations under different hydrogen prices

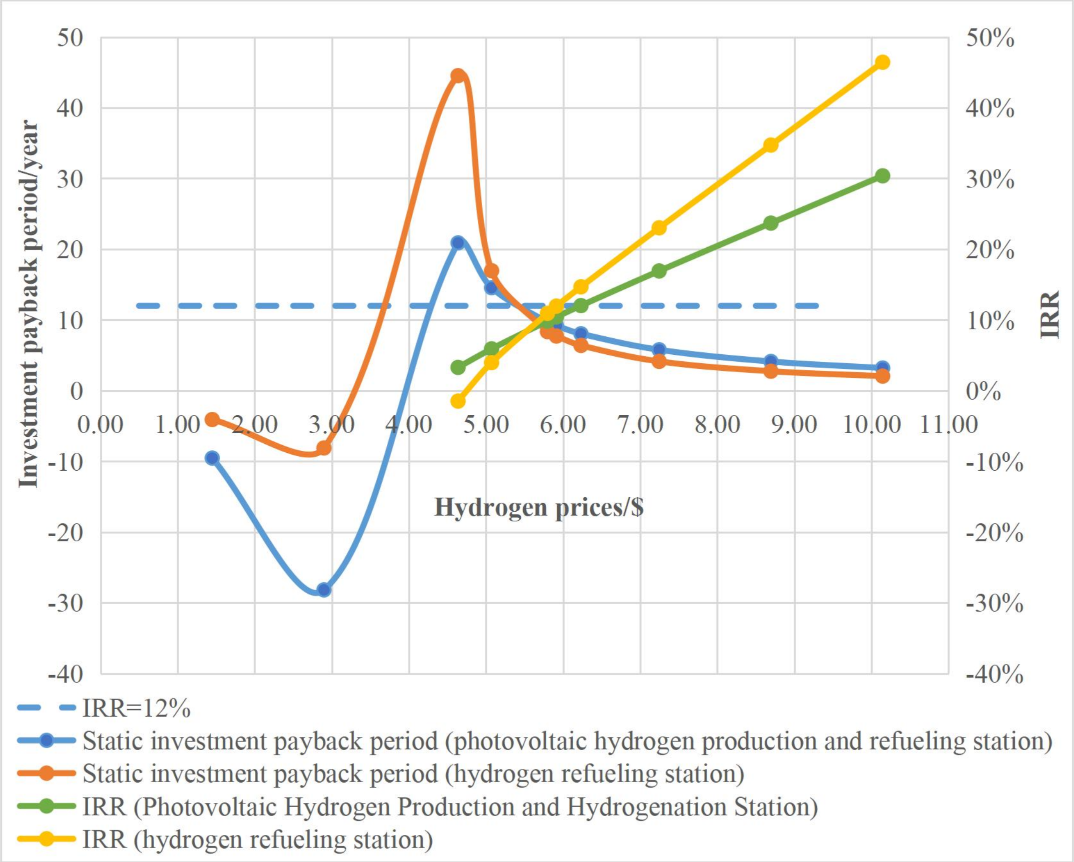


Fig.4-15 Comparison of static investment payback period and IRR between photovoltaic hydrogen production and refueling stations under different hydrogen prices

In terms of energy conservation and emission reduction in social benefits, under ideal conditions, hydrogen fuel cell vehicles fueled by this refueling station can reduce carbon dioxide emissions by approximately 2737.5 tons per year compared to traditional fuel vehicles. At the same time, based on the 1070kW photovoltaic system configured in this paper, the annual power generation is approximately 1241MWh, which can reduce carbon emissions by approximately 1237.28 tons per year compared to commercial electrolysis hydrogen production or industrial by-product hydrogen. From this, photovoltaic hydrogen production and refueling stations will effectively support the transformation of the transportation sector towards green and low-carbon.

4.5 Summary

This chapter takes a hydrogen refueling station in Shanghai as the research object to study the application effect of photovoltaic hydrogen production and refueling stations. Due to the limitations of available building area and regional solar energy resources, a combination of external hydrogen supply and on-site hydrogen production is adopted to study the feasibility of the application of photovoltaic hydrogen production and refueling stations. The photovoltaic hydrogen production part bears a daily refueling capacity of 150kg, and the external hydrogen supply bears a daily refueling capacity of 350kg. Through comparative analysis with pure external hydrogen refueling stations, in terms of economy, the NPV value of photovoltaic-hydrogen refueling stations is always higher than the NPV value of hydrogen refueling stations, that is, the scheme and the investment benefit of the photovoltaic-hydrogen refueling station project are better. When the hydrogen price is not less than 5.91 US dollars, the hydrogen refueling station project has economic benefits; When the price of hydrogen is not less than $6.23, the photovoltaic hydrogen production and refueling station project has economic benefits. In terms of social benefits, hydrogen refueling stations that combine photovoltaic hydrogen production with external hydrogen supply can reduce carbon emissions by approximately 1237.28 tons per year. Therefore, photovoltaic hydrogen production and refueling stations will have good application effects and prospects at appropriate gas selling prices.

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Chapter 5

RESEARCH ON THE APPLICATION EFFECT EVALUATION OF HYDROGEN FUEL CELL COGENERATION IN AIRPORT TERMINAL BUILDING

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5.1 Content

Airports, with their special functions and distinctive features, have become the most distinctive and important buildings in cities, an important component of developed cities, and have been deeply integrated into urban life. As an important part of the airport and a special type of large public building, the terminal has higher Functional requirement and comfort requirements. According to statistics, the average power consumption of Chinese airport terminals is about 177, among which the energy consumption of heating and air conditioning systems accounts for 45% to 70% of the operating energy consumption of airport buildings[1]. Therefore, energy conservation and emission reduction in airport terminals are urgent. As a "zero carbon" energy source, the application of hydrogen energy will inevitably become an important development direction for energy supply in the construction field.

Among the forms of hydrogen energy application, hydrogen fuel cell cogeneration is one of the main forms of hydrogen energy application in the construction field because of its advantages of high efficiency, low noise, small size and low emissions. To explore its application feasibility, this chapter will take an airport terminal in shanghai as an example to study the application feasibility of hydrogen fuel cell cogeneration system under different hydrogen cost prices.

5.2 Load characteristic analysis of airport terminal building

This paper takes the departure hall of an airport terminal in Shanghai as the research object, the airport is located in Pudong New Area, Shanghai, one of the three major gateway complex hubs in China, according to 2019 data this airport has an annual passenger throughput of 76,153,400 passengers, an annual cargo and mail throughput of 3,635,600 tons, and 51,846 annual flights[2].

The departure hall of the airport terminal, with a total area of 57,960 m^2, is the first stop for departing passengers, with its large scale and high passenger throughput, and is also the most important public space in the terminal[3]. Before entering the security check, passengers need to complete a series of formalities here. Its basic function is a series of check-in procedures. Because some passengers have plenty of time, the departure hall is equipped with commercial, catering services and other public services, so there is a large flow of people and a large energy demand.

5.2.1 Load characteristics analysis

This section mainly analyzes the load characteristics of the airport terminal and the influencing factors of its load space-time characteristics, with a view to doing a good job in theoretical basic research for load forecasting analysis.

(1) Building characteristics of airport terminal

The airport terminal building is a typical large space building. The difference is that the terminal has a wide range of functions, large energy saving potential, high personnel density and strong mobility. For visual and aesthetic effects, glass curtain wall enclosure structure is adopted in a large area, which makes the space open. With the development of civil aviation, the passenger throughput of the airport is growing rapidly. These buildings carry a large number of passengers every day and need to maintain operation for a long time. All these factors will lead to very high air conditioning energy consumption [4], with great energy saving potential.

The functions of the airport terminal are complex and diverse. The positioning of the terminal is not limited to traffic purposes, but is intended to become a commercial and cultural exchange center [5]. The functional composition generally includes arrival, departure and public service. Meet the diversified functions of indoor passengers such as check-in, landing, shopping, catering and rest, and the functional design needs to conform to the rationality of people flow and logistics, which puts forward high requirements for the architectural design and energy supply control of the terminal. In addition, based on its unique functions, the terminal usually has buildings with open space (indoor height is 10-30m), glass curtain walls and high-density indoor heat sources (i.e. indoor equipment and personnel). There are open entrances of different heights connecting with the outdoor environment or other buildings (such as subway stations, railway stations, hotels). These characteristics lead to complex airflow in large spaces.

The density of personnel in the terminal is high and the mobility is strong. In the past ten years, the number of civil aviation passengers has increased at an annual rate of 5%～10%. According to the classification standard of airport hub terminals in China, the passenger throughput is large and the mobility of personnel is strong, which is accompanied by huge service pressure. The passenger throughput needs to be predicted in advance for security check, check-in, emergencies, and baggage consignment.

Table 5-1 China Airport Hub Terminal Division Standard

Type name	**Passenger throughput (person time)**	**Main functions**	**Typical city where the airport is located**
Super large hub terminal	More than 50 million	Transfer connection between international routes	Beijing, Shanghai (Pudong), Guangzhou
Large hub terminal	30-50 million	Transfer between domestic flights and international routes	Chengdu, Shanghai (Hongqiao), Kunming, Xi'an, Chongqing, Hangzhou
Medium hub terminal	10-30 million	Transit connection between domestic routes	Nanjing, Wuhan, Urumqi, Tianjin, Shenyang

The terminal has a large building area and transparent enclosure structure. In order to pursue permeability and artistic effect, the designer will use glass curtain wall as the enclosure structure in a large area, with sufficient lighting equipment and bright indoor light. According to Wikipedia, the world's largest terminal T3 of Dubai International Airport covers an area of 1.71 million square meters, with 180 service counters to meet various needs of passengers. The construction area of the T3 terminal of the Capital International Airport is also up to 986000 square meters.

(2) Load characteristics of airport terminal building

As one of the important infrastructure and transportation centers, most cities now have more than one airport. For decades, China's economic and technological development has driven the rapid development of the civil aviation industry and the construction of the airport terminal. The airport terminal is a public building with special functions to meet the basic needs of people during their travel, such as entry and exit, waiting, shopping and rest. The service function and use characteristics of these typical public transport buildings make their energy consumption level generally higher than that of ordinary public buildings.

The green performance investigation and test report of the civil airport terminal shows that the energy consumption per unit area of the airport terminal is 129–281 kWh/(m^2•a) [6], and the average energy consumption per unit area is 180 kWh/(m^2•a)[7], about 2.9 times that of other public buildings[8] , which has huge energy conservation potential. More than 50% of the energy consumption of the airport terminal is consumed by the air conditioning system. The refrigeration period of the airport is longer than the heating period, and there is a demand for refrigeration throughout the year, which leads to the air-conditioning cooling load being greater than the heating load in terms of energy consumption.

From the perspective of building space, the number of floors is small, the space span is large, and the plane area is wide. The length of the general airport terminal is 200-1000m. The main building has 3-5 floors, some of which are as high as 20m. Building shapes include gallery, satellite hall, front row, ferry car and multi terminal building. Different building shapes cause problems such as large window wall ratio, huge overhanging canopy, large opening area of hall roof, etc. The characteristics of airport terminal building in large area cause complex pipeline layout, high cost of energy equipment, and great impact on building load. In addition, the terminal often adopts metal grid structure, and the heat conduction of wall insulation layer is uneven, resulting in thermal bridge effect, which has an impact on indoor ventilation and insulation of enclosure structure.

From the perspective of the surrounding environment of the building, the airport terminal is generally far away from the city center, the urban heat island effect disappears, the ambient temperature around the building is relatively low, and the environmental quality is high, but the surrounding environment is spacious, the solar radiation is stronger than that of the city center building, and the wind speed is significantly increased. However, because streamline roof is often used in roof design, and the overhang is huge, the sunshine angle in different time periods leads to dynamic changes in the shadow area and angle of the building. The result is too large according to the conventional load calculation.

In addition, as the airport terminal operates all year round, it is equipped with multi-functional areas such as restaurants, shopping, rest, and office, which have multiple and disordered functions, which brings certain difficulties to the control and division of the air conditioning system in the whole area. The all-weather operation and glass curtain wall structure result in a large amount of heat source for lighting equipment. In addition, due to the high opening frequency of the entrance and exit doors, the air infiltration through the entrance and exit is large. The airport personnel density fluctuates greatly, the passenger flow is constantly updated with the flight number, the indoor personnel density is large, and the personnel flow in different security inspection areas is uneven.

Based on the above building characteristics, the airport terminal building leads to the irregular fluctuation of indoor cooling and heating load, and it is difficult to maintain high indoor comfort. The air flow organization is interlaced, and the air conditioning energy consumption is higher than that of ordinary buildings. According to previous studies, the main factors affecting the energy consumption of the air-conditioning system are passengers and outdoor meteorological parameters[9]. In the air conditioning system load, the load directly related to the terminal residents and the fresh air supply of terminal residents account for 40%~60% of the total load. Influenced by many factors, airport load is characterized by randomness, nonlinearity and dynamics.

5.2.2 Analysis on influencing factors of load space-time characteristics

(1) Load time characteristics of airport terminal

The airport terminal provides cooling throughout the year, and the cooling period is longer than the heating period. Due to the particularity of the building, the complexity of the indoor functional area and the strong personnel mobility, the load presents the characteristics of random, nonlinear and dynamic. In terms of time characteristics, the main reason lies in the time series changes of indoor personnel caused by flight schedule and passenger behavior.

1) Flight schedule

Due to the influence of weather, emergencies and other factors, the flight frequency will lead to the non-linear change of passenger flow, resulting in irregular fluctuation of load for a period of time. The research shows that the indoor load of the terminal has obvious correlation with the flight takeoff and landing time and sorties[10].

Under normal circumstances, the flight frequency is different according to weekdays, holidays, rest days and seasonal characteristics, but will not affect the check-in. The indoor passenger flow is within the predictable range according to the flight frequency announced in advance.

However, due to uncontrollable factors such as weather, flight delay may lead to overcrowding in some areas of the airport, such as seating areas and restaurants, which may cause trouble to the analysis of indoor passenger flow. Li[11] and others pointed out when investigating an international airport in Chengdu that the average delay time of the airport in 2017 was about 36.8 minutes. Ren Peng[10] and others also studied and analyzed that due to flight delay, on the premise that the airport informed in advance, the non check-in passengers would delay arriving at the airport, but within two hours of delay, most passengers would stay in the terminal. This will cause a temporary surge in the flow of people to the airport restaurant, shopping center, check-in point and waiting hall. Therefore, the fluctuation of passenger flow caused by flight delay has a certain impact on indoor load.

2) Passenger behavior

The behavior and stay time of passengers after entering the terminal are also the main factors affecting the indoor passenger flow. Different purposes of passengers entering the terminal will cause them to use different service facilities (i.e. check-in counters, security check counters, boarding gates, etc.) and also determine the indoor environmental quality (i.e. temperature, humidity, CO_2 concentration, etc.) in a certain period of time. Therefore, the analysis of passenger path and residence time in the terminal will help to improve the prediction of passenger flow in a certain period of time, improve the overall performance of the airport and save energy consumption.

From the perspective of passenger flow process, passengers need to pass through the check-in hall, security inspection area and departure hall before boarding. In the check-in hall, you can choose counter check-in or self-service check-in, and choose whether to go to restaurants, shopping malls or rest areas. In the departure hall, they can choose where to stay and wait for the flight. Before leaving the terminal, passengers need to pass through the arrival channel, baggage claim area and arrival hall. Some people will stand near the baggage conveyor belt and wait for their baggage. For example, business travelers often use the airport more frequently and are more familiar with the use and entry mode of the airport. These passengers usually spend less time in the terminal and less in existing stores, but they do spend in restaurants and cafes. The situation of leisure travelers is almost the opposite. For typical activities, the metabolic rate of passengers in the departure hall is relatively low (i.e. sitting down, chatting, eating, shopping, etc.), while they will continue to walk or stand in other halls. Especially in the check-in hall, baggage claim area, arrival hall and transfer hall, they will walk with heavy luggage. The passenger flow diagram is as follows.

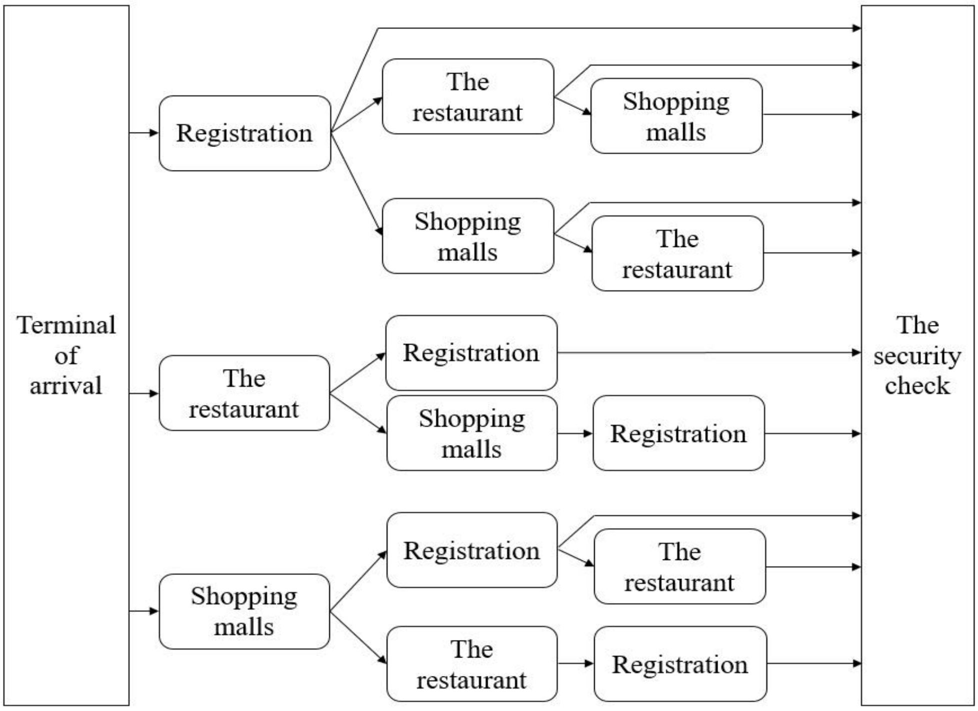


Fig.5-1 Passenger flow diagram

The stay time of passengers in the building will affect the indoor environment. The stay time is affected by different function halls, the scale of airport terminals and the personal preferences of passengers. Liu[12] et al. Investigated the typical three-month passenger flow characteristics of a hub airport terminal in China in three different seasons. The results show that the average expected stay time of passengers in the check-in hall and departure hall is 131 minutes. These values are only 67 minutes and 48 minutes compared with the two Korean airport terminals. Therefore, the stay time is related to the size of the airport.

In addition, the stay time during departure is longer than that during arrival. Especially in the departure hall, the average actual stay time can reach 132 minutes, and the average stay time in the check-in hall is 34 minutes. However, passengers often pass through the area in the process of arrival[13]. According to the survey results, the stay time in the baggage area varies from 9 minutes to 18 minutes, which is less than half of the stay time in the check-in hall. The night stay time is shorter than the day stay time. The average stay time of passengers in different functional areas of the terminal is shown in the table below.

Table 5-2 The average stay time of passengers in different functional areas of the terminal[14]

	Departure process		Arrival process			
	Check-in hall	Departure hall	Arrival Channel	Baggage Claim	Arrival Hall	Transfer Hall
Average stay time of passengers (minutes)	34	132	≤10\	5-18	≤5	≤5
Typical passenger activity	walk; stand; dragging luggage; check-in	various activities (shopping, dining, waiting)	walk	walk; stand; dragging luggage	walk; stand; dragging luggage	walk; stand; dragging luggage

Predicting the residence time of indoor personnel can improve the accuracy of airport passenger flow forecast and provide effective help for regional load control.

(2)Load space characteristics of airport terminal

The complexity of thermal environment heterogeneity of airport large space buildings stems from many interrelated factors. Solar radiation, enclosure temperature and indoor heat source lead to large space overheating and thermal stratification. According to the analysis of load space characteristics, the main problem of large space load is indoor thermal stratification, and solar radiation, enclosure temperature and indoor heat source are the main influencing factors of thermal non-uniformity.

