Chapter 3

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Chapter 3

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Yan Long and Jishi Zhao

1. Introduction

As a kind of clean energy, hydrogen energy can improve China's energy structure and alleviate environmental pollution. Hydrogen energy is an important way of achieving carbon neutrality. The hydrogen energy industry is an important starting point to achieve high-quality economic transformation and development. However, compared with oil and natural gas, the cost of hydrogen energy is higher, seriously restricting the development and commercialisation of the industry. To realise hydrogen energy's commercialisation, the technical and the economic feasibility should be satisfied.

Guangdong Province is where the hydrogen energy industry was deployed earlier in China. It has a complete hydrogen energy industry chain and complete industrial development supporting facilities. It covers the entire industrial chain of hydrogen production, hydrogen transportation, hydrogen refuelling, fuel cells and systems, and hydrogen fuel-cell vehicles, etc. In terms of demonstration applications, more than 1,600 fuel-cell operating vehicles have been promoted in the province, initially achieving large-scale demonstration applications. For infrastructure construction, 23 hydrogen refuelling stations, mainly in Foshan and Yunfu, were completed and implemented. However, in the face of the province's increasing plans, the provincial hydrogen energy supply has been cramped. For example, some hydrogen fuel-cell vehicles in Foshan can only be suspended. Transporting hydrogen from other provinces is then imperative. Many scholars had conducted related research on hydrogen production and trans-regional storage and transportation of hydrogen renewable energy. Sherif, Barbir, and Veziroglu (2005) described hydrogen technology as the production, storage, distribution, and utilisation of hydrogen. They also discussed the possibility of generating hydrogen from wind energy and using hydrogen to enhance the competitiveness of wind power generation (Sherif et al., 2005). Abe briefly introduced hydrogen as the ideal sustainable energy carrier for the future economy, emphasising that the main key to the comprehensive development of the hydrogen economy is safe, compact, portable, and cost-effective hydrogen storage. Suman Dutta (2014) described several main hydrogen production methods and storage methods. Amongst them, the main methods for producing hydrogen are by water, glycerol, and biomass. The storage methods of hydrogen mainly include compressed gas hydrogen, liquid hydrogen, metal organic framework, etc. (Suman, 2014). Timmerberg and Kaltschmitt (2019) studied the options for producing renewable hydrogen energy through water electrolysis in North Africa. The hydrogen is then mixed into the existing natural gas pipeline system and then transported to Central Europe. Assuming that in the four natural gas pipelines between North Africa and Europe, the mixing ratio of hydrogen is 10%, which can provide 9.6 TWh of hydrogen (Timmerberg and Kaltschmitt, 2019). Zabrzeski et al. (2019) described the change when hydrogen is added to the existing natural gas pipeline. Such changes may lead to additional savings. **The** quantity of hydrogen in the natural gas system would be different depending on its production; hence, it should be sent via pipeline as an additional component next to natural gas. Due to the difference in its physico-chemical parameters concerning the characteristics of natural gas, the work of gas compressors at different hydrogen concentrations will be different. When considering the effect of hydrogen on the compressor's performance, the change of the main parameters characterising the flow is also considered. It may turn out that they will also positively influence the work of compression needed in the same compressor stations (Zabrzeski et al., 2019).

Liu et al. (2019) proposed a novel solution for the unbalanced energy distribution in China. A novel project solution for large-scale hydrogen application is proposed using surplus wind and solar-generated electricity for hydrogen generation and NG pipeline transportation for hydrogen-natural gas mixtures (called HCNG). The project proves to be feasible through profitability analysis. The main influence items are tested individually to guarantee project profitability within 22 years. The project can reduce 388.40 M Nm^3 CO2 emissions and increase 2998.52 M$ incomes for solar and wind power stations.

Hydrogen can be transported in its different states: gaseous hydrogen (GH2), liquid hydrogen (LH2), and solid hydrogen (SH2).The first two pressurise or liquefy the hydrogen before transportation; this method is currently being used by hydrogen refuelling stations.

Hydrogen is usually pressurised and then transported via containers, long-tube trailers, and pipelines. The long-tube trailer transport technology is mature, and the specifications are perfect. Therefore, many foreign refuelling stations use long-tube trailers to transport hydrogen (Ma et al., 2008). Pipelines are used for large-scale and long-distance hydrogen transport, which can effectively reduce transport costs. Pipeline transport methods are mainly divided into natural gas mixed with hydrogen transportation and hydrogen-dedicated pipelines. Because the economic distance of high-pressure hydrogen gas is about 200 km and the interprovincial transportation distance is more than 500 km, high-pressure hydrogen gas is not suitable for interprovincial transportation. However, pipeline transportation is relatively insensitive to distance and suitable for large-scale transport, so it is included in this project's scope.

The volume density of liquid hydrogen is 70.8 kg/m, and the volume energy density reaches 8.5 MJ/L, which is 6.5 times that of gas hydrogen at a transportation pressure of 15 MPa. Therefore, after the hydrogen is cryogenically cooled to 21 K and liquefied, it can be transported by tank trucks or pipelines to improve transportation efficiency significantly. Furthermore, foreign hydrogen refuelling stations use tank trucks to transport liquid hydrogen slightly more than gaseous hydrogen. Since liquid hydrogen is the key direction of hydrogen energy development in the future, and transporting liquid hydrogen within 500–1,000 km across provinces is suitable, it is included in this project's scope.

In the early 1970s, the Philips Company of the Netherlands and Brookhaven Laboratory of the United States successively discovered that $LaNi_5$, Mg_2Ni, and other alloys had reversible adsorption and can release hydrogen; they also 'bind' H atoms in solid hydrogen storage materials through chemical bonds. Thus, solid hydrogen storage technology is recorded in the annals of history (Reilly and Wiswall, 2012). However, due to the low-mass hydrogen storage density, for practical application, solid hydrogen only stays in the laboratory.

Hydrogen production by electrolysis is one of the most potential hydrogen production methods due to its green environmental protection, flexible production, high hydrogen purity (> 99.97%), and high-value oxygen by-product. The leading hydrogen production technologies by electrolysis are alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis. Amongst them, China's alkaline electrolysis technology, the most mature technology with low production cost, is leading worldwide. The proton exchange membrane electrolysis process is simple, but the energy consumption is large and the use of precious metal catalyst leads to high production costs. Finally, solid oxide electrolysis needs to work in a high-temperature environment, which consumes the most energy, and the technology is still at the laboratory R&D stage (Azadeh and Michael, 2017; Buttler and Spliethoff, 2018) .