1) Solar radiation

Airport large space buildings usually have transparent enclosure structure and large area windows for lighting, natural heating, beauty and other purposes. Lu et al.'s field survey of the terminal shows that the glass ratio of the wall and roof reaches 0.3-0.7 and 0.35-0.1 respectively [15]. In a cold climate, such a space can be used as a sunshine space on sunny days and as a buffer zone under harsh external environmental conditions. In contrast, in a hot climate, solar radiation plays an important role in leading to large space overheating and thermal stratification. Research shows that [15], if solar heating is prevented, the cooling demand can be reduced by 75%.

On the one hand, solar radiation heats the buoyant air accumulated in the upper region, and then increases the temperature or depth of the air layer. Due to the large building height and indoor and outdoor temperature difference, the chimney effect of large space is significantly enhanced. Wang et al.[16] showed that temperature difference caused by solar radiation can promote natural ventilation driven by buoyancy in atrium buildings. On the other hand, solar radiation significantly affects the temperature of roofs (including steel frames) and other interior surfaces. In addition, the wall area of large space buildings is large, and a large part of them are adjacent to the outdoor environment. Therefore, due to the strong solar radiation and high temperature inside surface, the indoor environment of large space is different from that of general buildings. The investigation shows that [17], for a 40m high atrium, the bottom layer is partially heated to 33-46℃; For the 5-meter high atrium, about 45% of the atrium is overheated to 36-53℃, and the temperature of the skylight and window of the railway station also reaches 44 and 36℃ respectively; In contrast, the temperature of envelope surface of other envelope structures reached 30-35 ℃. Therefore, the solar radiation causes the temperature of the envelope surface of the enclosure structure to rise, and the indoor thermal stratification and overheating phenomenon occurs. The indoor thermal environment of large space buildings caused by solar radiation is shown in the following figure.

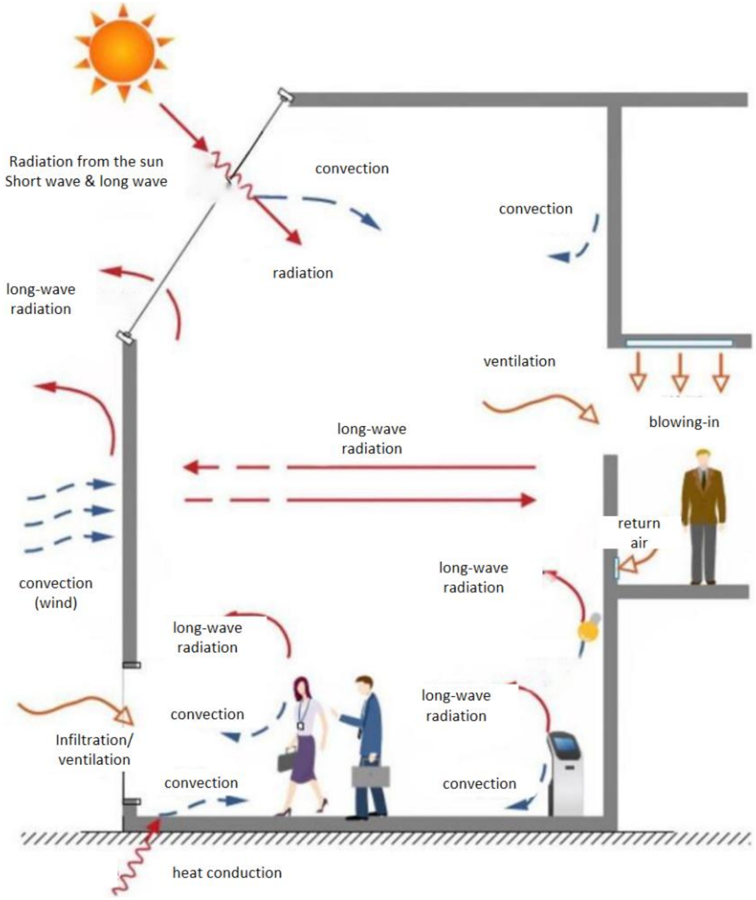


Fig.5-2 Indoor thermal environment of large space building

2) Temperature of building envelope

As previously mentioned, some inner surfaces absorb incoming solar radiation and reach relatively high temperatures. This leads to uneven temperature distribution on the building envelope. According to scholars' research[18], the maximum wall temperature difference between the first and fifth floors in atriums in severe cold regions of China is about 10℃. In order to obtain ideal simulation results, many scholars assume that the wall surface temperature changes only in the vertical direction, or assume that the wall is insulated except for the glass curtain wall. ASHRAE standard recommends[19] that the vertical temperature gradient should be estimated by dividing the wall surface into air-conditioned and non air-conditioned areas in a large space of a layered air conditioning system. Especially for glass curtain walls, the third boundary condition is sometimes used to improve the accuracy, which is also the main reason for the use of layered air conditioning systems in large space buildings.

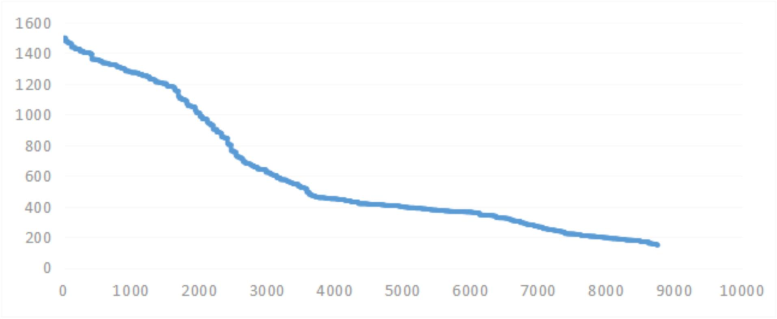
3) Internal heat source

The internal heat sources of airport terminal buildings include indoor personnel heat dissipation, lighting and electrical equipment, which generate thermal plumes and vertical temperature gradients in large space. The indoor air distribution and temperature distribution are affected not only by the room geometry and heat flux, but also by the location and shape of the heat source. The characteristics of passenger flow in different areas of the terminal are different, but the volume occupied by personnel is relatively small. Therefore, in many simulation cases, it is reasonable to assume a uniform composite heat source with a fixed heat flux in the entire floor area[11]. Part of the energy generated by the internal heat source convection to the indoor air, the rest of the energy radiation to the solid surface.

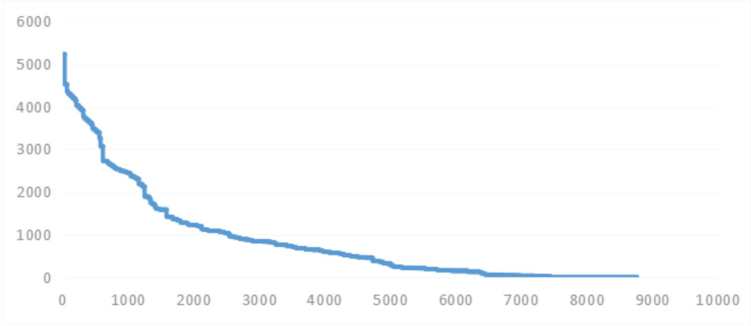
This chapter analyzes the load characteristics of airport terminal buildings, which is different from other large space buildings. The airport terminal has complex functional areas, large building area, large glass curtain walls in the enclosure structure, and operates year-round. The cooling period is longer than the heating period. From the analysis of load time characteristics, the load is stochastic, nonlinear and dynamic, and the main influencing factors are flight number and passenger behavior; From the analysis of load space characteristics, airport terminal buildings are prone to overheating and indoor thermal stratification, and the main influencing factors are solar radiation, indoor heat source, and enclosure temperature.

5.2.3 Load analysis

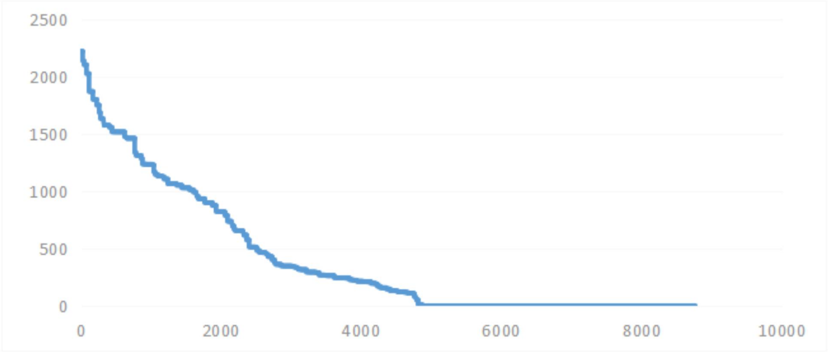
Based on the research and analysis of load forecasting model, the electrical, cooling and thermal load curves of the departure lounge of this airport terminal for 8760 hours are shown in Fig.5-3 shown. The cold load, heat load, and electric load curves for typical days in winter, summer, and transition seasons are shown in Fig.5-4.



(a) Electrical load

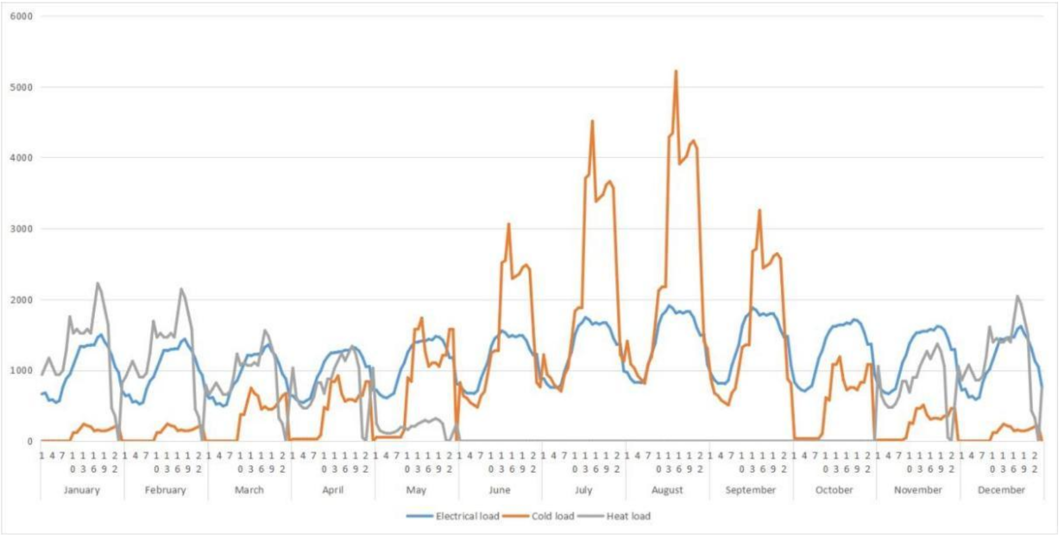


(b) Cold load

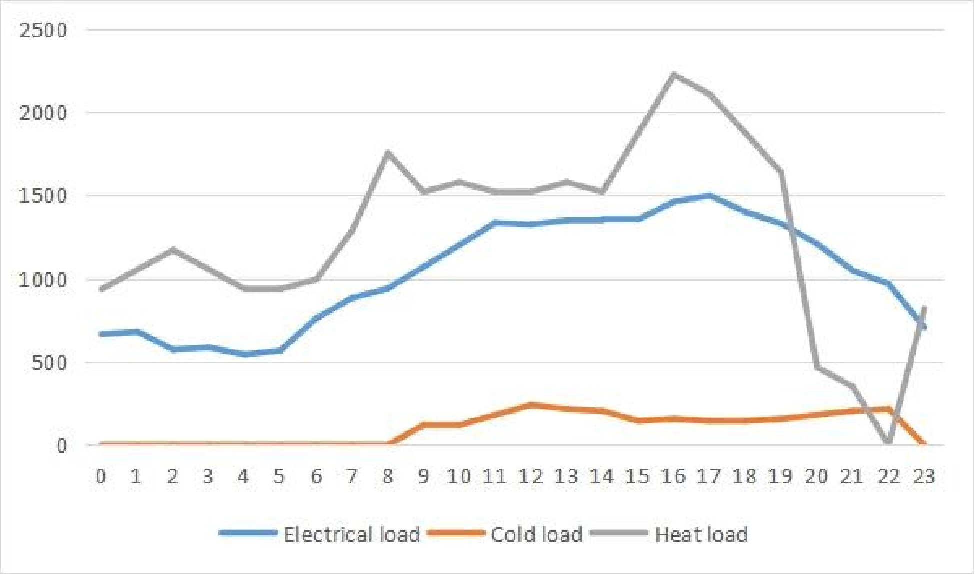


(c) Heat load

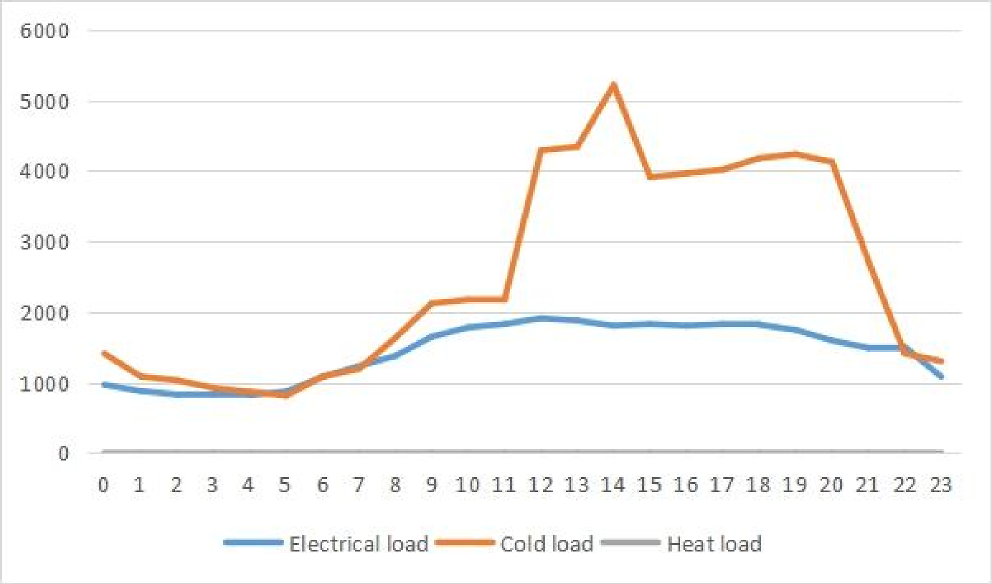
Fig.5-3 8760 hourly load curve



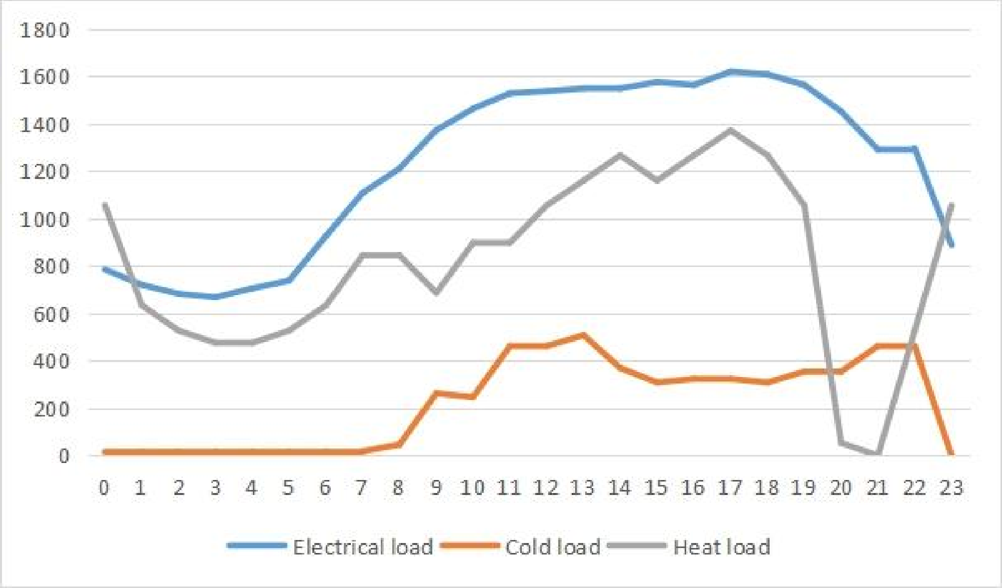
(a) Typical daily load curve of each month



(b) Typical daily load curve in winter



(c) Typical daily load curve in summer



(d) Typical daily load curve in the transitional season

Fig.5-4 Typical daily load curve

5.3 System configuration and basic data

5.3.1 Equipment composition

Based on the load analysis, the hydrogen fuel cell cogeneration system proposed in this thesis will consist of a hydrogen fuel cell cogeneration unit, a heat pump, a lithium bromide unit, a water storage tank, and a battery. The main parameters are shown in Table 5-3 to 5-7.

Table 5-3 Hydrogen fuel cell cogeneration unit parameters

Parameters	Numerical value
Available fuel	99.97% pure hydrogen
Fuel consumption	56.7 kg/h
Rated power generation efficiency	1000 kW
Rated heat generation power	700 kW

Table 5-4 Heat pump unit parameters

Parameters	Numerical value
Refrigeration capacity	1634 kW
Refrigeration input power	288.6 kW
Heat production power	1775.4 kW
Heating input power	369.6 kW

Table 5-5 Lithium bromide absorption chiller parameters

Parameters	Numerical value
Cooling water inlet and outlet temperature	15℃/10℃
Cooling water inlet and outlet temperature	32℃/38℃
Hot water inlet and outlet temperature	95℃/80℃
Model 1	
Cooling capacity	1828 kW
Hot water flow	145 m^3/h
Model 2	
Cooling capacity	2110 kW
Hot water flow	167 m^3/h

Table 5-6 Water storage parameters

Parameters	Numerical value
Type	Water storage
Storage loss	2% per 24hours

Table 5-7 Battery parameters

Parameters	Numerical value
Type	Sodium-sulfur
Storage loss	0.95

5.3.2 Economic parameters

The annual cost of the system includes annual investment cost, annual operation cost, annual operation and maintenance cost, and carbon trading cost. Among them, the average annual investment cost of each equipment considering the service life, residual value rate and basic rate of return is shown in Table 5-8; the system involves fuel price in operation including hydrogen price, market electricity price, feed-in tariff, heat price, etc. as shown in Table 5-9; the annual operation and maintenance cost is calculated as 2% of the annual investment cost; the carbon trading price is calculated as the current average market trading price.

Table 5-8 Energy equipment parameters[20]

Hydrogen fuel cell	Unit Price	90.92 $/kW
Lithium bromide absorption chiller	Unit Price	21.02 $/kW
Heat pump	Unit Price	5.3 $/kW
Water storage	Unit Price	0.82 $/kWh
Battery	Unit Price	26.6 $/kWh

Table 5-9 Fuel unit price

Hydrogen price（\$/kg）		4.8
Electricity price（\$/kWh）	Valley time	0.04
	Normal time	0.082
	Peak time	0.14
On-grid electricity price（\$/kWh）		0.06
Heat price（\$/kWh）		0.02
Carbon Trading Price (\$/ton)		8.2

5.4 Results and discussion

5.4.1 Operation strategy analysis

The market price of hydrogen as fuel at this stage is 4.8$/kg, according to the calculation, the unit cost of electricity production of the equipment selected in this thesis is about 0.26$/kWh, by comparing the analysis with the market price of electricity, the principle of the operation strategy of the system can be determined as follows.

When the price of hydrogen is reduced by 50%, the cost of power generation is higher than the peak hour electricity price, but considering the demand of carbon emission reduction, hydrogen fuel cell system can be run appropriately at the peak hour.

When the price of hydrogen is reduced by 50%-70%, the cost of power generation is higher than the usual price and lower than the peak price, the hydrogen fuel cell system and hot water lithium bromide unit can be run in the peak time, and the heat pump system and utility power supply can be run in the usual and valley time.

When the price of hydrogen is reduced by 70%-80%, the cost of power generation is higher than the price of electricity in the valley and lower than the price of electricity in the ordinary time, the hydrogen fuel cell system and the hot water lithium bromide unit can be operated in the peak and ordinary time, and the heat pump system and the utility power supply can be operated in the valley.

When the price of hydrogen is reduced by 90% , the cost of power generation will be lower than the price of electricity in the valley, which will not be discussed in this paper because it is impossible to realize this phenomenon in the short term.

Table 5-10 Comparative analysis of power generation cost and market electricity price

Hydrogen price discount rate	Hydrogen price ($/kWh)	Comparative analysis of power generation cost and market electricity price
Reduced by 0%	0.2644	Power generation cost > market peak hour tariff
Reduced by 10%	0.2365	Power generation cost > market peak hour tariff
Reduced by 20%	0.2086	Power generation cost > market peak hour tariff
Reduced by 30%	0.1807	Power generation cost > market peak hour tariff
Reduced by 40%	0.1528	Power generation cost > market peak hour tariff
Reduced by 50%	0.1248	Market Weekday Tariff < Generation Cost < Market Peak Hour Tariff
Reduced by 60%	0.0969	Market Weekday Tariff < Generation Cost < Market Peak Hour Tariff

Reduced by 70%	0.0690	Market Valley Tariff < Generation Cost < Market Usual Tariff
Reduced by 80%	0.0411	Market Valley Tariff < Generation Cost < Market Usual Tariff
Reduced by 90%	0.0131	Power generation cost < market valley hour tariff

Based on the above economic operation strategy, when the hydrogen price is reduced by 0%, 50% and 70%, its equipment configuration is optimized, and its installed equipment capacity is shown in Table 5-16. Among them, since when the hydrogen price is reduced by 50%, its power generation price is lower than the peak time and higher than the usual time, it mostly operates in the peak time with priority, so its equipment configuration is the same as that at the original hydrogen price; when the hydrogen price is reduced by 70%, its power generation price is lower than the usual time and higher than the valley time, so it mostly operates in the usual time and peak time with priority, so the installed equipment capacity is increased. As a result, the hourly output of each unit and the hourly load curve of a typical day for the hydrogen fuel cell cogeneration system under different hydrogen prices in different seasons and different equipment configuration schemes are shown in Fig.5-5 to Fig.5-11.

Table 5-11 Equipment configuration options at different hydrogen prices

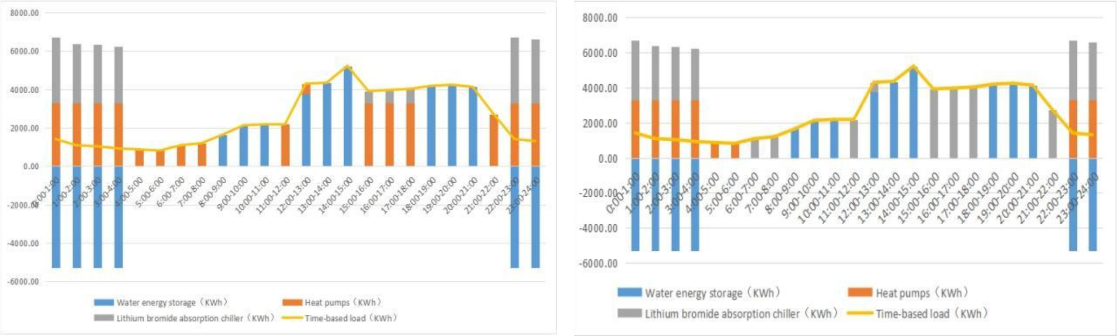
Hydrogen price discount rate Equipment	Reduced by 0%	Reduced by 50%	Reduced by 70%
Hydrogen fuel cell cogeneration	Electric power：1*1000 kW Heat power：1*700 kW	Electric power：1*1000 kW Heat power：1*700 kW	Electric power：2*1000 kW Heat power：2*700 kW
Heat pumps	Heat production：2*1634 kW Refrigeration capacity：2*1775.4 kW	Heat production：2*1634 kW Refrigeration capacity：2*1775.4 kW	Heat production：2*1634 kW Refrigeration capacity：2*1775.4 kW
Lithium bromide absorption chiller	Refrigeration capacity：3*1828 kW	Refrigeration capacity：3*1828 kW	Refrigeration capacity：2*2110 kW
Water Energy Storage	Heat storage capacity：2300 kW Cooling storage capacity：2300 kW	Heat storage capacity：2300 kW Cooling storage capacity：2300 kW	Heat storage capacity：2300 kW Cooling storage capacity：2300 kW
Battery	Electricity storage capacity：2000 kW	Electricity storage capacity：2000 kW	Electricity storage capacity：2000 kW

(a) Reduced by 0%, 50% (b) Reduced by 70%

Fig.5-5 Hourly output and hourly load curve per unit for winter heating

(a) Reduced by 0%, 50% (b) Reduced by 70%

Fig.5-6 Hourly output and hourly load curve per unit for winter power supply



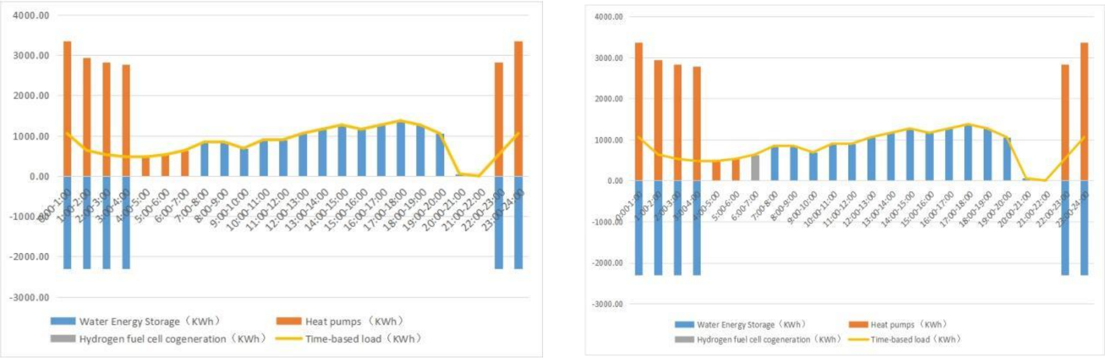
(a) Reduced by 0%, 50% (b) Reduced by 70%

Fig.5-7 Hourly output and hourly load curve per unit for summer cooling

(a) Reduced by 0%, 50%

(b) Reduced by 70%

Fig.5-8 Hourly output and hourly load curve per unit for summer power supply



(a) Reduced by 0%, 50%

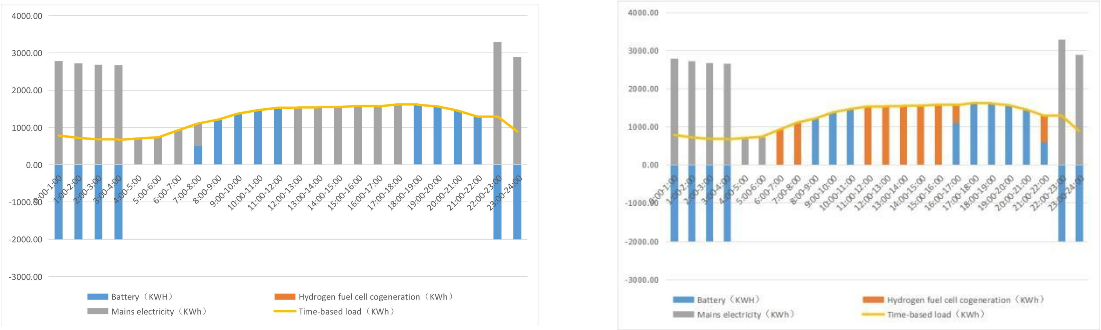
(b) Reduced by 70%

Fig.5-9 Hourly output and hourly load curve per unit for heating in the transitional season

(a) Reduced by 0%, 50%

(b) Reduced by 70%

Fig.5-10 Hourly output and hourly load curve per unit for cooling in the transitional season



(a) Reduced by 0%, 50%　　(b) Reduced by 70%

Fig.5-11 Hourly output and hourly load curve of each unit for power supply in the transitional season

5.4.2 Economic and social benefit analysis

It is estimated that when the hydrogen price is reduced by 50%, the total annual cost will be reduced by about 20.8% compared with that under the original hydrogen price; when the hydrogen price is reduced by 70%, the carbon dioxide emission reduction will be increased by 1.82 times compared with that under the original hydrogen price, and the annual end cost will be reduced by about 46.2%. Therefore, it is known that when the hydrogen price is the original price, it is mainly used to help achieve carbon emission reduction, and the annual carbon emission can be reduced by about 2,054,600 tons; when the hydrogen price is reduced by 50%, the hydrogen fuel cell cogeneration will have economic; when the hydrogen price is reduced by 70%, the hydrogen fuel cell cogeneration will have economic and social benefits at the same time.

Therefore, to promote the application of hydrogen fuel cell cogeneration in the building sector, the focus is on reducing the price of hydrogen, which can be achieved through multiple means such as government subsidies, reducing the cost of hydrogen production and revitalizing the carbon trading market.

Table 5-12 Total annual costs and carbon emissions at different prices

	Hydrogen consumption (tons)	Carbon reduction (kiloton)	Total cost (million USD)
Reduced by 0%	103.42	2054.64	119.58
Reduced by 50%	103.42	2054.64	94.76
Reduced by 70%	220.96	5794.99	64.37

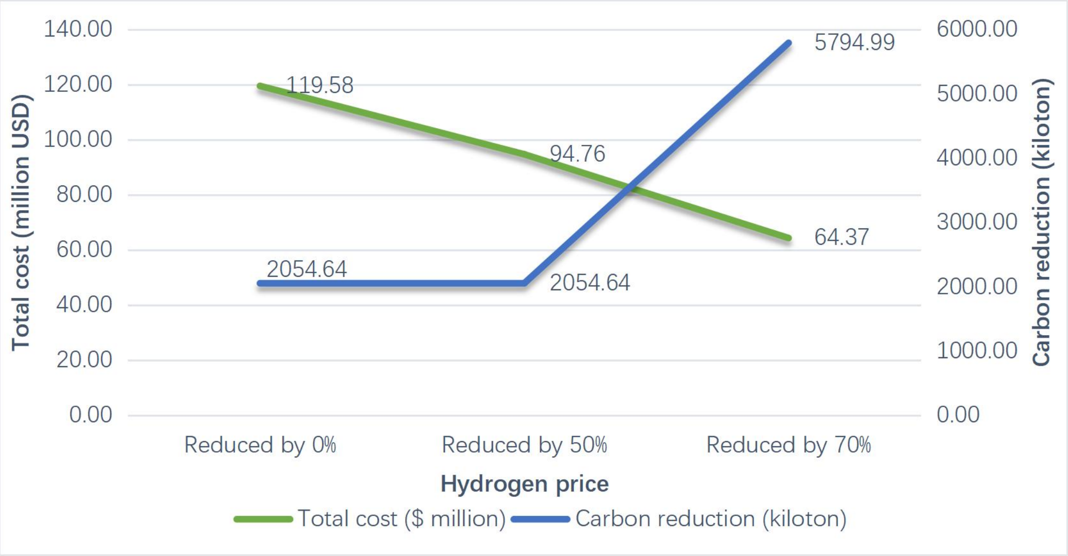


Fig.5-12 Hourly output and hourly load curve of each unit for power supply in the transitional season

5.5 Summary

Based on the load analysis of a terminal building in Shanghai for 8760 hours and typical days in each season, the annual investment cost of each equipment, the annual operating cost, fuel unit price, etc., this chapter compares and analyzes the equipment configuration, operation optimization strategy, and economic and social benefits of the hydrogen fuel cell cogeneration system when the hydrogen price drops by 0%, 50%, and 70%. The results show that when the hydrogen price drops by 50%, it has certain economic benefits; When the price of hydrogen drops by 70%, it has good economic and social benefits.

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Chapter 6

RESEARCH ON THE APPLICATION OF NEAR ZERO CARBON ENERGY SYSTEM IN INDUSTRIAL PARKS BASED ON HYDROGEN-FUELED GAS TURBINES

CHAPTER SIX : RESEARCH ON THE APPLICATION OF NEAR ZERO CARBON ENERGY SYSTEM IN INDUSTRIAL PARKS BASED ON HYDROGEN-FUELED GAS TURBINES

RESEARCH ON THE APPLICATION OF NEAR ZERO CARBON ENERGY SYSTEM IN INDUSTRIAL PARKS BASED ON HYDROGEN-FUELED GAS TURBINES

6.1 Content

In response to the challenge of global climate change, China has actively implemented the national strategy of "carbon peaking and carbon neutrality", and attaches great importance to the green and low-carbon transformation of economy and society. In 2021, the State Council of the CPC Central Committee issued the Opinions on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job in carbon neutrality[1], which clearly pointed out that by 2025, the energy consumption per unit of GDP will be 13.5% lower than that in 2020; The carbon dioxide emissions per unit of GDP have decreased by 18% compared to 2020; By 2030, the energy consumption per unit of GDP will significantly decrease; The carbon dioxide emissions per unit of GDP have decreased by over 65% compared to 2005. By 2060, the economic system of green and low carbon cycle development and the clean, low carbon, safe and efficient energy system will be fully established, and the goal of carbon neutrality will be successfully achieved.

As the largest city in China and an international metropolis, Shanghai has actively played a leading role. In July 2022, it successively issued a series of policy documents, such as the Implementation Opinions on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job in carbon neutrality[2], and the Implementation Plan of Shanghai's Carbon Peak[3], which clearly put forward that by 2025, energy consumption per unit of GDP will be 14% lower than that of 2020, The proportion of non fossil fuels in total energy consumption is expected to reach 20%, and the carbon dioxide emissions per unit of gross domestic product are guaranteed to meet the national targets; By 2030, the proportion of non fossil fuels in total energy consumption will reach 25%, and the carbon dioxide emissions per unit of gross domestic product will decrease by 70% compared to 2005, ensuring that carbon emissions reach their peak before 2030.

As the "dual carbon" target year approaches, high energy consumption areas such as transportation, construction, and industry are increasingly paying attention to low-carbon development. Among them, industrial parks serve as the main battlefield of a strong manufacturing country, an important source of greenhouse gas emissions, and a major source of energy consumption. The construction of "near zero carbon industrial parks" has become an important measure to achieve the scientific and orderly promotion of the "dual carbon" strategic goals, as well as an innovative development model to promote green, low-carbon, sustainable, and high-quality development of industrial parks. The core connotation of "near zero carbon emissions" is that the overall carbon emissions tend to be zero, with distinct relativity[4][5][6]. A "near zero carbon industrial park" refers to a modern industrial park where the total amount of carbon dioxide emissions directly or indirectly generated within an industrial park is partially offset within a certain period through digital energy carbon management, clean energy utilization, energy conservation and emission reduction, carbon recovery technology, energy storage and exchange, and is close to zero carbon emissions, thereby achieving "zero carbon emissions" of carbon elements throughout the year.

Industrial structure adjustment, energy efficiency improvement, energy structure optimization, and carbon capture are the four strategic paths to promote deep carbon reduction in industrial parks. Among them, optimizing the energy structure will bring significant carbon reduction effects to industrial parks. The most significant energy sources expected to contribute to carbon reduction are hydrogen energy, wind power, and photovoltaic. According to relevant research[7], the total contribution rate of these three energy sources to carbon reduction in China's industrial parks can reach 73% -81% by 2050, especially hydrogen energy, which can contribute 36% -37% of the emission reduction potential from 2015 to 2035 and 46% -50% from 2035 to 2050, It is the most promising measure for deep emission reduction. Therefore, exploring the application of hydrogen energy in near zero carbon industrial parks has practical significance.

Due to the need for a large amount of energy of different qualities such as electricity and heat in industrial parks, and the majority of carbon sources in industrial parks are concentrated in the field of energy activities, this chapter mainly studies the "near zero carbon" energy system. Among various energy supply methods, gas turbines have the advantages of high power density, fast startup speed, high reliability of startup and operation, which will ensure the energy consumption of industrial parks and ensure the safety of energy supply. In addition, with the increasingly mature application technology of hydrogen energy, hydrogen energy replaces natural gas, promoting the transformation of industrial parks from "low-carbon" to "near zero carbon". Therefore, this article will conduct research on the application of hydrogen turbines in near zero carbon industrial parks, and explore and analyze the impact of carbon trading prices on gas turbine and hydrogen turbine applications.

6.2 Application conditions analysis of hydrogen-fueled gas turbines

There is a significant difference between the characteristics of hydrogen combustion and natural gas. The combination of the two does not utilize gas turbines for stable power generation, and currently cannot be commercialized in large gas turbines. Therefore, this chapter takes small gas turbines as the research object to analyze the economic performance and carbon emissions impact of gas turbine operation under different hydrogen blending ratios.

6.2.1 Economic analysis of hydrogen production

(1) Cost analysis of hydrogen production

At present, hydrogen production models mainly include fossil energy hydrogen production, industrial by-product hydrogen production, electrolytic water hydrogen production, and other methods.

Fossil energy hydrogen production refers to the chemical reforming of coal and natural gas as raw materials to produce hydrogen. The technology is mature and widely used. Both coal based hydrogen production and natural gas based hydrogen production are susceptible to fluctuations in the prices of major raw materials. Among them, coal accounts for 36.9% of the cost of hydrogen production from coal gasification, and oxygen accounts for 25.9% of the cost. The cost of producing hydrogen from natural gas accounts for over 70% of the total cost. Under current technical conditions, the price of coal for hydrogen production ranges from 1.41 to 1.99 $/kg when the price of coal is between 65.22 to 137.68 $/ton; When the price of natural gas ranges from 0.24 to 0.40 $/cubic meter, the price of hydrogen production from natural gas ranges from 1.42 to 1.98 $/kg.

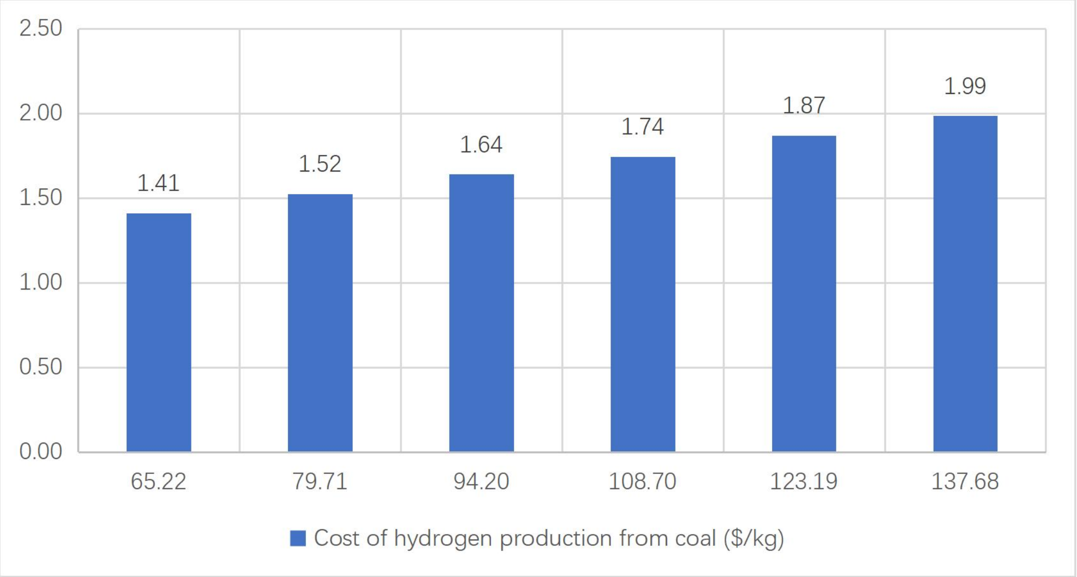

Fig.6-1 Cost of hydrogen production from coal ($/kg)[12]

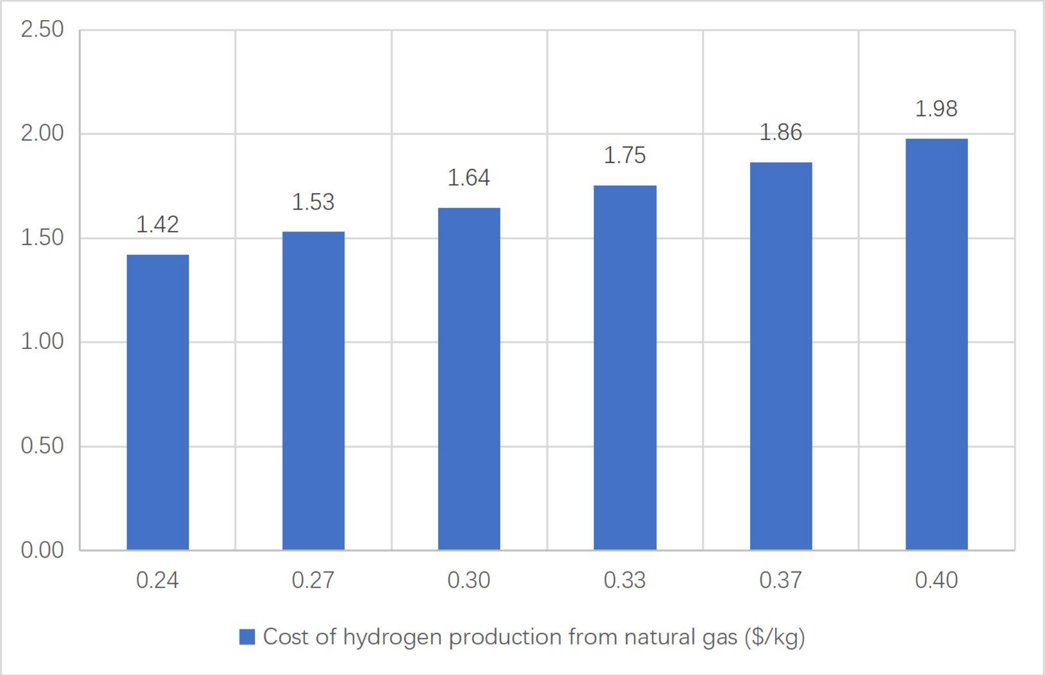

Fig.6-2 Cost of hydrogen production from natural gas ($/kg)[12]

Industrial by-product hydrogen production refers to the hydrogen production method of separating and purifying hydrogen from industrial tail gas rich in hydrogen through pressure swing adsorption and other technologies, including by-product hydrogen from coke oven gas, chlor alkali chemical industry, synthetic ammonia/methanol and other processes. The cost of industrial by-product hydrogen is approximately 1.35-3.25 $/kg. Industrial by-product gases contain a large amount of impurities in addition to hydrogen. Removing impurities and purifying hydrogen is a key process flow, so purification cost is a relatively important cost in addition to production cost. Given the large scale of China's existing industrial by-product hydrogen production capacity, the feasibility of this model becoming a green transition plan for hydrogen energy is relatively high.