In all links of the hydrogen energy industry chain, upstream hydrogen production has always been the main factor restricting the sustainable and healthy development of hydrogen energy in Guangdong. Significantly as the scale of promotion and application of hydrogen fuel-cell vehicles expand, the demand for hydrogen increases accordingly. Hydrogen source guarantee issues, such as lack of hydrogen and high prices, have restricted the rapid development of the hydrogen energy industry in Guangdong province. At present, hydrogen resources in Guangdong are mainly industrial by-products, and hydrogen fuel-cell vehicles must be purified many times. Therefore, the balance between cost control of hydrogen production and hydrogen quality standard faces severe challenges. The current high cost of electrolysed water restricts the large-scale development of water electrolysis from renewable energy sources, such as abandoning wind and water. However, with future technological breakthroughs, hydrogen production from renewable energy sources is an effective way of producing high-purity hydrogen for fuel-cell vehicles. Combined with the current technical status and cutting-edge research, hydrogen energy transport mainly considers liquid hydrogen and pipeline.

Based on geographical location and local renewable resource endowment, this study analyses the potential of existing renewable energy hydrogen production projects in the neighbouring provinces of Guangdong province, such as Guizhou, Yunnan, Sichuan, Guangxi, Hunan, Jiangxi, Fujian, and Hainan, and the technical and economic feasibility of liquid hydrogen storage and transportation technology, as well as pipeline hydrogen transportation technology. It provides path analysis to solve hydrogen source problems in

Guangdong province, optimises the hydrogen energy supply network system, and ensures sustainable and high-quality development of the hydrogen energy industry.

2. Economic Analysis Model

The economic analysis model used in this project is the total cost of ownership or TCO model. By analysing the total cost of hydrogen production and storage and transportation, we have included all the involved processes into the cost calculation. First, we calculated the total cost of the hydrogen production side and the cost of different transportation methods. Finally, we compared the costs of the three transportation methods and presented a reasonable transportation plan.

2.1. Hydrogen Production Cost

Hydrogen production costs include equipment cost, construction cost, land cost, and operation and maintenance (O&M) costs. Related items can be further refined, such as equipment costs, including electrolyser, compressor, lithium battery, etc. O&M costs include electricity, raw material water, cooling water, potassium hydroxide (KOH), depreciation, maintenance and repair, labour, and others. Table 3.1 shows the cost of hydrogen production being mainly composed of three categories of 11 items.

Table 3.1: Cost of Hydrogen Production

Cost Item	Cost Structure
Equipment	Lithium battery
	Hydrogen production equipment
	Hydrogen compressor
Land and construction cost	Land
	Construction
Operation and maintenance	Electricity
	Raw water
	Cooling water
	Potassium hydroxide (KOH)
	Labour
	Maintenance

Source: Authors.

2.2. Hydrogen Transport Cost

Hydrogen production, liquefaction, liquid hydrogen tank trucks, and liquid hydrogen refuelling stations form a complete liquid hydrogen industry chain. To transport liquid hydrogen, an additional hydrogen liquefaction station must liquefy the gaseous hydrogen produced by the hydrogen plant. At present, the construction of China's civil liquid hydrogen plant is gradually taking shape, and the prospects are excellent. Liquid hydrogen tanker transportation refers to cooling hydrogen to –253°C, liquefying it, and then loading it into a low-temperature storage tank for transport. Due to the high mass density of liquid hydrogen (70.6kg/m^3), the single transport volume of liquid hydrogen tank trucks can reach more than 3,000 kg, which has higher transportation efficiency than long-tube trailers.

For storage and transportation, we need to discuss different storage and transportation methods, which include fixed and variable costs. Table 3.2 shows that the cost of liquid hydrogen transportation is divided into two parts: the transport of liquid hydrogen tankers in liquefaction stations.

Table 3.2: Cost of Liquid Hydrogen Transportation

Cost Item	Cost Structure
Liquefaction station liquefaction	A one-time investment in liquefaction equipment (including land and construction costs)
	Liquid nitrogen cost
	Liquefaction electricity
	Operator
	Labour cost
	Maintenance fees
Liquid hydrogen tanker transportation	Tanker depreciation
	Labour cost
	Vehicle insurance
	Maintenance fee
	Fuel costs
	Tolls

Source: Authors.

A pipeline system is built underground in pipeline transport, suitable for large-scale and long-distance transport of hydrogen. Pipeline transport efficiency is high, but its initial construction cost is high. The total mileage of China's hydrogen pipeline is about 400 km, mainly distributed in the Bohai Bay, Yangtze River Delta, and other places. Pipeline transport is more suitable for fixed end users, such as hydrogen production plants and hydrogen gate stations.

Table 3.3: Cost Items for Hydrogen-Dedicated Pipeline Transportation

Mode	Cost Item
Exclusive pipeline transportation	Pipeline depreciation
	Maintenance and management fees
	Labour cost
	Compress electricity
Hydrogen transport	Pipeline usage fee
	Separation and purification costs

Source: Authors.

3. Potential Project Analysis

In Guangdong, mainly in Foshan and Yunfu, hydrogen energy supply is primarily hydrogen production from fossil fuels and industrial by-products. These emit greenhouse gases and produce less green hydrogen supply, which do not meet the requirements of sustainable development. Considering the current shortage of hydrogen energy supply in Guangdong province, renewable hydrogen production in other provinces can reduce the pressure on the ecological environment, provide green power to Guangdong, and boost its economy. This chapter discusses the renewable resource endowments of the neighbouring provinces of Guangdong, and the preliminary formulation of local hydrogen sources.

3.1. Distribution of Renewable Energy Resources around Guangdong

This section introduces the endowment and consumption of surrounding renewable resources and looks for areas with abundant renewable resources to meet the supply of green hydrogen in Guangdong.