Electrolysis of water to produce hydrogen refers to the use of electricity to provide energy, breaking down water molecules into hydrogen and oxygen on electrodes, including alkaline electrolysis of water to produce hydrogen (AWE), proton exchange membrane electrolysis of water to produce hydrogen (PEM), and solid oxide electrolysis of water to produce hydrogen (SOEC). Among them, alkaline electrolysis water technology is currently the most mature electrolysis water hydrogen production process and the most economical electrolysis water hydrogen production route at present. Due to its advantages such as more flexible operation, more flexible operation (load range 0-150%[13]), and more suitable for renewable energy fluctuations, proton exchange membrane electrolyzers (PEMs) are increasingly receiving attention.

At present, the price of domestically produced alkaline electrolytic cells is 289.86-434.78 $/kW, and the price of PEM electrolytic cells is 1014.49-1739.13 $/kW. Assuming the industrial electricity price is 0.06 yuan/kWh, the cost of hydrogen production from alkaline electrolysis water is about 4.33 $/kg under existing conditions, and the cost of hydrogen production from PEM electrolysis water is about 5.78 $/kg. The electricity consumption cost of alkaline electrolysis and PEM electrolysis water accounts for 74.91% and 50.56% of the total cost, respectively, making them the largest part of the cost expenditure end. Due to the higher cost of PEM electrolysis water equipment compared to alkaline electrolysis cells, the depreciation cost of PEM electrolysis water is higher than that of alkaline electrolysis water at this stage. The economic efficiency of hydrogen production from alkaline electrolyzed water and PEM electrolyzed water under existing conditions is far from that of fossil energy hydrogen production and industrial by-product hydrogen.

When the electricity price of renewable energy is reduced to 0.02 $/kWh, and the prices of alkaline electrolysis and PEM system electrolysis equipment are reduced to 144.93 $/kW and 398.55 $/kW, respectively, the costs of alkaline electrolysis water hydrogen production and PEM electrolysis water hydrogen production are 1.69 $/kg and 2.08 $/kg, which are equivalent to the costs of fossil energy hydrogen production; When the electricity price of renewable energy is reduced to 0.02 $ /kWh, and the prices of alkaline electrolysis and PEM system electrolysis equipment are reduced to 115.94 $/kW and 202.90 $/kW, respectively, the cost of alkaline electrolysis water hydrogen production and PEM electrolysis water hydrogen production is 1.33 $/kg and 1.45 $/kg, which is equivalent to the current cost of fossil energy hydrogen production.

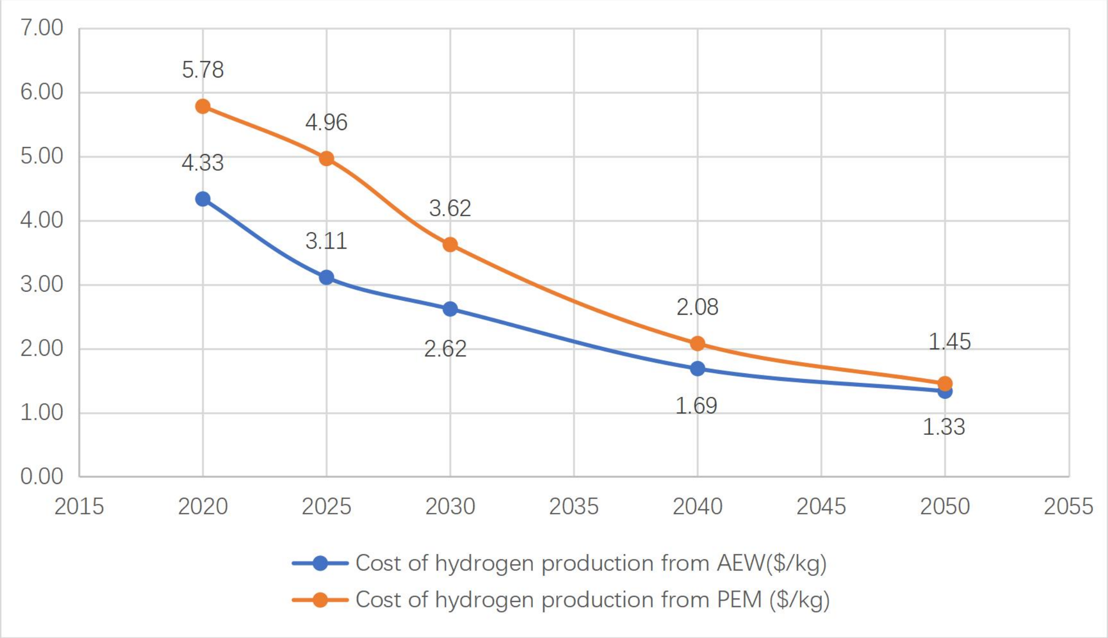

Fig.6-3 Cost of Hydrogen Production from Electrolytic Water[14][15]

Table 6-1 Hydrogen Production Costs for Different Hydrogen Production Modes

Hydrogen production mode		Hydrogen price ($/kg)
Hydrogen production from fossil fuels	Hydrogen production from coal	1.41-1.99
	Hydrogen production from natural gas	1.42-1.98
Industrial by-product hydrogen	Purification of coke oven gas for hydrogen production	1.35-3.25
Hydrogen production by electrolysis of water	Hydrogen production by alkaline electrolysis of water	4.33
	Hydrogen production by PEM electrolysis of water	5.78

(2) Comparative Analysis of Unit Calorific Value Cost between Hydrogen and Natural Gas

Although the calorific value per unit mass of hydrogen is about 2.85 times that of natural gas, due to the low density of hydrogen, the calorific value of the mixed gas is lower than that of natural gas. The higher the mixing ratio, the lower the calorific value. Under existing conditions, the cost of burning hydrogen is higher than that of burning natural gas in the same calorific value demand.Therefore, for gas power generation enterprises, although hydrogen doped power generation has significant emission reduction benefits, there is also a huge economic burden.

Table 6-2 Comparison of Hydrogen Substitution Prices for Natural Gas Blended with Hydrogen

Gas energy varieties	Calorific value Mj/kg	Density kg/Nm^3	Energy density Mj/Nm^3	Unit price $/Nm^3	Unit price of calorific value $/Mj
Hydrogen	143	0.0899	12.586	0.432	0.0336
Natural gas	50.1	1.293	91.803	0.42	0.0117

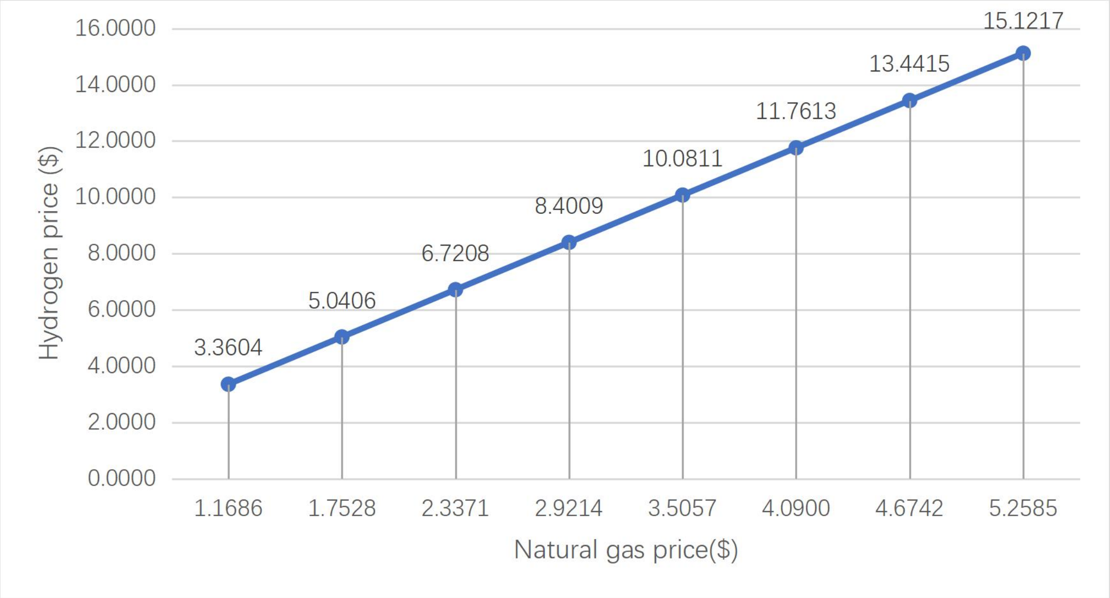

Fig.6-4 Natural gas and hydrogen prices at constant calorific value

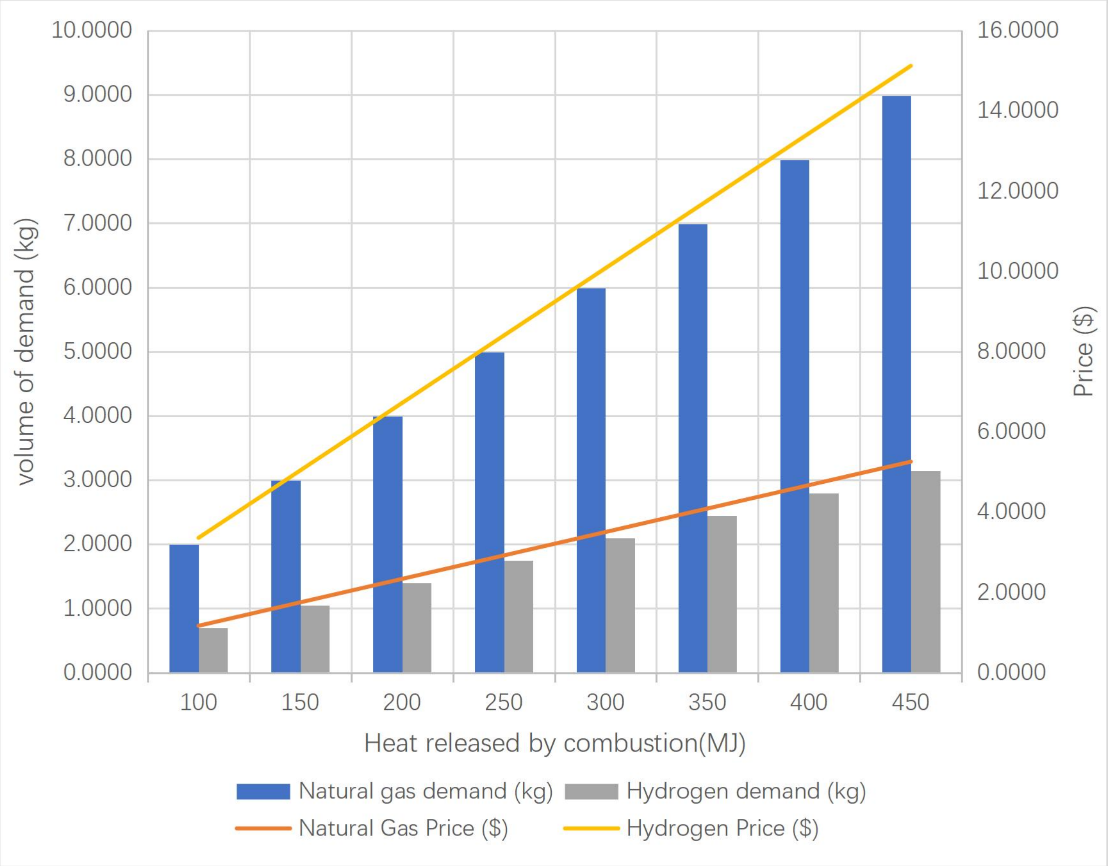

Fig.6-5 Change in demand and price of hydrogen and natural gas under equal calorific value

6.2.2 Analysis of gas turbine applications with different hydrogen doping ratios

This chapter will use the current natural gas cost price of 0.42 $\$/m^3$ as the benchmark to study and analyze the impact of hydrogen prices and carbon emissions trading prices on the operating costs of hydrogen doped gas turbine applications. To ensure the demand for 8500 kW thermal load and 6000 kW electrical load in an industrial park in Shanghai, two 4404 kW gas turbines are configured, and their equipment parameters are shown in Table 6-3.

Table 6-3 4404 kW Gas Turbine Parameters

Parameter	Value
power output	4404 kW
thermal output	4263 kW
power generation efficiency	up to 46.5%
thermal efficiency	up to 47.4%
fuel type	natural gas, hydrogen, etc

To meet the energy needs of users, gas turbines need to ensure the same power output when adding hydrogen. Therefore, the volume ratio of hydrogen and natural gas in the mixed fuel should be adjusted with the goal of supplying the same heating value. When the gas turbine operates at full rated power, it will consume 1894.19 m^3 of natural gas. From Fig.6-6 and Fig.6-7, it can be seen that when hydrogen is mixed, the higher the proportion of hydrogen, the higher the total consumption volume of mixed fuel compared to pure natural gas, and the higher the operating cost compared to pure natural gas. Moreover, due to the fact that natural gas belongs to clean and low-carbon energy, at the current carbon trading cost of 8.2 $/t and hydrogen price of 0.432 $\$/m^3$, the impact on the operating cost of hydrogen doped gas turbines is relatively small. Therefore, under existing conditions, even if the hydrogen ratio is higher and the carbon reduction is higher, hydrogen doped gas turbines still do not have economic viability.

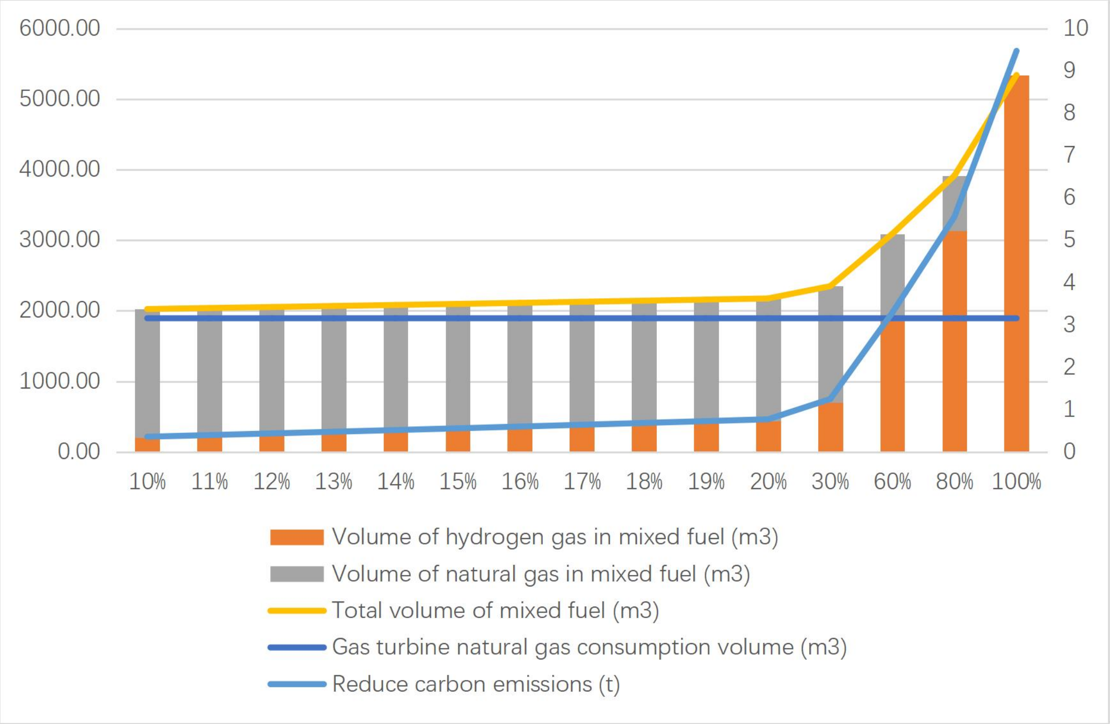

Fig.6-6 Volume and carbon reduction of mixed fuels with different hydrogen doping ratios under equal power output

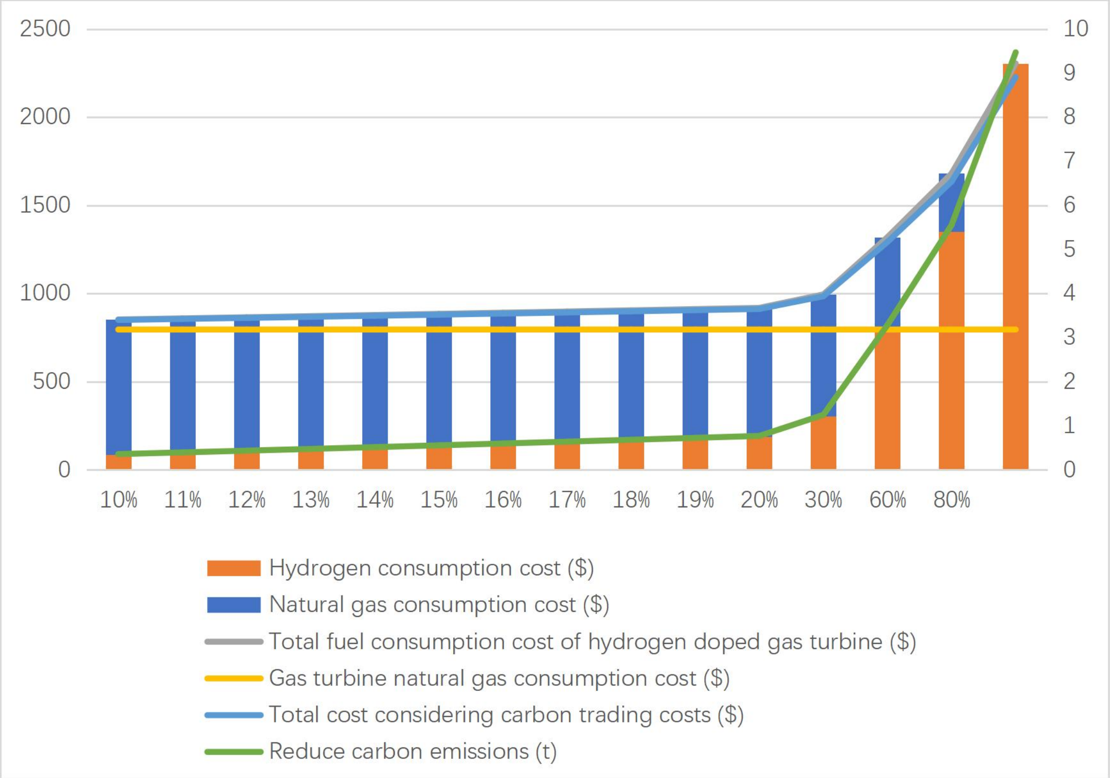

Fig.6-7 Consumption cost of mixed fuels with different hydrogen doping ratios under equal power output

For a 100% hydrogen doped gas turbine, i.e. a hydrogen fired turbine, as shown in Fig.6-8:

- When the carbon trading cost is 8.2 $/t and the hydrogen price is not higher than 37.87% of the original hydrogen price, the fuel consumption cost of hydrogen turbines will be lower than that of gas turbines.
- When the carbon trading cost is 13.4 $/t and the hydrogen price is not higher than 40% of the original hydrogen price, the fuel consumption cost of hydrogen turbines will be lower than that of gas turbines.
- When the carbon trading cost is 37.7 $/t and the hydrogen price is not higher than 50% of the original hydrogen price, the fuel consumption cost of the hydrogen turbine will be lower than that of the gas turbine.
- When the carbon trading cost is 62.1 $/t and the hydrogen price is not higher than 60% of the original hydrogen price, the fuel consumption cost of hydrogen turbines will be lower than that of gas turbines.
- When the carbon trading cost is 86.5 $/t and the hydrogen price is not higher than 70% of the original hydrogen price, the fuel consumption cost of hydrogen turbines will be lower than that of gas turbines.
- When the carbon trading cost is 159.6 $/t, at the current hydrogen price, the fuel consumption cost of hydrogen turbines is lower than that of gas turbines, which has considerable economic benefits.

Fig.6-8 Changes in fuel consumption costs with different hydrogen blending ratios under different carbon emission trading unit prices

6.3 Case study on the application of hydrogen turbines in near zero carbon industrial parks

Based on the research and analysis in Chapter 6.2, under existing technological and economic conditions, hydrogen gas turbine projects do not have economic viability. However, in order to meet the high demand for energy supply security in the construction of "near zero carbon industrial parks" in industrial parks, the combination of hydrogen turbines and photovoltaic power generation systems will not only ensure energy supply security but also achieve near zero carbon emissions. Therefore, this chapter will study and analyze the feasibility of the application of the combination of hydrogen turbines and photovoltaic power generation systems in near zero carbon industrial parks.

6.3.1 Research object and load analysis

The research object of this chapter is an industrial park in Shanghai, which includes factory buildings and employee apartments. The factory building area is approximately 8000m^2, and the employee apartment building area is approximately 8500m^2. Due to its complex production process, the industrial park requires a large amount of energy of different qualities such as electricity and heat, with a power load of approximately 6400 kW and a thermal load of approximately 8000 kW. At present, a 2MW gas turbine (as shown in Table 6-5) system has been built in the industrial park to supply energy. In order to save costs in building a near zero carbon industrial park, it is planned to transform the gas turbine into a 2MW hydrogen turbine and fully utilize local solar energy resources. Solar photovoltaic panels will be laid on the available building area. The daily and annual average curves of power load, thermal load, and photovoltaic power generation in the industrial park are shown in Fig.6-9.

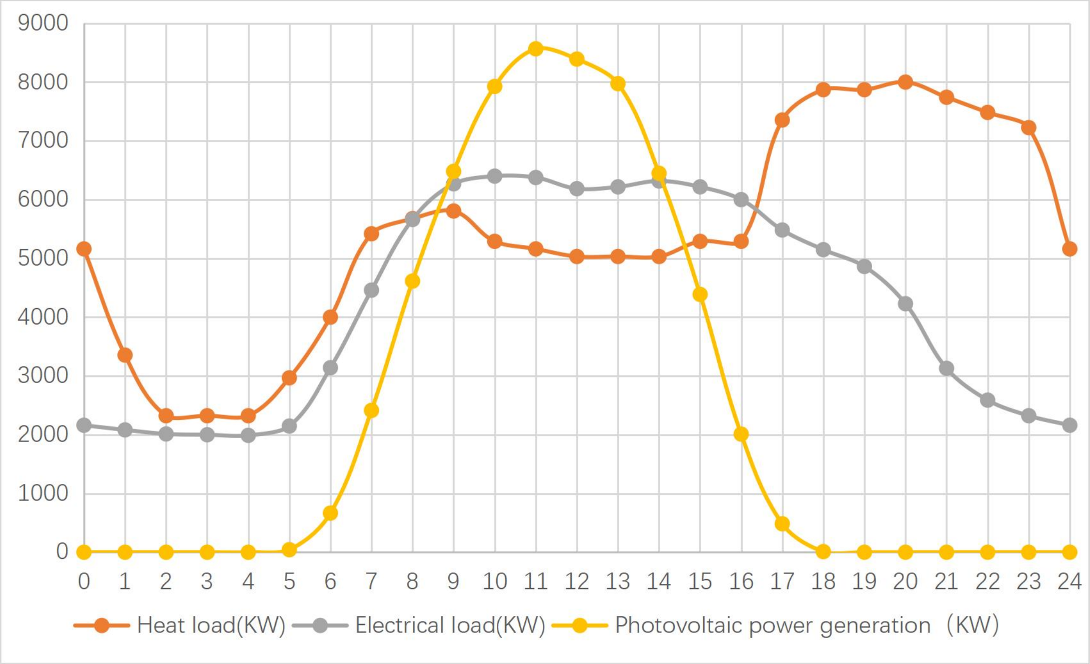

Fig.6-9 Daily load and daily photovoltaic power generation curve of industrial park (annual average)

6.3.2 Equipment composition and related parameters

The original gas turbine system was mainly composed of gas turbine units, heat pumps, and energy storage equipment, as shown in Fig.6-10 . The equipment parameters are shown in Table 6-4 to Table 6-7.

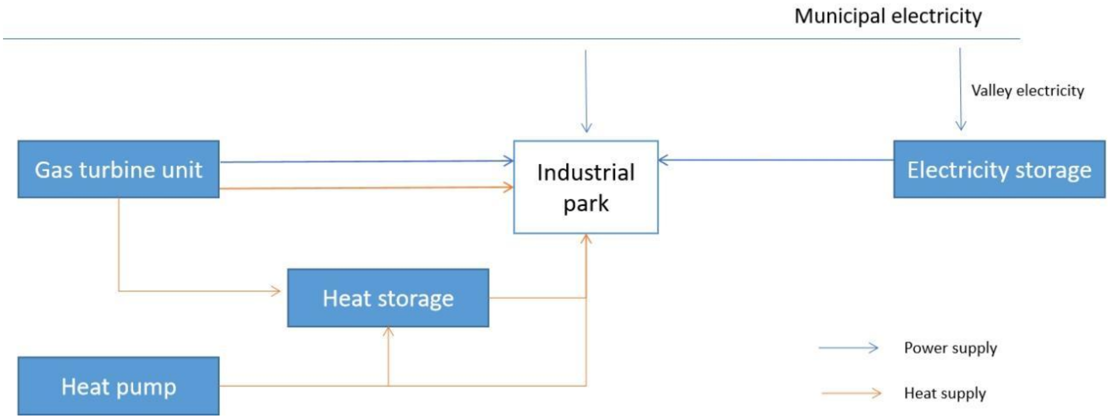

Fig. 6-10 Gas turbine system composition and energy supply process

Table 6-4 Gas turbine unit parameters

Parameter	Value
Rated electrical power	2090 kW
Rated power generation efficiency	20.50%
Exhaust temperature	610 ℃
Exhaust flow rate	12.0 kg/s
Natural gas consumption	1078 Nm³/h
Refrigeration/heating power	9011/5764 kW
Cooling/heating area	100100-225300 ㎡
Equipment depreciation	25 years
Unit cost	615 $/(kW·year)

Table 6-5 Heat pump equipment parameters

Parameter	Value
Heating capacity	1305.9 kW
Heating input power	269.1 kW
Hot water flow rate of condenser	226.9 m^3/h
Heat source water flow rate	113 m^3/h
Equipment depreciation	25 years
Unit cost	5.3 \$/(kW·year)

Table 6-6 Water storage equipment parameters

Parameter	Value
Type	Water storage
Storage loss	2% per 24hours
Equipment depreciation	25 years
Unit cost	0.82 \$/(kW·year)

Table 6-7 Storage equipment parameters

Parameter	Value
Type	Sodium-sulfur
Storage loss	0.95
Equipment depreciation	10 years
Unit cost	26.6 \$/(kW·year)

The equipment composition of the modified hydrogen turbine system includes hydrogen turbine units, photovoltaic power generation systems, heat pumps, energy storage equipment, etc. The system composition is shown in Fig.6-11.

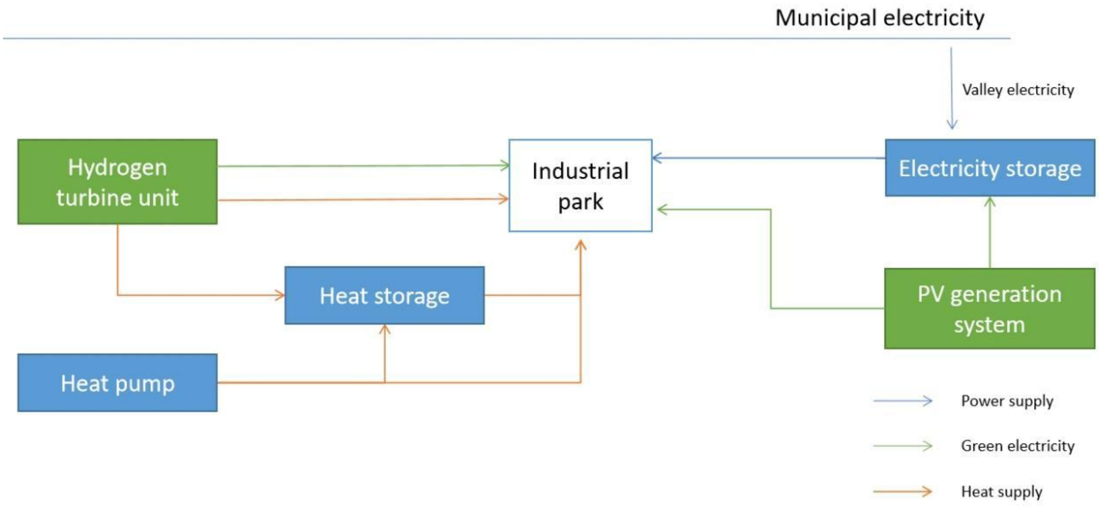

Fig.6-11 Composition and energy supply process of hydrogen turbine and photovoltaic power generation system

Table 6-8 Parameters of hydrogen turbine unit

Parameter	Value
Rated electrical power	2090 kW
Rated power generation efficiency	20.50%
Hydrogen consumption	3041.38 Nm^3/h
Refrigeration/heating power	9011/5764 kW
Equipment depreciation	25 years
Unit cost	700 $/(kW·year)

Table 6-9 Photovoltaic power generation system parameters

Parameter	Value
Total installed capacity	18829 kW
Unit cost	0.388 $/W
Equipment depreciation period	25 years

The economic parameters involved in this chapter are as follows:

Table 6-10 Economic parameters

Natural gas price ($\$/m^3$)		0.42
Hydrogen Price ($\$/m^3$)		0.43
Electricity price（$/kWh）	Valley time	0.04
	Normal time	0.082
	Peak time	0.14
Heat Price ($/kWh)		0.02
Carbon trading price ($/ton)		8.2

6.4 Results and discussion

6.4.1 Operation strategy analysis

In the renovation plan and the original plan, since the electrical and thermal power output of the gas turbine and hydrogen turbine have not changed, the system's thermal energy supply plan has not been changed. It determines the system's operation strategy based on the basic principle of "gas turbine operation as the main part, and heat storage and heat pump as the auxiliary part". Therefore, the thermal energy supply operation curve is shown in Fig.6-12. In terms of power supply, due to the addition of photovoltaic power generation, the power supply operation strategies of the two schemes have changed.

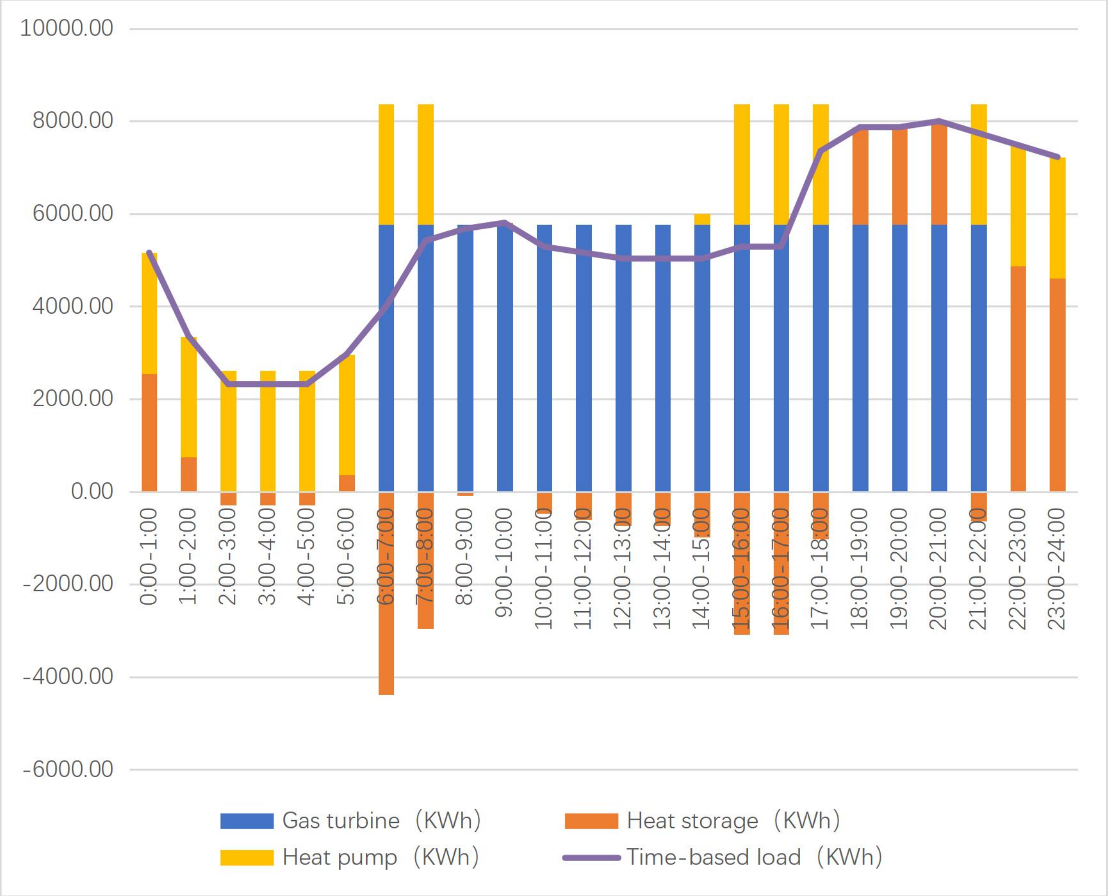

Fig.6-12 Hourly output and hourly load curve of each heating unit

In the original plan, the gas turbine system supplied electricity to the industrial park based on the basic principle of "gas turbine operation as the main source, supplemented by electricity storage and valley electricity". The operating curve is shown in Fig.6-13.

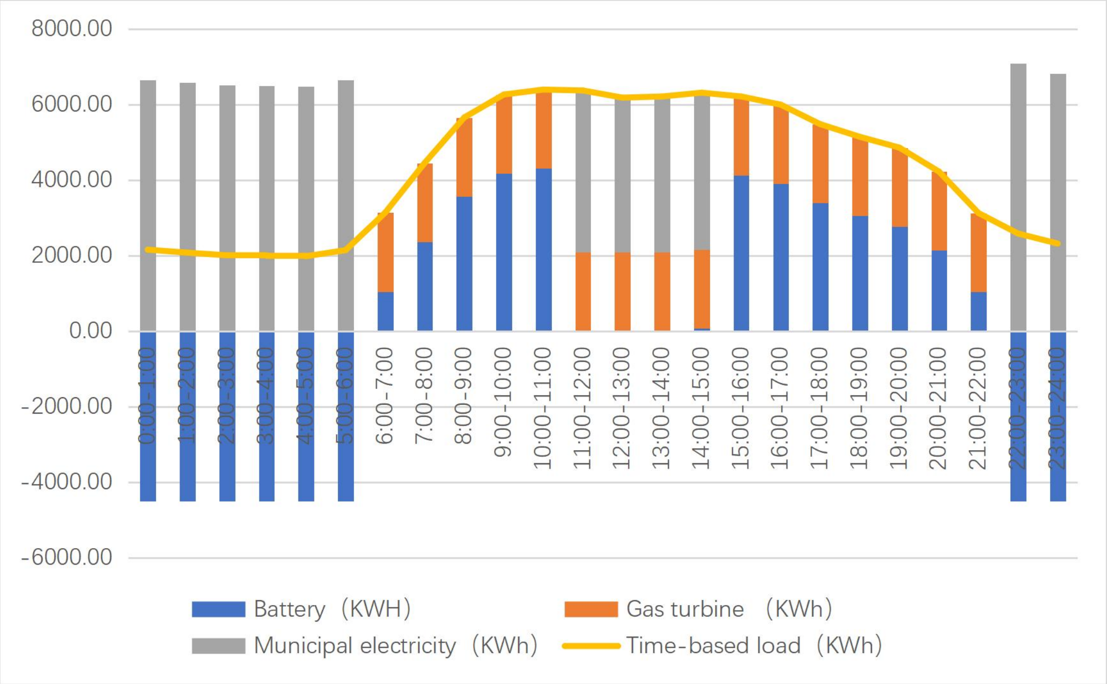

Fig.6-13 Hourly output and hourly load curve of each unit powered by gas turbine

In the renovation plan, the hydrogen turbine system supplies electricity to the industrial park based on the basic principle of "gas turbine operation, photovoltaic power generation operation as the main, and power storage as the auxiliary". The operating curve is shown in Fig.6-14.

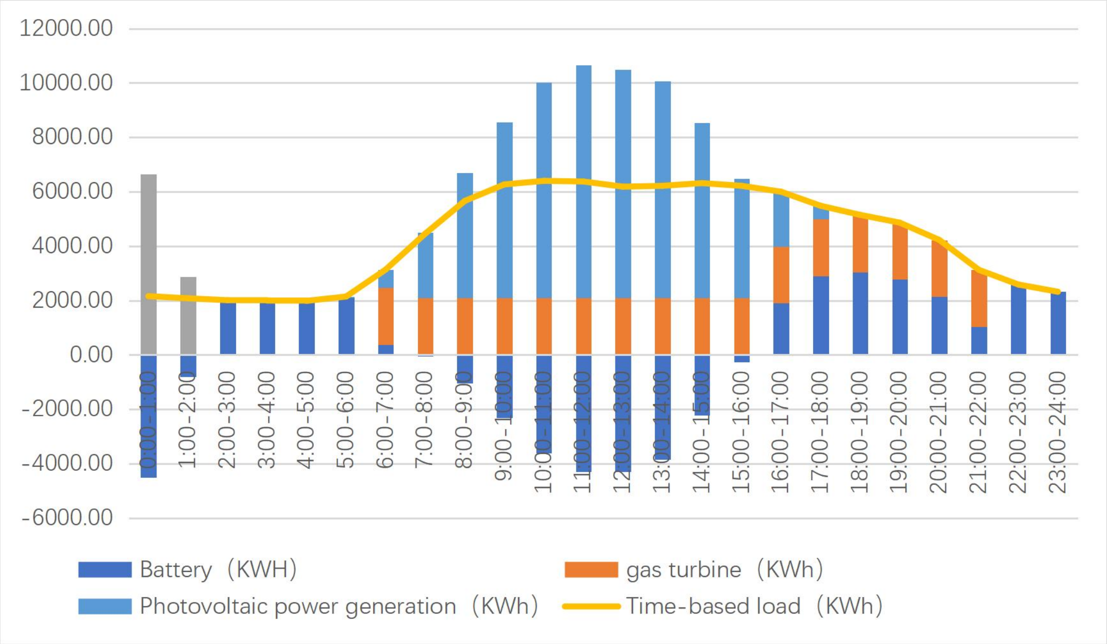

Fig.6-14 Hourly output and hourly load curve of each unit supplied by hydrogen turbine and photovoltaic power generation system

6.4.2 Economic and social benefit analysis

With the goal of building a "near zero carbon industrial park", when there are still carbon emissions, carbon trading can be used to purchase carbon quotas to achieve near zero carbon emissions. In the original plan, due to natural gas and electricity consumption, its annual carbon emissions were approximately 7320.66 tons; In the renovation plan, due to the limitation of available building area, photovoltaic power generation cannot fully cover the electricity demand, so it needs to be supplemented with municipal electricity, with an annual carbon emissions of about 2.6 tons.