3.1.1. Endowment of renewable resources with tolerable reserves

The average annual wind speed at the height of 70 m in China is 5.5 m/s. It can reach 6 m/s in central and southern Ningxia, northern Shaanxi, western and northern Gansu, most of the Western Sichuan Plateau, central and eastern Yunnan–Guizhou Plateau, Guangxi and coastal areas, and most of central and southern China. It can reach 5 m/s in most mountainous areas such as the southwest. The average wind power density of 70 m is 232.4 w/m^2 in the western Sichuan Plateau and Yunnan–Guizhou Plateau ridge areas, central and western Guangxi. It exceeds 300 w/m^2 in other places and can reach 200 w/m^2 in the eastern and coastal areas and central mountainous areas.

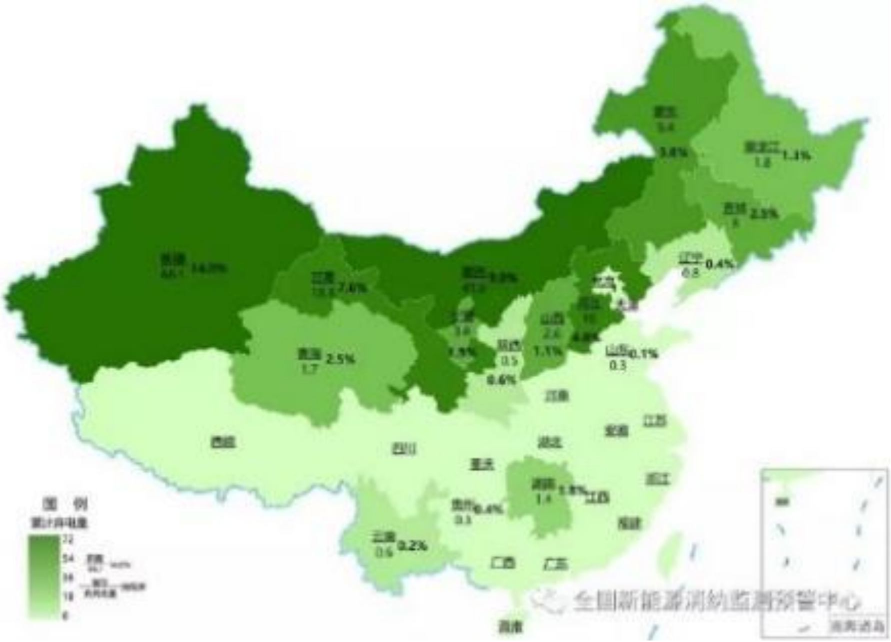
The total solar radiation of the national land average horizontal plane is 1,470.5 kWh/m^2, of which 1,400–1,750 kWh/m^2 is in western Sichuan, most of Yunnan, and Hainan, and 1.050–1.400 kWh/m^2 is in Jiangnan and most of South China (China Meteorological Administration’s Wind and Solar Resources Assessment Center, 2019).

Guangdong's surrounding provinces have acceptable wind and solar resources, while offshore wind power resources are relatively good.

3.1.2. Consumption of wind power and photovoltaic (PV) power generation

In 2019, the national average annual wind power utilisation rate and PV power utilisation rate were 96% and 98%, respectively, an increase of 3.0 and 1.0 percentage points year on year. As of the end of December, the cumulative abandonment of wind power (100 million dry watt-hours) and wind abandonment rate in various places are shown in Figure 3.1. And the cumulative solar power generation (100 million dry watt-hours) and the rate of abandoned solar energy in each region are shown in Figure 3.2. Around Guangdong, Hunan, Guizhou, and Yunnan provinces have wind abandonment, and only Yunnan has a small amount of solar power abandonment.

Figure 3.1: Cumulative Wind Abandonment Volume (100 million kWh) and Wind Abandonment Rate in All Regions of China, 2019



Source: China New Energy Consumption Early Warning Center (2020).

Figure 3.2: Cumulative Solar Power Abandonment Volume (100 million kWh) and Wind Abandonment Rate in All Regions of China, 2019

Source: China New Energy Consumption Early Warning Center (2020).

In the first and second quarters of 2020, China's overall consumption and utilisation of new energy continued to improve. Its abandoned wind power was 9.53 billion kWh, and wind power utilisation rate was 96.1%, up 0.8 percentage points year on year. The PV power consumption was 2.78 billion kWh, and the utilisation rate of PV power generation was 97.9%, up 0.3 percentage points year on year.

Figure 3.3 shows the cumulative curtailment of wind power (100 million kWh) and wind curtailment rate in various regions. The cumulative solar power generation (100 million dry watt-hours) and the rate of abandoned solar energy in each region are shown in Figure 3.4.

The consumption of new energy in neighbouring provinces of Guangdong is similar to that in 2019.

Figure 3.3: Cumulative Wind Abandonment Volume (100 million kWh) and Wind Abandonment Rate in All Regions of China, January–June 2020

Source: China New Energy Consumption Early Warning Center (2020).

Figure 3.4: Cumulative Solar Power Abandonment Volume (100 million kWh) and Wind Abandonment Rate in All Regions of China, January–June 2020

Source: China New Energy Consumption Early Warning Center (2020).

In conclusion, Guangdong's surrounding provinces have a relatively good wind power consumption and PV power. But Hunan and Yunnan have wind abandonment, and Guizhou and Yunnan have solar abandonment.

3.2. Potential Hydrogen Source Points

Based on the endowment of renewable resources in the surrounding provinces of Guangdong, four potential sources of hydrogen will be objectively proposed. Most regions surrounding Guangdong have included them, which will diversify the hydrogen sources exported to Guangdong. In terms of types, there are renewable energy hydrogen production projects planned by the local government and diversified types of resources that have not yet been fully utilised and are difficult to absorb.

Jiangxi Taihe County Wind Power Hydrogen Production Project. Jiangxi is in south-eastern China, on the south bank of the middle and lower reaches of the Yangtze River. It belongs to the East China region, and the south is connected to Guangdong. In December 2019, the Jiangxi Provincial Energy Bureau approved the 30 MW decentralised wind power hydrogen production project in Taihe County, Jiangxi. It is the only renewable energy hydrogen production project in the surrounding provinces of Guangdong and one of the potential hydrogen sources for hydrogen production to Guangdong.

Fujian offshore wind power hydrogen production. Fujian is in the south-eastern part of China, connected to Guangdong Province in the southwest. Fujian vigorously plans offshore wind power, an excellent source of electricity for hydrogen production by electrolysis of new energy sources. At the same time, it is close to Guangdong. Therefore, a hydrogen production station built in Fujian to produce hydrogen will be a potential source for hydrogen production in Guangdong.

Guangxi offshore wind power hydrogen production. Guangxi is in the western part of South China. The vigorous development of onshore wind power is the energy support for Guangxi's development of renewable energy hydrogen production. It is also a potential source for hydrogen production and transportation to Guangdong.

Hunan absorbs insufficient wind power photoelectric hydrogen production. Table 3.4 shows the status of wind and light abandonment in the neighbouring provinces of Guangdong.

Table 3.4: Cumulative Solar Power and Wind Abandonment Volume (100 million kWh) and Wind Abandonment Rate in All Regions of China

	Wind Power		Solar Power	
June 2020	Hunan 2.5 5.2%	Yunnan 1.4 0.9%	Guizhou 0.2 1.1%	Yunnan 0.2 0.6%
March 2020	Hunan 1.4 6.7%	Yunnan 1.6 1.8%	Guizhou 0.4%	Yunnan 0.1 0.7%
December 2019	Hunan 1.4 1.8%	Yunnan 0.6 0.2%	Guizhou 0.1 0.4%	Yunnan 0.2 0.4%
September 2019	Hunan 1.4 2.4%	Yunnan 0.6 0.3%	Guizhou 0.1 0.5%	Yunnan 0.1 0.3%
June 2019	Hunan 1.1 2.9%	Yunnan 0.5 0.7%	Guizhou 0.1 0.7%	Yunnan 0.1 0.3%
March 2019	Guizhou 0.3 1.3%	Yunnan 0.3 0.3%	Guizhou 0.1 1.4%	Yunnan 0.02 0.2%

Source: China New Energy Consumption Early Warning Center (2020).

In southern China, Hunan and Yunnan have wind abandonment, while Yunnan and Guizhou have light abandonment; both regions are close to Guangdong (Table 3.4).

The conversion of renewable electricity in Hunan, Yunnan, and Guizhou provinces, which have consumption problems, into hydrogen energy is a potential source for hydrogen production and transmission to Guangdong.

4. Case Analysis

Since the calculation method in the four cases is the same, the detailed calculation process of Fujian is presented. The calculation results of other cases are shown in the form of tables.

4.1. Case Description

This section briefly describes the case background and actual situation and makes basic assumptions about the proposed technical approach.

4.1.1. Jiangxi case

In December 2019, the Jiangxi Provincial Energy Bureau approved the Nanxi Distributed Wind Power Hydrogen Production Project in Taihe County, one of the projects with the fastest progress in renewable energy hydrogen production around Guangdong. Therefore, we selected this project as the hydrogen source in our case, and hydrogen was transported to Foshan.

The distance from Nanxi, Jiangxi to Foshan, Guangdong is more than 500 km, far beyond the application range of high-pressure gas hydrogen for more than 400 km.

Therefore, high-pressure gas was not considered in this case. Due to the limited production capacity of the 30 MW hydrogen production project, the daily production is about 12.36 t/day. If pipeline transport is used, its utilisation rate will be too low.

Therefore, this case does not consider the use of pipeline storage and transportation. Based on the above results, the Taihe 30 MW project in Jiangxi should adopt liquid hydrogen transportation.

4.1.2. Fujian case

Fujian province is on the southeast coast of China and connected to Guangdong province. Due to its coastal and long coastline characteristics, offshore wind power has great potential. As early as March 2017, the National Energy Administration agreed to the Fujian Provincial Offshore Wind Farm Project Planning Report. The reply stated that the total scale of offshore wind power planning in Fujian was 13.3 million kW, including 17 wind farms in the sea areas under the jurisdiction of Fuzhou, Zhangzhou, Putian, Ningde, and Pingtan. By the end of 2020, the installed scale of offshore wind power in Fujian province will reach more than 2 million kW; by the end of 2030, it will be more than 3 million kW. Analysis of the case of Fujian revealed it was utilising the local offshore wind power resources to produce hydrogen and transport to Guangdong. The total cost was calculated, including the entire process of hydrogen production and transportation.

4.1.3. Guangxi case

In 2011, the Guangxi Electric Power Design Institute made a preliminary plan, predicting that offshore wind power development capacity would be no less than 30 GW. On 6 January 2021, the construction of the first project in Guangxi officially started in Qinzhou. The initial stage was to build a standardised offshore wind farm with a capacity of 10 million kW, generating nearly 35 billion kWh of electricity annually. Hydrogen production under Guangxi's high-quality offshore wind power resources is a potential hydrogen source point. Presently, there is no planned offshore wind power hydrogen production project in Guangxi, so we have built a virtual hydrogen production station, referring to Jiangxi and planning to to set different power in contrast to Fujian. We assume that the Guangxi hydrogen production station is in Qinzhou, and the hydrogen production power is 40 MW. In terms of transportation mode, similar to the Jiangxi project, more than 590 km is not applicable to gas and hydrogen transport. Therefore, we will carry out the calculation of pipeline and liquid hydrogen. Since the west–east gas transmission pipeline runs from Guangdong to Guangxi, it cannot transport hydrogen from Guangxi to Guangdong; thus, only exclusive pipelines are considered.

4.1.4. Hunan case

In 2019, 140 million kWh of wind was abandoned, with a wind abandonment rate of 1.8% in Hunan. So, we would like to use the wind curtailment in Hunan to imagine a hydrogen production project, and then analyse what kind of storage and transportation would be suitable.

Like Jiangxi, due to the long distance and the low daily hydrogen production capacity, we determined that the high-pressure gas and pipeline storage and transportation are not suitable. Thus, we chose liquid hydrogen storage and transportation as the final transport mode.

4.2. Case Calculation

The four cases discussed in this chapter adopted a similar calculation method. Thus, only the Fujian case is described in detail.

4.2.1. Scenario hypothesis

Since Fujian province does not have clear and indexable documents indicating that offshore wind power is used to produce hydrogen, this case for conservatism assumes that 10% of offshore wind power is used as renewable energy hydrogen production capacity, i.e. 200 MW.

Due to the scattered distribution of offshore wind farms in Fujian, we chose Fuzhou as the starting point for inter-provincial hydrogen energy storage and transportation and Foshan as the end point.