Due to the need to consider purchasing carbon quotas to achieve "near zero carbon", the total project cost consists of annual investment cost, annual operating cost, annual maintenance cost, and cost of purchasing carbon quotas, as shown in Table 6-11, due to the addition of photovoltaic systems, the annual investment cost of the renovation plan is higher than that of the original plan. Meanwhile, due to the fact that the volumetric calorific value of natural gas is about three times that of hydrogen, the volumetric demand for hydrogen with the same output power will be about three times that of natural gas. Therefore, the annual operating cost of the renovation plan is much higher than that of the original plan.

Table 6-11 Composition of various costs

Cost	Annual Investment Cost ($)	Annual operating cost ($)	Annual maintenance cost ($)	Cost of purchasing carbon quotas ($)	Total Cost ($)
Original plan	191106.54	2644118.40	3822.13	60029.45	2899076.52
Renovation plan	491580.25	7637511.72	9831.61	21.28	8138944.86

(1) Analysis of the Impact of Hydrogen Price on the Economy of Hydrogen Gas Turbines

To study and analyze the application feasibility of hydrogen turbines, this chapter calculates the static investment payback period, NPV, and IRR of two schemes. As shown in Table 6-12:

In the original plan, when the gas price is 0.42 $/m^3, the static investment payback period is 12 years, and the IRR is<12%. When the gas price is 0.405 $/m^3, the static investment payback period is about 8.7 years, with IRR=12%, indicating the feasibility of the project.

In the renovation plan, when the current hydrogen price is 0.43 $/m^3, the project is not feasible; When the price of hydrogen is 0.215 $/m3, although the project begins to make profits, its static investment payback period is equivalent to an infinite period and IRR<0, making the project unfeasible; When the price of hydrogen is 0.1471 $/m^3, the static investment payback period is about 8.67 years, with IRR=12%, indicating the feasibility of the project. Therefore, when the hydrogen price is not higher than 0.1471 $/m^3, this renovation plan is economically feasible.

In terms of current hydrogen production technology, the price of hydrogen produced from fossil fuels such as natural gas and coal is basically in line with the requirements. However, due to the goal of "near zero carbon", it is necessary to consider using renewable hydrogen sources as much as possible. According to existing data[15], it is expected that hydrogen prices can drop to around 0.147 \$/m^3 by 2040.

Table 6-12 Economic analysis under different energy unit prices

Programme	Energy unit price（\$/m^3）	Profit（\$）	Static investment payback period (years)	NPV	IRR
Original plan	0.4050	248494.64	8.70	1901846.18	12.0%
	0.4200	342927.44	12.00	763008.33	8.5%
Renovation plan	0.1471	1208369.38	8.67	6727810.59	12.0%
	0.1660	872674.10	12.00	2679402.70	8.5%
	0.2000	267925.10	39.09	-4613731.07	1.0%
	0.2100	90308.55	115.97	-6755745.83	-1.9%
	0.2150	1500.28	6980.79	-7826753.21	-3.6%
	0.4300	-3817255.59	-2.74	-53880070.44	/

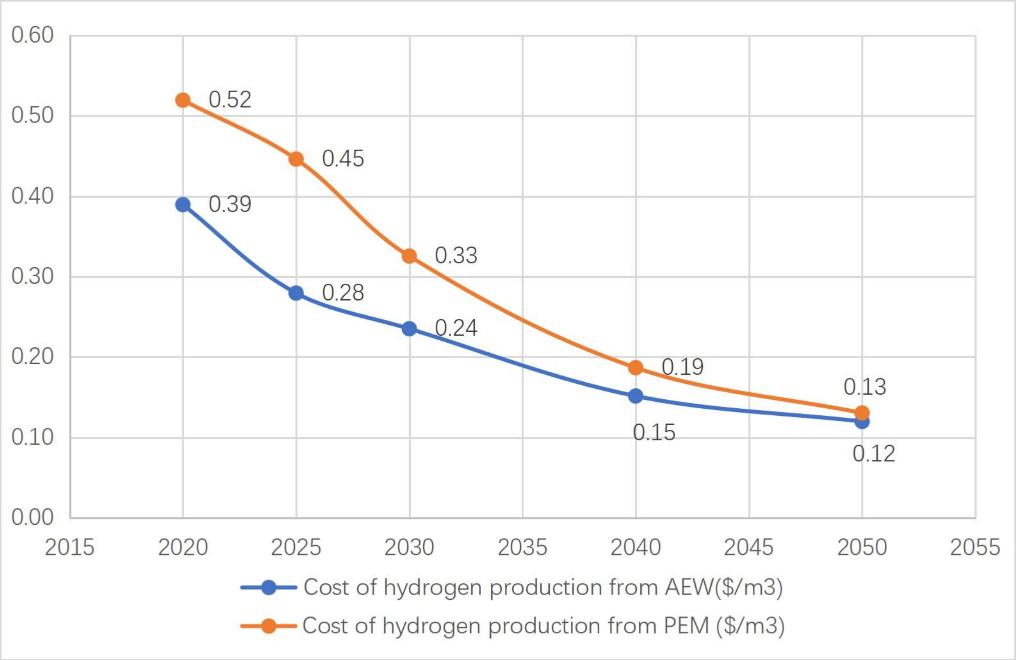

Fig.6-15 Cost of Hydrogen Production from Electrolytic Water

(2) Analysis of the Impact of Carbon Trading Price on the Economy of Gas Turbines

By studying the impact of hydrogen prices on the economic performance of hydrogen turbines, it can be concluded that promoting the use of hydrogen turbines still takes time, and at present, adopting gas turbines is still a highly feasible solution. But as the "dual carbon" target year approaches, the carbon market will become more active, and carbon trading prices will show an annual growth trend. Therefore, carbon trading prices will affect the economy of gas turbines. Through calculation (as shown in Table 6-13), when the carbon trading price is not less than 42.15 $/t, gas turbine projects will experience losses.

Table 6-13 Economic Analysis of Gas Turbines under Different Carbon Trading Prices

Carbon trading price ($/t)	Cost of purchasing carbon quotas ($)	Profit（$）	Static investment payback period (years)
42.15	308566.0264	-41.93348987	-71116.51
20	146413.2984	162110.7945	18.40
8.2	60029.45235	248494.6406	12.0

6.5 Summary

This chapter analyzes the cost of hydrogen production under different hydrogen production modes and studies the economic application of hydrogen doped gas turbines under existing conditions. Due to the higher volume and cost of hydrogen consumption compared to natural gas consumption under the same heating value demand, the application of hydrogen doped gas turbines still needs time at this stage. However, under the "dual carbon" strategic goal, the construction of near zero carbon industrial parks and the high requirements for energy supply security in industrial parks pose a demand for the coupling application of hydrogen turbines and renewable energy systems. By taking a certain industrial park as an example and comparing it with the original plan of the gas turbine and municipal electricity coupling system, it can be concluded that when the hydrogen price is not higher than 0.1471 $\$/m^3$, the transformation plan of the coupling between the gas turbine and the renewable energy system is feasible for the project. However, due to the constraints of hydrogen production costs, it is predicted that the renovation plan can be promoted and widely applied by around 2040. Meanwhile, with the continuous growth of carbon trading prices, the original plan will not be economically viable when the carbon trading price is not less than 42.15 $/t.

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Chapter 7

ANALYSIS OF HYDROGEN APPLICATION DEMAND POTENTIAL IN SHANGHAI

CHAPTER SEVEN: ANALYSIS OF HYDROGEN APPLICATION DEMAND POTENTIAL IN SHANGHAI

ANALYSIS OF HYDROGEN APPLICATION DEMAND POTENTIAL IN SHANGHAI

7.1 Content

With the diversified and large-scale development of hydrogen application scenarios in Shanghai, the demand for hydrogen application will increase accordingly. To effectively ensure hydrogen energy supply, it is necessary to analyze the potential demand for hydrogen application in Shanghai.

In the hydrogen application mode, hydrogen fuel cell vehicles are the main form of hydrogen energy application and an important means of achieving low-carbon transportation. Under China's strategic goal of "2030 carbon peak 2060 carbon neutral", hydrogen fuel cell vehicles will surely usher in rapid development opportunities. Shanghai, as one of the cities with the most developed transportation and the most complete means of transportation in China, and a major city in the automotive industry, attaches great importance to the construction of green transportation and actively promotes the large-scale development of hydrogen fuel cell vehicles.

Based on the fact that hydrogen fuel cell vehicles are the most mature hydrogen energy application model in Shanghai, this chapter will first calculate the number and hydrogen demand of hydrogen fuel cell vehicles in Shanghai, and then predict the total hydrogen demand in the transportation sector of Shanghai. Finally, based on the proportion relationship of hydrogen demand in various fields such as industry, construction, and transportation in 2030 and 2060, the total hydrogen demand of Shanghai in 2030 and 2060 will be estimated.

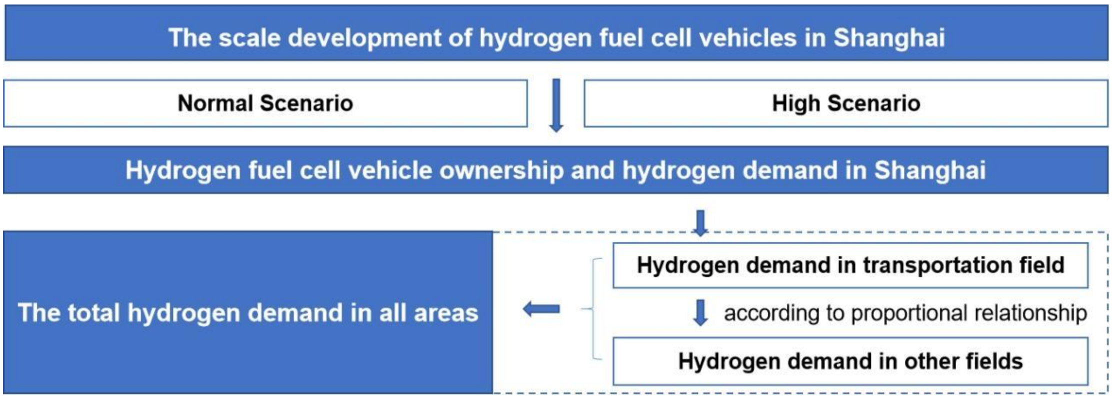

Fig.7-1 Logic Diagram of Hydrogen Energy Demand Potential Analysis in Shanghai

7.2 Research on the Scale Development of Hydrogen Fuel Cell Vehicles in Shanghai

As one of the cities with the most developed transportation and the most complete means of transportation in China and an important automobile industry town, Shanghai attaches great importance to the construction of green transportation and actively promotes the large-scale development of hydrogen fuel cell vehicles. Under this background, this chapter proposes to use SWOT analysis method to conduct in-depth analysis on the internal advantages and disadvantages, external opportunities and challenges of realizing the large-scale development of hydrogen fuel cell vehicles in Shanghai, so as to propose the development goals of hydrogen fuel cell vehicles in Shanghai in 2030 and 2060, and put forward relevant development suggestions for promoting the sustainable large-scale development of hydrogen fuel cell vehicles in Shanghai.

7.2.1 Analysis of the development scale of hydrogen fuel cell vehicles in shanghai based on SWOT analysis

This chapter takes the large-scale application of hydrogen fuel cell vehicles in Shanghai as the research object, and analyzes its application and development status from four perspectives of internal advantages and disadvantages, external opportunities and challenges by using SWOT analysis method, so as to provide a basis for the proposal of development.

(1) Internal advantages

1) Industrial advantages

According to the composition of fuel cell vehicle system, the industrial chain of fuel cell vehicle is divided into stack and its parts, auxiliary parts and system integration, vehicle manufacturing and application from upstream to downstream :

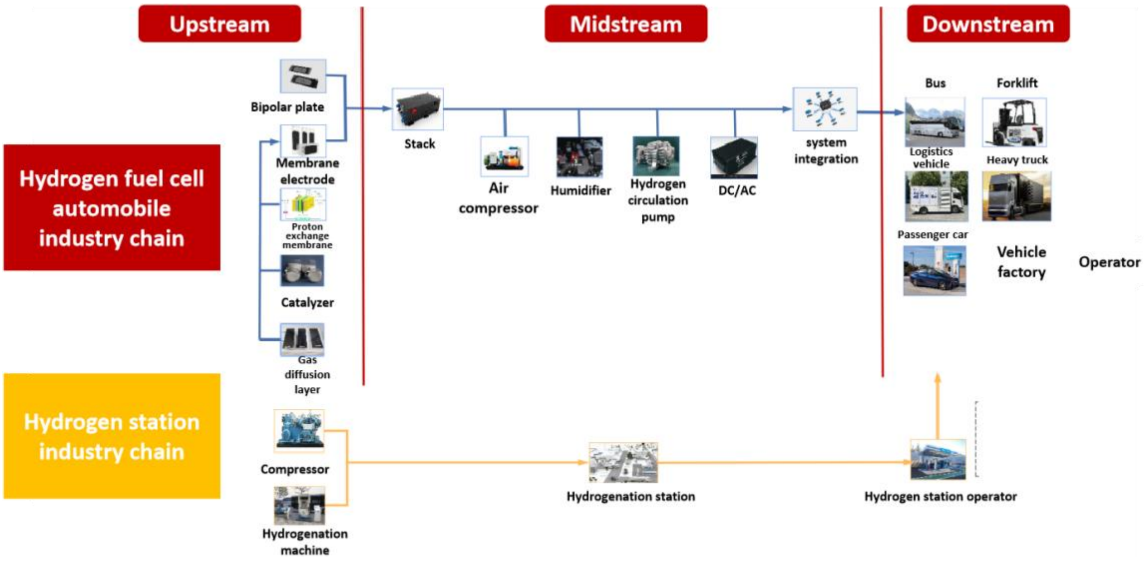

Fig.7-2 Hydrogen fuel cell automobile industry chain

- Upstream: stack and its parts / materials are the core of the whole fuel cell vehicle industry, and the technical threshold is high. At present, foreign suppliers are the main suppliers in this field.
- Midstream: integrate the stack and accessories into a fuel cell system. The key component of auxiliary parts is air compressor. Different integration schemes and control algorithms of the system have a great impact on the performance and reliability of the system.
- Downstream: Vehicle Integration and application. The core of vehicle integration is dynamic system matching, thermal management design and energy management strategy.

Shanghai is a pioneer in the development of hydrogen fuel vehicle industry. It has realized the full coverage of passenger cars, buses, trucks and other models, and basically formed the development ecology of the whole industry chain of fuel cell vehicles. Moreover, a large number of domestic production enterprises have gathered in the core parts such as stack, membrane electrode, bipolar plate, proton exchange membrane and catalyst.

Table 7-1 Development status of hydrogen fuel cell vehicle industry chain in Shanghai

Key parts	Development status	Existing enterprises in Shanghai
Stack	The product performance has reached the international average level, but the specific power and durability need to be improved. It has realized vehicle application, independent R & D and technology introduction	Jiehydrogen technology, Guohong hydrogen energy, Weishi energy, Shanghai Shenli, SAIC Group, Xinyuan power, Tongji technology, Shanghai Fanye, qingneng Co., Ltd., hydrogen morning new energy, Xiaolan new energy, and Jifu hydrogen energy
membrane electrode	It can achieve mass production and is at the international leading level	Xinyuan power, Shanghai Tangfeng, Xiaolan hydrogen energy, yi hydrogen Technology
Proton exchange membrane	The performance needs to be improved, and stable products cannot be formed yet. The core materials depend on imports	Shanghai Shenli, zhongxinneng, kunai new material, Hancheng new material
catalyzer	Small batch production, key materials still rely on imports, mass production technology needs to be breakthrough	Shanghai Hesen, Zhongke Kechuang
Gas diffusion layer	Small scale production, performance to be verified	Shanghai Hesen and Huayi Group
Bipolar plate	Domestic graphite bipolar plates were realized, and domestic metal bipolar plates were started	Graphite: Shanghai Hongfeng, Guohong hydrogen energy Metal and composite materials:

	and applied in small batches	new source power, Shanghai Zhizhen
Fuel cell system	Mass production can be realized and the performance can meet the loading requirements	Reshaping technology, jiehydrogen technology, Luzhi Xinneng, Gufu technology, qingneng new power
Air compressor	With small-scale production capacity, reliability and service life need to be further verified	Hesen electric
Humidifier	Small batch production, more dependent on imports	Zhengfei technology and Xiaolan Xinneng

2) Application advantages

Shanghai has actively carried out demonstration and promotion of vehicles of various models and scenarios, forming a pattern of commercial vehicles dominated and passenger vehicles developed in parallel. In 2021, the number of hydrogen fuel cell vehicles promoted in Shanghai will be about 1500 (accounting for about 20% of the national total)[1], including about 1000 logistics vehicles, about 300 passenger cars, and about 100 passenger cars, involving various scenarios such as passenger car leasing, bus line operation, commuting / customized buses, logistics distribution, postal delivery, and in plant transportation. At the same time, Shanghai has built 10 hydrogen stations and nearly 30 kilometers of hydrogen transmission pipelines[2], laying a solid foundation for the further application and promotion of hydrogen fuel cell vehicles.

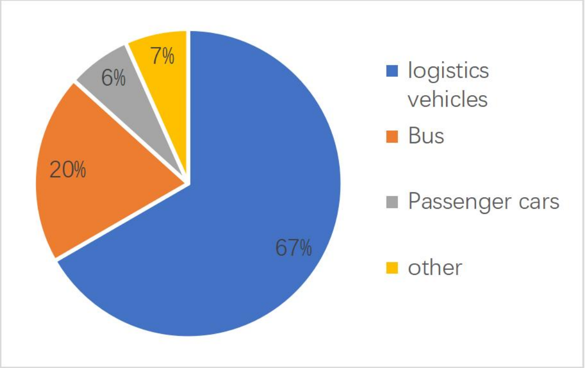

Fig.7-3 Composition of various types of hydrogen fuel cell vehicles in Shanghai in 2021

(2) Internal disadvantage

There are still gaps and weak links in the whole industrial chain of hydrogen fuel cell vehicles. In the actual mass production, the key materials and core technologies are not yet independent. The key materials of fuel cells, including catalysts, proton exchange membranes and carbon paper, are mostly imported materials; The preparation process of key components is in urgent need of improvement, and the performance of bipolar plate, air compressor, hydrogen circulation pump, hydrogen storage bottle, etc. is far from the international level. Technical factors lead to the high cost of manufacturing hydrogen fuel cells, which affects the commercialization and promotion of hydrogen fuel cell vehicles. In addition, an authoritative testing and certification institution has not yet been formed, and there is a lack of a strong innovative R & D platform and a hydrogen fuel cell vehicle measurement and testing platform.

(3) External opportunities

1) Policy support

Since 2010, Shanghai has issued a series of policy documents to support the development of hydrogen fuel cell vehicles.