The distance between the two places is about 870 km. It is far beyond the scope of gas hydrogen storage and transportation (Section 2.2). Therefore, this case considered three storage and transportation methods: liquid hydrogen, exclusive pipeline, and HCNG with west–east gas pipeline.

4.2.2. Economic feasibility analysis

a) Hydrogen production cost estimation

Table 3.5 shows the pipeline's capacity, output, and power consumption, assuming the annual operation time is 8,000 h.

Table 3.5: 200 MW Hydrogen Production Capacity, Output, and Power Consumption

Item	Parameter
Hydrogen production capacity (MW）	200.00
Production capacity (m^3/h）	41,538.59
Annual output (ten thousand m^3/year）	33,230.87
Annual output （t/year）	29,670.42
Power consumption （ten thousand kWh/year）	160,000.00
Power consumption（ten thousand kWh/d）	438.36
Daily output （t/d）	82.42

Source: The authors

The cost of hydrogen production from renewable energy mainly arises from land lease costs, plant construction costs, equipment costs, O&M costs, and regular maintenance costs. According to the literature of Liu et al. (2019), land lease costs, plant construction costs, and equipment costs are directly related to the production capacity.

Assuming that the price of land in Fujian is 200 yuan/m^2, the construction period of the hydrogen plant is 1 year, and the construction cost is 71,300 yuan/MW. The equipment maintenance cycle is 5 years. The construction cost of 200 MW hydrogen production cost is shown in Table 3.6.

Table 3.6: 200 MW Hydrogen Production Cost

Item	Cost (million yuan)
Land price	8.00
Construction cost	14.26
Li battery price	37.32
Hydrogen production equipment price	353.08
Hydrogen compressor price	83.08
5th year overhaul cost	35.31
Battery replacement cost	37.32
Total cost	**568.36**

Source: Authors.

The O&M costs of renewable energy electrolysis of hydrogen production mainly consist of electricity costs, raw water, cooling water, potassium hydroxide (KOH), and labour costs. According to a new report issued by the Electricity and Renewable Energy Business Unit (formerly MAKE), 'China's Offshore Wind Power Market Outlook', with the continuous development of offshore wind power technology, the average domestic offshore wind power LCOE (levelized cost of energy) will drop to 0.41 yuan/kWh. Therefore, the offshore wind power rate, in this case, is 0.41 yuan/kWh and the offshore wind power rate is 0.41 yuan/kWh. Table 3.7 lists the cost of hydrogen production at 200 MW, according to relevant data supplied by Suzhou Jingli Hydrogen Production Equipment Limited company. The equipment is depreciated for 10 years.

Table 3.7: 200 MW Hydrogen Production Cost

Cost Item	Unit Price	Unit	Consumption (per m^3 of hydrogen)	Unit	Cost (yuan/N m^3)
Electricity	0.41	yuan/kWh	4.8148	kWh	1.9741
Raw water	3.5	yuan/t	0.00117	t	0.0041
Cooling water	0.25	yuan/t	0.001	t	0.0003
Potassium hydroxide (KOH)	10	yuan/kg	0.0006	kg	0.006
Annual depreciation expense			4957.361	ten thousand yuan/year	0.1492
Annual maintenance cost			374.9252	ten thousand yuan/year	0.0113
Overhaul costs			726.2753	ten thousand yuan/year	0.0219
Other operating expenses			437.3283	ten thousand yuan/year	0.0132
Wage	7.5	ten thousand yuan/year	2	person/MW	0.0903
Total					**2.2701**

Source: Authors.

In summary, the unit cost of the 200 MW offshore wind power hydrogen production in Fujian province is about 2.27 yuan/Nm^3, and the total cost is about 75,400 yuan.

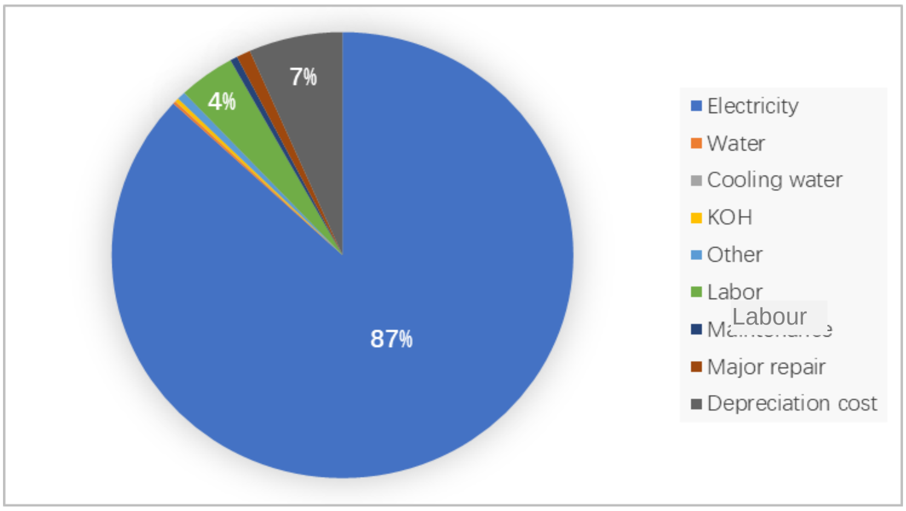
Table 3.8 summarises the cost items of hydrogen production. Figure 3.5 shows the proportion of each part.

Table 3.8: Summary of Hydrogen Production Cost

Cost Item	Lower Item	Cost (yuan/kg)
Electricity	Electricity	22.18
O&M	Water	0.05
	Cooling water	0.003
	Potassium hydroxide	0.07
	Other	0.15
	Labour	1.01
	Maintenance	0.13
	Major repair	0.25
Equipment and construction	Depreciation cost	1.68
SUM		**25.51**

Source: Authors.

Figure 3.5: Proportion of the Hydrogen Production Cost



Source: Authors.

The offshore wind power price accounts for 87% of the total hydrogen production cost. Therefore, if investors want to reduce the total cost of producing hydrogen, they must adopt relevant measures to reduce the price of offshore wind power, for example, by using the floating offshore wind power to reduce the construction cost of offshore wind farms, etc.

b) Storage and transportation cost estimation

1) Liquid hydrogen storage and transportation

First, liquid hydrogen storage and transportation must choose the process and equipment for hydrogen liquefaction. For the 200 MW capacity the Claude cycle (hydrogen expansion refrigeration cycle) method is used because its daily output exceeds 80 t. This liquefaction method requires equipment, such as a hydrogen compressor, pre-cooling compressor, cold box, control system, and storage tanks. At the same time, according to the research results of Linde and the Technical University of Munich, the daily output of this project is 50–150 t/d, so the liquefied electricity fee is 6.9 kWh/kg. The equipment was depreciated for 10 years and referred to the actual parameters of Zhangjiagang Hydrogen Cloud New Energy Research Institute Co., Ltd. Table 3.9 records the liquefaction costs.

Table 3.9: Hydrogen Liquefaction Costs

Cost Item	Lower Item	Cost（yuan/kg)
Liquefaction	Electricity charge	4.49
	Liquefaction equipment	1.93
	Liquid nitrogen	3.64
	Maintenance	0.25

Source: Authors.

It is necessary to consider truck depreciation, labour, insurance, maintenance, fuel, and tolls in storing and transporting liquid hydrogen. According to the auxiliary data from Foshan Gas and CLP Fengye and other industry information (Table 3.10), combined with the production capacity, the storage and transportation link cost can be calculated and recorded (Table 3.10).

Table 3.10: Auxiliary Data of Hydrogen Storage and Transportation

Items	Amount	Unit
Truck price	4,500,000	yuan/set
Depreciation period	10	year
Single effective transportation volume of tanker	4,000	kg
Workday	360	d/year
Working hours per day	12	h
Average speed of tanker	50	km/h
Fuel consumption per hundred kilometres	28	L
Diesel price	6.4	yuan/L
Vehicle insurance	25000	yuan/year
Maintenance fee	0.3	yuan/km
Tolls	0.6	yuan/km
Staff costs	100,000	yuan/person/year
Number of people	4	person
Hydrogen charging and unloading time	2	h

Source: Authors.

Table 3.11: Liquid Hydrogen Transport Cost

Cost Item	Lower Item	Cost (yuan/kg)
Transportation	Depreciation cost	0.96
	Labour cost	0.85
	Insurance	0.05
	Maintenance	0.13
	Oil	0.78
	Toll	0.26

Source: Authors.

Adding the cost of the liquefaction and the transportation links can result in a unit cost of 13.33 yuan/kg for the liquid hydrogen storage and transportation method of 200 MW offshore wind power generation in Fujian, and a total cost of 395.51 million yuan/year.

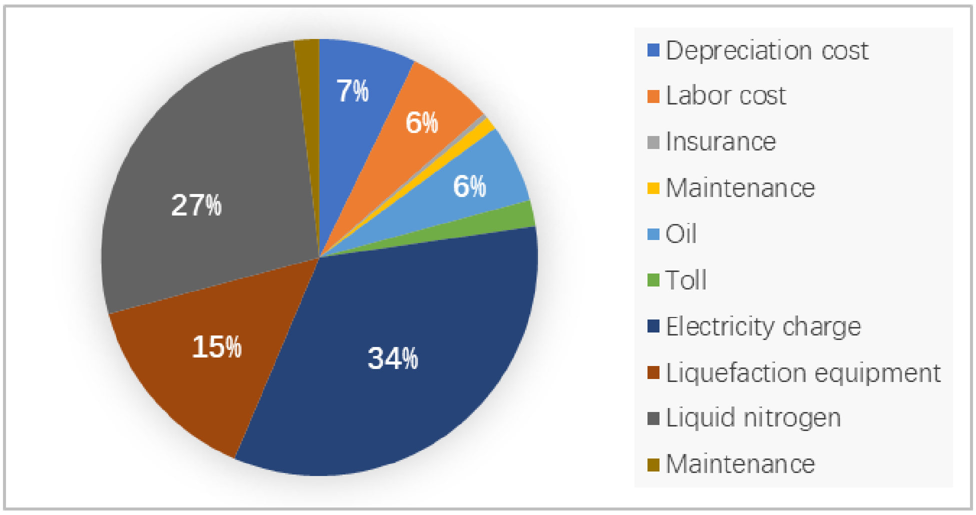
Table 3.12 summarises the liquid hydrogen storage and transportation cost items.

Table 3.12: Summary of Liquid Hydrogen Storage and Transport Costs

Cost Item	Cost (yuan/kg)
Transportation	3.03
Liquefaction	10.31
SUM	**13.34**

Source: Authors.

Figure 3.6: Proportion of Liquid Hydrogen Storage and Transportation



Source: Authors.

The price of liquefied electricity and liquid nitrogen has a more significant impact on the storage and transportation of liquid hydrogen. Therefore, if investors want to reduce costs, they must reduce liquefied electricity bills and liquid nitrogen use.

2) Exclusive pipeline storage and transportation

Considering the large capacity in this case and the long distance from Fuzhou to Guangzhou, we can consider the construction of hydrogen storage and transportation pipeline The major cost items include pipeline construction depreciation costs, maintenance and management costs, labour costs, and compressed electricity costs for compressing hydrogen to the pressure applicable to pipeline transportation. According to the recommended data from the Foshan Environmental Energy Institute, the diameter of the dedicated pipeline is assumed to be 406 mm, the construction cost is 5 million yuan/km, and the compressed delivery pressure is 4 MPa. Table 3.13 shows specific auxiliary data assumptions.

Table 3.13: Exclusive Pipeline Storage and Transportation Auxiliary Data

Items	Numerical Value	Unit
Pipe diameter	406	mm
Pressure	4	Mpa
Workday	360	d
Construction cost per unit length	5	million/km
Service life	20	yr
Maintenance and management costs	8%	(a)
Compression power consumption	0.6	kWh/kg
Electricity price	0.65	yuan/kWh
Wage	0.1	million yuan/person/yr (b)

[a] Operation, maintenance, and management costs mainly include the O&M of various equipment and installations of gas transmission stations, pipeline inspection, evaluation and repair, etc.

[b] One gas transmission station is set up every 100 km. Each gate station requires 10 people and an additional 2 people every 10 km.

Source: Authors.

The auxiliary data can be used to calculate the exclusive pipeline storage and transportation costs. The total unit cost is 9.2 yuan/kg, and the total cost is 27,297 yuan/year. Table 3.14 records the various costs.