In 2010, Shanghai took the opportunity of the World Expo to carry out the demonstration application of hydrogen energy. Shanghai became the first city in China to participate in the field of hydrogen energy fuel cells, and the relevant scientific and technological development technology is leading in China. Through the introduction of policy documents such as Shanghai fuel cell vehicle development plan and Shanghai fuel cell vehicle industry innovation and development implementation plan, hydrogen fuel vehicles will be taken as an important direction for the development of new energy vehicles in Shanghai.

In September 2017, the Shanghai Municipal Science and Technology Commission, the Shanghai Economic and Information Technology Commission and the Shanghai Development and Reform Commission jointly released the Shanghai fuel cell vehicle development plan[3], which proposed that by 2025, the fuel cell vehicle demonstration area should be planned to explore mass production in the areas of regional public transport, official vehicles and commercial logistics, so as to improve the international competitive advantage of the fuel cell vehicle industry chain. At the level of demonstration operation and promotion, there should be no less than 20000 passenger cars and no less than 10000 other special vehicles. On the basis of successful pilot operation of public transport, commercial buses and logistics vehicles in the early stage, the promotion scale should be expanded as appropriate. By 2030, it will become an internationally influential fuel cell vehicle application city with comprehensive and mature industrialization, further market promotion for private users, drive hydrogen energy transportation, and radiate the rapid development of the fuel cell vehicle industry throughout the country. At the level of demonstration operation and promotion, the fuel cell vehicle industry chain and value chain in Shanghai will eventually radiate to the whole country and drive the transformation of social energy and power in the future.

In November 2020, the Shanghai Municipal Economic and Information Commission, Shanghai Development and Reform Commission, Shanghai Transportation Commission, Shanghai Science and Technology Commission, Shanghai Housing and Urban Rural Construction Management Commission and Shanghai Finance Bureau jointly issued the implementation plan for the innovative development of the fuel cell vehicle industry[4]. It is pointed out that by 2023, the development of the fuel cell vehicle industry will achieve the overall goal of "100 stations, 100 billion and 10000 vehicles". Nearly 10000 fuel cell vehicles have been promoted, and the application scale is leading in the country. By 2025, Shanghai will become the development highland of the global fuel cell vehicle industry, and the promotion and application of fuel cell vehicles will reach more than 10000 vehicles. The "one ring" industrial layout is basically formed, and an annular area along the "outer ring" forms the whole industry chain link of the integrated manufacturing of fuel cell vehicles, the R&D and production of core components such as battery systems and stacks, the commercial operation of multi-scenario vehicles, the "production, storage, transportation, processing"supporting facilities, the testing and certification services.The independent ability of "four innovations" has been greatly improved, and the four in one innovation system of technology, product, application and environment has been developed with high quality.The development scale of the "six belts" continues to expand, Jiading, Qingpu, Jinshan, Lingang New Area, Pudong, Baoshan and other areas have formed fuel cell automobile industry clusters.

In February 2021, the general office of the Shanghai Municipal People's government issued the implementation plan for accelerating the development of new energy vehicle industry in Shanghai (2021-2025)[5], which proposed that by 2025, the total number of fuel cell vehicles will exceed 10000. More than 70 various hydrogenation stations have been built and put into use, achieving full coverage of key application areas. Promote the construction of hydrogenation infrastructure and improve the standards and specifications for the production, storage, transportation and filling of vehicle hydrogen. Support policies to support the development of the fuel cell vehicle industry will be introduced, and subsidies will be given to the demonstration operation of vehicles, the application of key components, the construction and operation of hydrogen stations, etc. In November of the same year, the Shanghai Municipal Development and Reform Commission, the Shanghai Municipal Finance Bureau, the Shanghai Municipal Economic and Information Commission, the Shanghai Municipal Housing and Urban Rural Construction Management Commission, the Shanghai Municipal Transportation Commission, and the Shanghai Municipal Science and Technology Commission printed and issued several policies on supporting the development of the fuel cell vehicle industry in this city[7], which clearly defined the need to increase financial support in supporting the demonstration and application of complete vehicle products, encouraging mode innovation in key areas, and promoting the demonstration and application of fuel cell buses, to support the sustainable and healthy development of fuel cell vehicles in the city and encourage large-scale demonstration and application.

On June 2022, the Shanghai development and Reform Commission, the Shanghai Science and Technology Commission, the Shanghai Economic and Information Commission, the Shanghai Planning and Resources Bureau, the Shanghai housing and Urban Rural Construction Management Commission, the Shanghai Transportation Commission, the Shanghai emergency response Bureau and the Shanghai Market Supervision Bureau jointly formulated and issued the medium and long term plan for the development of the hydrogen industry in Shanghai (2022-2035)[2], specifying that by 2025, the number of fuel cell vehicles will exceed 10000.

In July 2022, the Shanghai Municipal People's government issued the Shanghai Carbon Peak Implementation Plan[7], which proposed to continuously promote the demonstration pilot and promotion of heavy cargo vehicles such as liquefied natural gas, biomass fuel and hydrogen fuel. By 2025, the total number of fuel cell vehicles will exceed 10000.

2) Application requirements

According to the development trend of hydrogen fuel cell vehicles, the demand is predicted and analyzed in two scenarios, namely the low scenario and the high scenario. Among them, the low scenario is to consider that the new energy vehicle market is gradually saturated, and there is a certain competitive relationship between the number of electric vehicles and the number of hydrogen fuel cell vehicles. According to the fact that the growth rate of Shanghai's new energy vehicle population is consistent with that of the whole country, and the proportion of hydrogen fuel cell vehicles in the number of new energy vehicles is consistent with that of the whole country. The high scenario does not consider the limit of hydrogen fuel cell vehicle ownership, and the growth rate of hydrogen fuel cell vehicle ownership is consistent with the national growth rate.

The calculation constraints include:

First, the Medium and Long term Plan for the Development of Shanghai's Hydrogen Energy Industry (2021-2035)[8]. By 2025, the number of fuel cell vehicles will exceed 10000.

Second, the Opinions on the Implementation of Further Promoting the Construction of Charging and Replacing Infrastructure in Shanghai proposed that Shanghai aims to form a moderately advanced urban charging network[9], which will meet the charging demand of more than 1.25 million electric vehicles by 2025, and the city's car pile ratio will not be higher than 2:1.

Third, according to the Planning of Technical Roadmap 2.0 for Energy Saving and New Energy Vehicles[10], the number of hydrogen fuel cell vehicles in China will reach 50000 to 100000 in 2025 and 800000 to 1000000 in 2030 to 2035, mainly trucks, buses, heavy trucks, etc.

Fourth, according to the China Hydrogen Energy Industry Development Report 2020[11], the number of electric vehicles in China will exceed 30 million by 2025 and reach 80 million by 2030. Moreover, after 2030, the economy of total cost of ownership (TCO) of hydrogen fuel cell buses, logistics vehicles, heavy trucks and passenger vehicles in the whole life cycle will be better than that of pure electric vehicles.

Fifthly, according to the Research on the Development Status and Industry Trend of Hydrogen Energy Industry: New Opportunities for Hydrogen Energy under the "Double Carbon" Goal[12], the development goal of hydrogen fuel cell vehicles nationwide will be 1.3 million by 2030 and 5 million by 2050. The scale of fuel cell vehicles in China in 2050 will be 4-5 times that in 2030.

As a pioneer in the development of fuel cell vehicles, Shanghai has developed at a relatively fast growth rate. Therefore, compared with 2030, the scale of fuel cell vehicles in Shanghai in 2060 will be appropriately expanded to 8 times under low scenarios and 9 times under high scenarios.

Table 7-2 Economic comparison of total cost of ownership (TCO) in the whole life cycle of various fuel cell and electric vehicle models

TCO cost economic trend (yuan / km)		2020	2025	2030	2050
Passenger car	Fuel cell bus	6.75	3.72	2.73	1.62
	Pure electric bus	4	3.12	3	2.21
Logistics vehicle	Fuel cell logistics vehicle	3.75	2.2	1.51	1.03
	Pure electric logistics vehicle	2.75	2.1	1.8	1.5
Heavy truck	Fuel cell heavy truck	10	5.6	3.61	1.94
	Pure electric heavy truck	7	5.5	3.8	2.5
Passenger car	Fuel cell passenger car	2	1.56	0.77	0.59
	Pure electric passenger car	1.2	0.89	0.62	0.59

Under the benchmark scenario, according to policy documents and industry experts' predictions, the number of electric vehicles in China will exceed 30 million by 2025 and reach 80 million by 2030; Shanghai plans to have 1.25 million electric vehicles in the city by 2025, so the measured number of electric vehicles in Shanghai will be about 3.3 million by 2030. However, the total number of hydrogen fuel cell vehicles in China will reach 800000 by 2030, accounting for 1% of the total number of electric vehicles. It is estimated that the total number of hydrogen fuel cell vehicles in Shanghai will reach 30000 by 2030 and 240000 by 2060.

Under the high scenario, with reference to the growth rate of the national hydrogen fuel cell vehicle population, the national hydrogen fuel cell vehicle population will reach 100000 in 2025 and 800000 in 2030, 8 times that of 2025. Therefore, on the basis of 10000 hydrogen fuel cell vehicles in Shanghai in 2025, it is measured that the number of hydrogen fuel cell vehicles in Shanghai will reach 80000 in 2030 and 720000 in 2060.

It can be seen that there is a high demand for hydrogen fuel cell vehicles in Shanghai and the industry has a good development prospect.

Table 7-3 Scale of hydrogen fuel cell vehicles in Shanghai in 2030 and 2060

Time node	2021	2025	2030		2060	
			Low Scenario	High scenario	Low Scenario	High scenario
Vehicle scale (vehicle)	1483	10360	30000	80000	240000	720000

At the same time, the development scale of hydrogen fuel cell vehicles in each district of Shanghai will be predicted by 2030 and 2060 according to the boundary conditions such as industrial structure, population proportion, existing development scale and development environment in each district of Shanghai, and based on this, the large-scale development direction of hydrogen fuel cell vehicles in each district of Shanghai will be proposed:

In Baoshan, Jinshan and other chemical regions as well as Yangshan Port import and export distribution center, hydrogen energy heavy trucks and forklifts can be built around the heavy logistics fields such as finished steel products, coal mines, vehicles and parts.

Aiming at logistics dumping, intercity logistics, suburban logistics and other scenarios in logistics industry cluster centers such as Qingpu and Jiading, we will improve the large-scale application of hydrogen fuel cell vehicles by building hydrogen energy logistics distribution demonstration projects such as special distribution, express delivery, postal service, and cold chain.

In Jiading District, based on its complete automobile industry chain, covering all links from research and development to production, we will make full use of the regional advantages of the Yangtze River Delta to build a full chain industrial park for hydrogen fuel cell vehicles, build a national platform for measurement and testing of hydrogen fuel cell vehicles, a municipal platform for data monitoring of fuel cell vehicles and hydrogen refueling stations, build a communication platform for domestic and foreign hydrogen energy industries, and promote the use of hydrogen fuel cells in municipal sanitation, public transportation Multiple types of substitution such as official vehicles and private passenger vehicles.

In Fengxian District, relying on the existing leading domestic fuel cell vehicle enterprises, we will focus on cultivating key fuel cell component R&D enterprises, form key enterprise incubators, and build a high-quality upstream and downstream industrial chain with the Port fuel cell vehicle intelligent manufacturing industrial park.

In the new area near the port, relying on the Sino Japanese hydrogen energy industrial park under construction, a fuel cell key technology research and development center will be established to build an intelligent manufacturing industrial park for fuel cell vehicles. The replacement of fuel cell vehicles will be gradually promoted through the development of medium volume public transport demonstration, and the application demonstration of heavy trucks and forklifts will be carried out in Pudong International Transport Hub and Waigaoqiao Port Area, two freight and logistics gathering areas.

Table 7-4 Development scale of hydrogen fuel cell vehicles in various regions of Shanghai (unit: vehicle)

Region	2030				2060			
	Baseline scenario		High scenario		Baseline scenario		High scenario	
	Passenger cars	Commercial cars	Passenger cars	Commercial cars	Passenger cars	Commercial cars	Passenger cars	Commercial cars
Baoshan,	539	3840	1438	10240	8627	23040	25881	69120
Jiading	442	4800	1180	12800	7079	28800	21237	86400
Qingpu	307	3600	818	9600	4906	21600	14718	64800
Songjiang	461	144	1229	384	7373	864	22118	2592
Minhang	640	168	1707	448	10240	1008	30721	3024
Jinshan	198	3360	529	8960	3176	20160	9528	60480
Fengxian	275	3600	734	9600	4404	21600	13213	64800
Pudong	1371	4320	3655	11520	21932	25920	65797	77760
Chongming	154	48	410	128	2462	288	7387	864
Central urban area	1613	120	4300	320	25800	720	77401	2160
Total	6000	24000	16000	64000	96000	14000	288000	43000
Overall scope	**30000**		**80000**		**240000**		**720000**	

(4) External challenges

1) Policy

Support policies have been issued frequently, but special plans and policy systems have not yet been formed. Although China affirms the development of hydrogen energy and fuel cell industry from the strategic perspective, there is no special planning and policy system, no top-level design, and scattered and unclear management departments. Moreover, there are few systematic hydrogen energy policies, the relevant standards are aging, and the test standards are missing.

2)Infrastructure

The construction of hydrogenation infrastructure is still insufficient, and "hydrogenation anxiety" is an important constraint factor for the development of hydrogen fuel cell vehicles. Hydrogen fuel cell vehicles are still in the initial stage, and there are few operating vehicles. The construction and operation of the hydrogen station cannot balance the revenue and expenditure through the economies of scale, resulting in immature construction and operation mode, insufficient industrialization capacity of the hydrogenation equipment and high cost. The lack of infrastructure in turn affects the promotion and application of hydrogen fuel cell vehicles.

7.2.2 Suggestions on the development of hydrogen fuel cell vehicles in Shanghai

Through the in-depth analysis of the development of Shanghai's hydrogen fuel cell vehicle industry by SWOT analysis, this section puts forward the development goals and development suggestions of Shanghai's hydrogen fuel cell vehicle industry in 2030 and 2060.

(1) Development objectives

By 2030, it will build a domestic leading fuel cell vehicle technology demonstration city, form a high-quality industrial chain resource aggregation effect, realize the complete upgrading of the whole fuel cell vehicle industry chain, overcome the key core technologies of the whole fuel cell vehicle industry chain, benchmark the international industry level, create brands on products, cultivate a number of leading enterprises, and create a comprehensive competitive fuel cell vehicle brand. We will comprehensively promote the commercial application of hydrogen fuel cells in various types of vehicles, expand the market of hydrogen fuel cell heavy trucks, passenger cars, trucks, forklifts and large passenger vehicles, achieve a total of 30000 to 80000 fuel cell vehicles, and the total output value of the whole industrial chain of hydrogen fuel cell vehicles will exceed 100 billion yuan. And promote the demonstration application of fuel cells in the fields of shipping and aviation, and constantly expand the scale of hydrogen energy application in the field of transportation.

By 2060, it will become a fuel cell vehicle application city with international influence. Its overall technology is close to the international advanced level, and some of its technologies have reached the international leading level. It will realize the high-speed and mature development mode of the output value of the whole fuel cell vehicle industry chain in Shanghai, and drive the diversified application of fuel cell products in China. Finally, Shanghai's fuel cell vehicle industry chain and value chain will radiate to the whole country and drive the transformation of social energy and power in the future. At the operational level, it should create a clean, safe and efficient hydrogen fuel cell logistics and transportation service new business form, further increase the proportion of fuel cell passenger vehicles in the city, build highways and urban and rural public hydrogenation systems, and improve the city's hydrogen station network.

(2) Development proposal

1)Improve the industrial chain

Give play to the advantages of existing enterprises such as Shanghai reshaping Energy Technology Co., Ltd., and cooperate with well-known enterprises such as Shanghai jiehydrogen Technology Co., Ltd. to establish a research and development center for key technologies and components, break through the design and mass production of electric stacks, and overcome core technical difficulties such as high corrosion-resistant carbon paper and on-board hydrogen storage system. Cultivate a number of domestically leading and internationally first-class "Gazelle" enterprises to realize independent research and development of key technologies of fuel cells and reduce costs. At the same time, relying on the foundation of Shanghai's automobile industry, it should introduce large-scale leading enterprise groups into the market, take high-tech enterprises as the industry leaders, speed up the cultivation of "unicorn" enterprises with international influence, and form a hydrogen fuel cell automobile industry alliance. Attract and accelerate the construction and agglomeration of industrial chain, form an independent and controllable whole line, and improve the reliability and durability of the system. Build a comprehensive competitive fuel cell vehicle brand, build a world-class hydrogen fuel cell vehicle ecological industrial park, and help promote the commercialization of hydrogen fuel cell products and vehicles.

2)Accelerate commercial application

Accelerate the application of hydrogen fuel cell vehicles in urban logistics, sanitation, municipal, tourism and other special vehicles as well as passenger and freight vehicles in specific areas in areas with hydrogen energy development foundation in Shanghai. In the international freight hub and other areas, it should focus on the development of long-distance, heavy-duty vehicles and forklift applications, lay out and build fuel cell vehicle application demonstration areas, and accelerate the commercial application of fuel cell vehicles. The commercialization and application of hydrogen fuel cell vehicles in various districts have progressed hand in hand, forming the "multi-point flowering" of Shanghai's characteristic demonstration of hydrogen fuel cell vehicles, and accelerating the industrial development of the city's hydrogen fuel cell vehicles.

3)Promote the construction of policies and standards

Through the top-level design of government policies and based on the development foundation and conditions of Shanghai, it should make overall planning and reasonable layout to grasp the direction, objectives and main tasks of the development of hydrogen fuel cell vehicle industry. In view of the technical bottleneck of hydrogen energy for vehicles and the main bottleneck faced by the short board of products and the large-scale demonstration operation of fuel cell vehicles, it should study and introduce corresponding support policies and supporting measures to guide the standardized and orderly development of the hydrogen energy industry, and make a phased layout from demonstration pilot to commercial promotion. Establish relevant standards and regulations, carry out the supervision and management of the hydrogen energy industry chain in an orderly manner, break down the standard inspection barriers and market access barriers that restrict the development of fuel cell vehicles as soon as possible, and strengthen and improve the top-level design for the development of fuel cell vehicles. Build a complete set of testing and certification platforms for fuel cell materials, stacks, power systems, complete vehicles and key parts, form a testing and certification service and test equipment supply system, and create a public service platform for testing and evaluation of fuel cell vehicles. Promote the construction of public service platform for inspection, testing and certification of hydrogen energy products and hydrogen energy product quality certification system.

4)Promote infrastructure construction

The hydrogen station is an indispensable cornerstone to support the development of the fuel cell vehicle industry and a breakthrough point for the commercialization of the hydrogen energy industry. It is necessary to continue to strengthen government support and guidance, increase industrial policy support, establish corresponding management departments and regulatory mechanisms, and solve the bottleneck problem of "land difficulty, approval difficulty and management difficulty". At the same time, establish a reasonable return mechanism for investment income, actively promote the reform of the investment system, open up diversified capital channels, encourage local governments to invest in hydrogen energy industry infrastructure by means of capital injection and investment subsidies, guide and attract social investment to participate in construction and operation, and give full play to the positive role of social capital in the development of hydrogen energy industrialization.

5)Cultivate talent team

Accelerate the construction of disciplines related to hydrogen fuel cell vehicles in local universities in Shanghai, and optimize the courses of machinery, chemical engineering, materials, energy and other disciplines. Cultivate and support key technical personnel and practitioners of fuel cell vehicles, and lay a solid foundation for innovative research and development of key technologies and materials of fuel cell vehicles. It should strengthen the incentive mechanism for talent introduction and attract overseas high-end talents specialized in relevant key technologies and equipment.

7.3 Forecast and analysis of hydrogen application demand in Shanghai

In view of the fact that hydrogen is not widely used, it is necessary to further tap the potential hydrogen demand through technological innovation. At this stage, the relevant statistical data, boundary conditions and more scientific basis required for the calculation of hydrogen application demand are lacking. In this paper, the total hydrogen demand will be estimated according to the development trend of hydrogen application at home and abroad, as well as the experience value and proportion relationship of hydrogen application in industries, buildings, transportation and other fields by combining scenario analysis and prediction with comparison and analogy prediction. Based on the fact that hydrogen fuel cell vehicles are the most mature hydrogen energy application model in Shanghai, this paper will first calculate the number of hydrogen fuel cell vehicles and hydrogen demand in Shanghai, then predict the total hydrogen demand in the transportation field based on this, and finally estimate the full caliber hydrogen demand in Shanghai in 2030 and 2060 according to the proportional relationship between hydrogen demand in industries, buildings, transportation and other fields in 2030 and 2060.

According to the estimation of the demand for hydrogen fuel cell vehicles in Shanghai in Section 7.2 of this paper, under the benchmark scenario, the number of hydrogen fuel cell vehicles in Shanghai will reach 30000 in 2030 and 240000 in 2060. Under the high scenario, the number of hydrogen fuel cell vehicles in Shanghai will reach 80000 by 2030, 720000 in 2060 (Among them, the benchmark scenario is to consider that the new energy vehicle market is gradually saturated, and there is a certain competitive relationship between the number of electric vehicles and the number of hydrogen fuel cell vehicles. According to the fact that the growth rate of Shanghai's new energy vehicle population is consistent with that of the whole country, and the proportion of hydrogen fuel cell vehicles in the number of new energy vehicles is consistent with that of the whole country. The high scenario is to consider that the number of hydrogen fuel cell vehicles is not limited, and the number of hydrogen fuel cell vehicles is increasing The speed is consistent with the national growth rate).

(1) Calculation of hydrogen energy demand for fuel cell vehicles

The annual hydrogen consumption of hydrogen fuel cell vehicles is calculated by modeling:

$$Q_{H_2} = N \times q_{H_2} \times T \times L \tag{7-1}$$

Where, Q_{H_2} is the annual hydrogen consumption in kg; N is the number of hydrogen fuel electric vehicles in volume; q_{H_2} is the hydrogen consumption of a hydrogen fuel cell vehicle in 100 km in kg/100km; T is the annual operating days in days; L is the daily mileage of the vehicle in km/day.

The constraints of hydrogen fuel cell hydrogen energy demand measurement include:

First, the proportion of passenger cars is 20% and commercial vehicles is 80% in 2030, and the proportion of passenger cars is 40% and commercial vehicles is 60% in 2060.

Second, the hydrogen consumption of hydrogen fuel cell vehicles is obtained according to the manufacturing test of the automobile industry: In the low scenario, the hydrogen consumption of passenger cars is reduced from 2.8kg to 1.5kg per year, and the hydrogen consumption of commercial vehicles is reduced from 5kg to 4kg per year. In the high scenario, the hydrogen consumption of passenger cars is reduced from 2.8kg to 0.82kg per year (data borrowed from: FAW Group's display of The fuel cell passenger car model Hongqi H5-FCEV has a hydrogen consumption of less than 0.82kg per 100km[13]), and the hydrogen consumption of commercial vehicles is reduced from 5kg to 2kg per 100km per year (data borrowed from: a 4.5 ton light truck equipped with a 60 kW fuel cell system released by Chongqing Hydrogen Energy Company in August 2021 has a hydrogen consumption of less than 2kg per 100km[14]).

Third, it is determined based on general vehicle driving, with a daily mileage of 300km for passenger cars and 200km for commercial vehicles, and the number of operating days increasing year by year for measurement.

Therefore, in the low scenario, the scale of hydrogen fuel cell vehicle development in the city in 2030 is 30,000 units, and the hydrogen energy demand is 69,500 tons; by 2060, the scale of hydrogen fuel cell vehicle development in the city is 240,000 units, and the hydrogen energy demand is 532,800 tons.

In the high scenario, the scale of hydrogen fuel cell vehicle development in the city will be 80,000 vehicles in 2030, and the hydrogen energy demand will be 127,200 tons; the scale of hydrogen fuel cell vehicle development in the city will be 720,000 vehicles in 2060, and the hydrogen energy demand will be 817,300 tons.

(2) Calculation of total hydrogen demand

The constraints for the calculation of total hydrogen demand include:

First, the proportion of hydrogen demand in various fields in Shanghai in 2020 is 99.5% in chemical industry and 0.5% in transportation.

Second, according to the "China Hydrogen Energy and Fuel Cell Industry White Paper 2020" released by China Hydrogen Energy and Fuel Cell Industry Innovation Strategy Alliance[15], in the carbon neutral scenario in 2060, the proportion of hydrogen demand in various fields in China is 60% in industry, 31% in transportation, 4.5% in construction, and 4.6% in power generation and grid balance.

Third, the hydrogen demand for Shanghai in 2020 is about 140,000 tons.

In the low scenario, it is calculated that by 2030, the scale of hydrogen fuel cell vehicle development in Shanghai will be 30,000 vehicles, the hydrogen energy demand will be 69,500 tons, and the total hydrogen demand in all areas of the city will be about 955,100 tons; by 2060, the scale of hydrogen fuel cell vehicle development in Shanghai will be 240,000 vehicles, the hydrogen energy demand will be 532,800 tons, and the total hydrogen demand in all areas of the city will be about 2,124,300 tons.

In the high scenario, it is calculated that by 2030, the scale of development of hydrogen fuel cell vehicles in the city will be 80,000 vehicles, the demand for hydrogen energy will be 127,200 tons, and the total amount of hydrogen required by various fields in the city will be 1,018,800 tons; by 2060, the scale of development of hydrogen fuel cell vehicles in the city will be 720,000 vehicles, the demand for hydrogen energy will be 813,000 tons, and the total amount of hydrogen required by various fields in the city will be 2,530,600 tons.

In summary, the total hydrogen demand in the city will be 955,100-1,018,800 tons by 2030, which is still mainly used by industrial chemical industry, and the hydrogen used in transportation field will increase. By 2060, the total hydrogen demand in the city will be 2,124,300-2,530,600 tons, although it is still mainly used by industrial and chemical industries, the proportion of hydrogen used in the transportation field will increase significantly.

Table 7-5 Basic data for calculation of hydrogen consumption of fuel-electric vehicles

Time nodes		**2021**	**2025**	**2030**		**2060**	
				Low scenario	High scenario	Low scenario	High scenario
Vehicle size (Vehicles)	Passenger cars	81	2431	600	16000	96000	288000
	Commercial vehicles	1402	7929	24000	64000	144000	432000
Hydrogen consumption per 100km(kg/100km)	Passenger cars	2.8	2.5	2	1	1.5	0.82
	Commercial vehicles	7.5	4.5	4.2	3	4	2
Annual operating days (days)	Passenger cars	10	170	250		300	
	Commercial vehicles	15	200	300		350	
Daily mileage (km/day)	Passenger cars	300					
	Commercial vehicles	200					

Table 7-6 Forecast of hydrogen fuel cell vehicle scale and hydrogen energy demand in Shanghai in 2030 and 2060

Time Nodes	2021	2025	2030		2060	
			Low Scenario	High scenario	Low Scenario	High scenario
Scale of passenger cars (units)	81	2431	6000	16000	96000	288000
Commercial vehicle scale (units)	1402	7929	24000	64000	144000	432000
Total vehicle size (vehicles)	1483	10360	30000	80000	240000	720000
Hydrogen demand in transportation (ton)	213	15486	69480	127200	532800	817344

Table 7-7 Hydrogen Demand Structure and Hydrogen Demand by Sector in Shanghai in 2030 and 2060

Time Nodes	2030				2060			
	Scenario share	Low scenario	Scenario share	High scenario	Scenario share	Low scenario	Scenario share	High scenario
Industry	91.22%	87.13	86.01%	87.63	69.94%	154.86	58.70%	148.55
Transportation	7.27%	6.95	12.49%	12.72	24.06%	53.28	32.30%	81.73
Construction	0.50%	0.48	0.50%	0.51	2.00%	4.43	4.00%	10.12
Energy (hydrogen for power system)	1.00%	0.96	1.00%	1.02	4.00%	8.86	5.00%	12.65
Total demand for hydrogen (10,000 tons)	100.00%	95.51	100.00%	101.88	100.00%	221.43	100.00%	253.06

7.4 Summary

With the iterative upgrading of hydrogen application technology, hydrogen application scenarios will show diversified development. To analyze the potential demand for hydrogen applications in Shanghai, this chapter starts with hydrogen fuel cell vehicles and analyzes the development trend of hydrogen fuel cell vehicles in Shanghai from the aspects of industrial development and application advantages, policy environment, technological development level, and infrastructure construction based on SWOT analysis method. The scenario analysis method is combined, predicted the number of hydrogen fuel cell vehicles and hydrogen demand in Shanghai in 2030 and 2060, and proposed large-scale development goals and suggestions for hydrogen fuel cell vehicles in Shanghai.

Based the number of hydrogen fuel cell vehicles and hydrogen demand in Shanghai in 2030 and 2060 in the low and high scenarios, this chapter estimates that :

In 2030 the total demand for hydrogen energy in the transportation sector of Shanghai is 695-127200 tons, and the total demand for hydrogen in Shanghai is 9551-1018800 tons.

In 2060, the total demand for hydrogen energy in the transportation sector of Shanghai was 532800-813000 tons, and the total demand for hydrogen in Shanghai was 22143-253060 tons.

Based on the comparison of hydrogen energy supply prediction data, it can be seen that by 2030, the supply and demand of hydrogen in Shanghai will be almost balanced, and by 2060, the demand for hydrogen in Shanghai will exceed the supply. In the future, more hydrogen sources will need to be considered.

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Chapter 8

CONCLUSION AND PROSPECT

CHAPTER EIGHT: CONCLUSION AND PROSPECT

CONCLUSION AND PROSPECT

8.1 Conclusion

Hydrogen energy, as the best energy application carrier for achieving large-scale and deep decarbonization in fields such as transportation, construction, and energy, has ushered in new development opportunities. Taking Shanghai as an example, according to the characteristics of different application scenarios in various fields, this paper studies the application effects of different hydrogen energy application forms and the potential of hydrogen energy application in Shanghai, with a view to promoting Shanghai to achieve the goal of "2030 carbon peak 2060 carbon neutrality" by expanding the application path of hydrogen energy in multiple scenarios.

The main works and results can be summarized as follows:

In Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THIS STUDY. This chapter analyzed the hydrogen energy development strategies of the United States, European Union, Japan, Korea, China and other countries and regions, and makes it clear that each country is actively promoting hydrogen energy technology research and development and industrialization, and seizing the first opportunity and high point of industrial development. In order to break the bottleneck of development and enrich the hydrogen energy application scenarios, this paper takes Shanghai, which has the foundation of hydrogen energy development, as the research object to carry out the environmental and economic assessment of hydrogen energy application. The total demand of hydrogen is about 140,000 tons/year; in terms of supply, the supply capacity of hydrogen energy in the city will be about 500,000 tons in 2020, so the supply exceeds the demand at this stage. How to expand the application of hydrogen energy and improve the utilization of hydrogen energy in Shanghai is also one of the focuses of this paper.

In Chapter 2, LITERATURE REVIEW OF HYDROGEN APPLICATION. This chapter analyzes the application forms of hydrogen energy mainly include direct combustion, conversion into electric energy through fuel cells, and nuclear aggregation, among which the application form of fuel cells into electric energy is the most mature. It also analyzes the main application forms of hydrogen energy in the fields of industry, transportation, construction and energy, and clarifies the effects of hydrogen application focusing on the transportation field, construction field and energy field. Then, the application and research status of the more maturely developed hydrogen fuel cell vehicles and their infrastructure - hydrogen refueling stations in the transportation field, the application and research status of hydrogen fuel cell cogeneration systems in the construction field, and the application and research status of hydrogen-doped internal combustion engines and hydrogen-fired internal combustion engines in the energy field where hydrogen is used as fuel to replace natural gas are analyzed. The current status of research on hydrogen-doped internal combustion engines and hydrogen-fired internal combustion engines in the energy sector.

*In Chapter 3,*THEORIES AND METHODOLOGY OF THE STUDY . This chapter is about methodological research and model building.First, the main load forecasting methods used at this stage are introduced and analyzed, and the load forecasting model and load forecasting accuracy evaluation model are constructed.Since load forecasting is the basis of subsequent research, a load forecasting method based on PSO- GRU neural network model load prediction method, the results show that the average absolute percentage error of PSO-GRU neural network model is only 0.7%, with high prediction accuracy and optimal results. Secondly, the equipment models of hydrogen energy systems involved in the subsequent chapters of this paper, such as photovoltaic hydrogen refueling station system and equipment model, hydrogen fuel cell cogeneration system and equipment model, and hydrogen-doped gas turbine system and equipment model, were established. Then, in order to predict the development scale of hydrogen fuel cell vehicles in Shanghai and the potential of hydrogen energy application in the city, the relevant prediction methods are introduced and analyzed. Finally, the total annual cost of energy model, dynamic cost-benefit analysis model, and carbon emission calculation model of energy system are constructed to provide the research theoretical basis for the environmental and economic assessment in the subsequent chapters.

In Chapter 4, RESEARCH ON THE APPLICATION EFFECT EVALUATION OF PHOTOVOLTAIC-HYDROGEN REFUELING STATION BASED ON HYDROGEN LOAD ANALYSIS, the feasibility of the application of photovoltaic hydrogen refueling station is studied. This chapter takes a hydrogen refueling station with a supply capacity of 500 kg/day in Shanghai as the research object, firstly, it analyzes the characteristics of hydrogen demand for different types of hydrogen fuel cell vehicles and the demand characteristics of hydrogen refueling stations throughout the day, and the analysis shows that the demand distribution shows a multi-peak curve; then, it determines the system equipment configuration of PV hydrogen refueling stations according to the hydrogen demand load; finally, it analyzes the operation strategy of PV hydrogen refueling stations at different hydrogen prices Finally, the operation strategies and socio-economic benefits of PV hydrogen refueling stations at different hydrogen prices are analyzed. The results show that compared with conventional hydrogen refueling stations, the PV hydrogen refueling station is a better solution and has better investment returns. In terms of carbon emissions, hydrogen fuel cell vehicles refueled by this hydrogen refueling station can reduce CO_2 emissions by about 2,737.5 tons per year compared with traditional fuel vehicles. Compared with conventional hydrogen refueling station, the PV hydrogen refueling station can reduce carbon emission by about 1,237.28 tons per year, which has good social benefits.

In Chapter 5, RESEARCH ON THE APPLICATION EFFECT EVALUATION OF HYDROGEN FUEL CELL COGENERATION IN AIRPORT TERMINAL BUILDING, the main study is on the feasibility of applying hydrogen fuel cell cogeneration system in airport terminals. Taking an airport terminal in Shanghai as an example, this chapter first analyzes the terminal building load characteristics and space-time characteristics, and predicts and analyzes the typical daily load of the terminal for 8760 hours and each season, and then focuses on the equipment configuration scheme, operation optimization strategy and economic and social benefits of the hydrogen fuel cell cogeneration system when the hydrogen cost price is reduced by 0%, 50% and 70%. When the hydrogen price is reduced by 50%, the total annual cost is reduced by about 20.8% compared with that under the original hydrogen price, which is economical. When the hydrogen price is reduced by 70%, the total annual cost will be reduced by about 46.2% compared with that under the original hydrogen price, the annual carbon emission can be be reduced by about 5,800,000 tons, which has good economic and social benefits.

In Chapter 6, RESEARCH ON THE APPLICATION OF NEAR ZERO CARBON ENERGY SYSTEM IN INDUSTRIAL PARKS BASED ON HYDROGEN-FUELED GAS TURBINES, the feasibility of the application of hydrogen-doped turbine is mainly studied. The feasibility of hydrogen-doped gas turbine application is firstly studied in this chapter. Through the analysis, it can be seen that under the condition that the cost of carbon trading is \$8.2/t and the price of hydrogen is \$0.432/m^3, the higher the proportion of hydrogen-doped gas turbine, the higher the carbon reduction but the higher the economic cost, so it is not economical at this stage. Then, under the demand of "zero-carbon" industrial park construction, the application effect of combining hydrogen turbine and photovoltaic system on the construction of "near-zero carbon" industrial park and the influence of carbon trading price on the application of gas turbine were studied in an industrial park in Shanghai. The results show that the application of hydrogen-fired turbine system is economically feasible when the cost of hydrogen is no less than 0.1471\$/m^3 under the condition of carbon emission price of 8.2\$/t. For the gas turbine, the economics will be affected as the carbon trading price increases, and the gas turbine system will not be economically viable when the carbon trading price is not less than \$42.15/t under the condition that the natural gas price is \$0.42/m^3..

In Chapter 7, ANALYSIS OF HYDROGEN APPLICATION DEMAND POTENTIAL IN SHANGHAI, the main study is on the potential of hydrogen energy application in Shanghai. Given that hydrogen fuel cell vehicles are the most mature hydrogen application method in Shanghai, this chapter firstly conducts an in-depth study on their development scale based on SWOT analysis, and puts forward development targets and suggestions, specifying two scenarios for hydrogen fuel cell vehicle development: the baseline scenario and the high scenario. Then, the development scale of hydrogen fuel cell vehicles and hydrogen demand in Shanghai under the two scenarios are predicted and analyzed. The results show that the development scale of hydrogen fuel cell vehicles in Shanghai will be 30-80,000 vehicles and the hydrogen demand in transportation will be 6.95-12.72 million tons by 2030, and the development scale of hydrogen fuel cell vehicles in Shanghai will be 240-720,000 vehicles and the hydrogen demand in transportation will be 53.28-81.73 million tons by 2060. 817,300 tons. Finally, based on the feasibility and development trend of hydrogen energy application in different fields, the proportional relationship of hydrogen demand in each field under different stages is clarified, and the total hydrogen energy demand in Shanghai is predicted and analyzed. The results show that the total hydrogen demand in Shanghai will be about 95.51-1.0188 million tons by 2030, and the total hydrogen demand in Shanghai will be 221.43-253.06 million tons by 2060.

*In Chapter 8,*CONCLUSION AND PROSPECT.

In conclusion, this paper assessed the application feasibility of photovoltaic hydrogen station, hydrogen fuel cell cogeneration system, and hydrogen turbine from both environmental and economic aspects, and analyzed and studied the hydrogen application potential in Shanghai based on the application feasibility of various fields and the development scale of hydrogen fuel cell vehicles.

For photovoltaic-hydrogen refueling station, the photovoltaic-hydrogen refueling station project is better than the conventional hydrogen station project and has better investment returns, but the conventional hydrogen station can achieve short-term investment recovery at a lower hydrogen price than the photovoltaic-hydrogen refueling station. If environmental impact is considered, it is obvious that the carbon emission reduction effect of photovoltaic-hydrogen refueling station is better.

For hydrogen fuel cell cogeneration system and hydrogen turbine, its application economy is limited by the hydrogen cost price. When the hydrogen cost price is reduced to about 30% of the existing price, the related projects will have good economy. According to the analysis of the cost and price of hydrogen production, this goal will be achieved by around 2040.

For the demand for hydrogen application in Shanghai, driven by the "dual carbon" goal, hydrogen energy application scenarios will be more diverse. It is expected that by 2030, the supply and demand of hydrogen in Shanghai will be almost balanced, and by 2060, the demand for hydrogen in Shanghai will exceed the supply, and more hydrogen sources will need to be considered.

Through the feasibility analysis of hydrogen energy application in different forms in different fields, it can be clear that its application and development are mainly limited by the price of hydrogen, while the carbon emission trading market brings infinite possibilities to the development of hydrogen. Therefore, in the process of promoting the application of hydrogen energy, it is not only necessary to pay attention to the key technologies that affect the cost of hydrogen, but also need to pay more attention to the price change trend of carbon emission trading, so as to improve the feasibility of hydrogen energy application and enrich the application scenarios of hydrogen energy, improve the utilization rate of hydrogen energy and assist in deep decarbonization. It is hoped that this study can provide a theoretical reference for hydrogen energy application promotion and practical application research.

8.2 Prospect

With the maturity of hydrogen application technology and the decline of hydrogen price, hydrogen application will be able to penetrate into transportation, energy, construction and other fields, so as to achieve deep decarbonization and promote Shanghai to achieve the strategic goal of "carbon neutrality".

In addition, based on this research, further research can be conducted on the application of hydrogen energy in the industrial field, as well as the application forms of hydrogen coupling technology in energy and power systems, long-distance hydrogen storage and transportation across seasons, ect, to provide a good development foundation for hydrogen applications.