Table 3.14: Exclusive Pipeline Storage and Transportation Costs

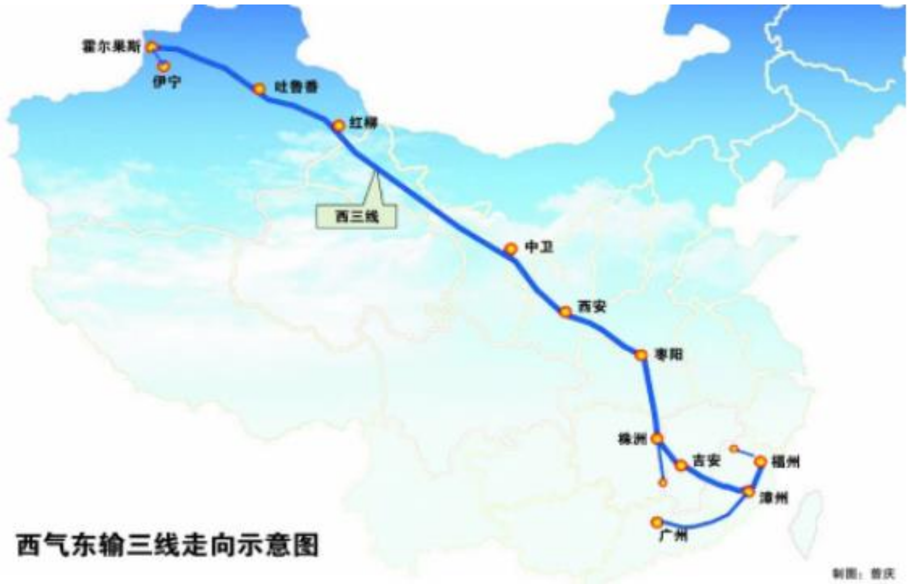
Cost Item	Lower Item	Cost (yuan/kg)
Compression	Electricity	0.39
Fixed charge	Depreciation cost	7.33
	Labour	0.89
	Maintenance	0.58
SUM		**9.2**

Source: Authors.

3) HCNG pipeline storage and transportation

Since Fuzhou and Guangzhou are on the east line of the west–east gas pipeline, they may use this gas pipeline to store and transport natural gas mixed with hydrogen. Zabrzeski et al. (2019) pointed out that x80 steel pipe material is safe and technically feasible when the HCNG ratio is about 5%. According to the data, the designed annual transportation volume of the Fuzhou–Guangzhou West–East Gas Pipeline is 5.8 billion cubic metres, and the hydrogen mixing rate of the 200 MW capacity is 5.73%, which is theoretically and technically feasible.

Figure 3.7: Diagram of West–East Gas Transmission Line Three



Source: China Railway Huatie Engineering Co. Ltd., Group http://ztht.crec.cn/.

For the storage and transport of natural gas mixed with hydrogen, the main cost items considered are pipeline usage and terminal natural gas hydrogen separation costs. After calculating the unit cost at 6.3 yuan/kg, the total annual cost is 186.92 million yuan/year (Table 3.15).

Table 3.15: Storage and Transportation Costs of Hydrogen-Mixed Pipeline

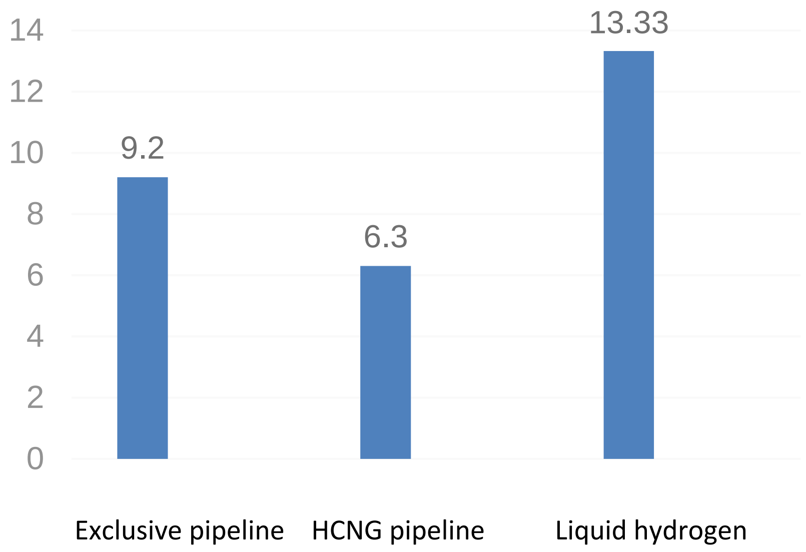
Cost Item	Cost (yuan/kg)
Pipeline toll	1.85
Refining	4.47
SUM	**6.3**

Source: Authors.

c) Brief evaluation of project feasibility

The cost of HCNG pipelines is less than the storage and transportation of liquid hydrogen and exclusive pipeline, saving the most cost. Therefore, under the premise of ensuring safety and technical feasibility, HCNG pipelines should be adopted for storage and transportation. Figure 3.8 shows unit transport costs for the three modes of transport.

Figure 3.8: Cost Comparison of Three Transport Modes (Yuan/Kg)

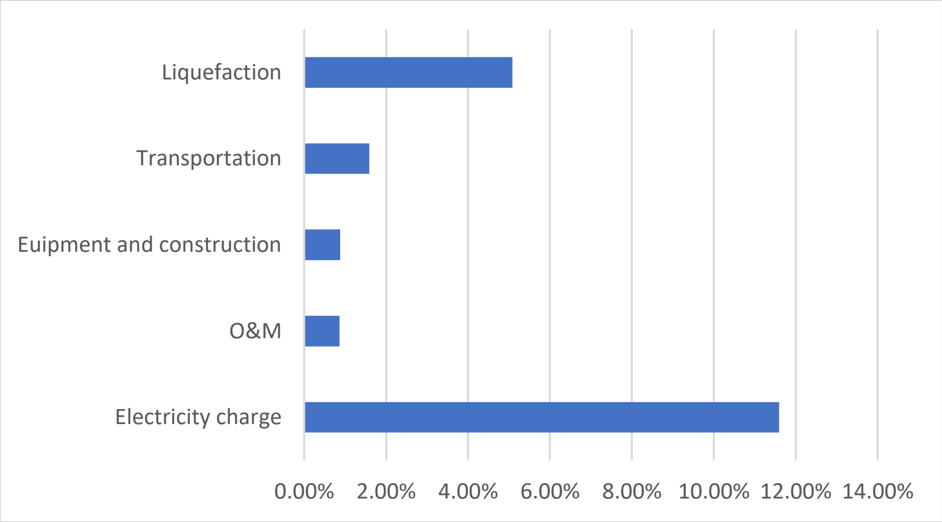


Source: Authors.

d) Sensitivity analysis

List the various costs and observe their impact on the total cost by applying a 20% change, and we can get the main factors affecting the total cost.

Figure 3.9: Sensitivity Rates of Different Parameters



Source: Authors.

Figure 3.9 shows that this project's hydrogen production electricity fee most significantly impacted total costs, followed by the liquefaction fee. Thus, it is necessary to find cheaper renewable resources to reduce the total cost while promoting the development and application of liquid hydrogen technology to reduce the liquefaction cost.

4.3. Case Result

4.3.1. Calculation result

The calculation method of the other three cases is the same as that of Fujian, but their detailed calculation process will not be described. Table 3.16 shows the calculation results.

Table 3.16. Results of the Four Cases, Summary

Case	Jiangxi	Guangxi	Hunan	Fujian
Route	Gangzhou–Foshan	Qinzhou–Foshan	Yongzhou–Foshan	Fuzhou–Foshan
Distance (km)	579	594	495	870
Power (MW)	30	40	7.875	200
Electricity cost of hydrogen production (yuan/kWh)	0.25	0.41	0.21	0.41
Hydrogen production cost (yuan/kg)	16.85	25.51	13.03	25.51
Liquid hydrogen cost (yuan/kg)	15.05	15.15	16.95	13.33
Pipeline (exclusive) (yuan/kg)	39.43	30.42	/	9.2
Pipeline (with NG) (yuan/kg)	/	/	/	6.3
SUM (yuan/Kg)	**31.9**	**40.66**	**30.71**	**31.81**

Project Type	Wind power	Offshore wind power	Wind curtailment	Offshore wind power

Source: Authors.

4.3.2. Analysis of results

Based on the preceding analysis, we can draw the advantage of developing hydrogen in Guangdong. Guangdong has a superior geographical location, convenient transportation, and accessible information. Guangdong's industrial chain is complete, and the hydrogen energy industry base, large-scale demonstration of fuel-cell vehicles, and hydrogen refuelling network planning are relatively mature. The province has made early progress in industrialisation, has high demands for environmental protection, and has a good acceptance of hydrogen energy by the private sector. Guangdong has a sound economic foundation, and the market has a high demand for hydrogen energy. Governments at all levels in Guangdong province strongly support the development of hydrogen energy. The province has formulated a new energy industry development strategy.

Domestic and foreign countries attach importance to developing the hydrogen energy industry and can learn advanced technology and excellent experience. The state has deployed important strategies in Guangdong, such as the full implementation of the Guangdong–Hong Kong–Macao Greater Bay Area and the ‘One Nuclear, One Belt, One District’ regional development strategy. The Guangdong region has gathered a group of leading domestic hydrogen energy companies and R&D innovation platforms. It has substantial competitive advantages in hydrogen energy technology, talents, and construction of hydrogen refuelling plural. The Chinese central government has proposed a carbon-neutral goal.

Based on the preceding analysis, we can draw the disadvantage of developing hydrogen in Guangdong. The level of hydrogen infrastructure is low. The number of leading enterprises is small, the R&D innovation platform is insufficiently supported, high-end innovative talents are lacking, and some core components are limited by foreign technology. Guangdong's new energy endowment is average.

The hydrogen energy industry has a high demand for funds and high financial risks. The standards are not uniform across the country, and there is the phenomenon of homogeneity. Hydrogen energy is still expensive. The increase in international trade barriers restricts the development of foreign markets. Globally, the overall hydrogen energy technology development.

Based on the above analysis, we can draw some suggestions:

- Clarify the development path of the hydrogen energy industry.
- Implement a hydrogen source guarantee.
- Make full use of renewable energy.
- Make full use of the advantages of industrial agglomeration. Strive for industry demonstration.
- Introduce talents and accelerate the R&D of core technologies.
- Do an excellent job in policy linkage and launch demonstration applications at an appropriate time.
- Improve policy support.
- Pay attention to coordinated development.
- Do overall planning and coordinated development to avoid invalid competition.
- Strengthen international cooperation in the hydrogen energy industry.
- Guarantee the investment and financing of hydrogen energy.

5. Conclusions

The interprovincial gas–hydrogen transportation method is not applicable because the distance exceeds 150 km. In the case of small transportation volume, liquid hydrogen transportation is better than pipeline transportation. For a large amount, if hydrogen-mixed pipeline is to be used, the transport capacity and distance must be considered.-. The two methods of liquid hydrogen storage and transportation with pipeline storage and transportation should be compared. When there is a natural gas transmission pipeline between the start and end of the storage and transport because the cost of hydrogen-added storage and transport is small, transport by hydrogen-mixed pipeline can be considered. However, safety and technical feasibility must be guaranteed.

After preliminary feasibility and case analyses, a feasible plan is to transport hydrogen energy from other provinces to Guangdong. In the long run, the price of hydrogen energy can reduce energy consumption by lowering renewable energy power generation costs, improving liquefaction technology, and increasing transportation sharing. Pipeline costs are used to improve the economics of green hydrogen in other provinces; case-based, small-scale transportation will result in low pipeline utilisation and high transportation costs. If the transportation volume increases, the unit transportation cost decreases. From a cost perspective, the cost of hydrogen production from renewable energy sources to Guangzhou may be higher than the hydrogen production cost from local natural gas. However, given that it can solve the high demand for hydrogen energy in Guangdong province, there is still value for consideration.

Hydrogen energy is the most promising clean energy and the driving force and future of sustainable social development. The hydrogen energy industry has entered the early stage of commercialisation worldwide. Hydrogen energy development in China has received extensive attention, but faces many challenges. Key technologies must be broken through, and costs need to be greatly reduced. As a pioneer in the development of hydrogen energy, Guangdong will exert efforts in energy conservation and emission reduction and contribute to the national carbon emission target.

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