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# Hydrogen Sourced from Renewables and Clean Energy: A Feasibility Study of Achieving Large-scale Demonstration

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**Hydrogen Sourced from Renewables and Clean Energy:**
**A Feasibility Study of Achieving Large-scale Demonstration**

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# Foreword

Leading economies around the world, including the United States, China, Japan, as well as the European countries, have announced or upgraded their plans for hydrogen in recent years, targeting several thousands of hydrogen refueling stations and millions of fuel cell vehicles. China is also emerging as one of the leading markets for hydrogen energy and fuel cell technologies.

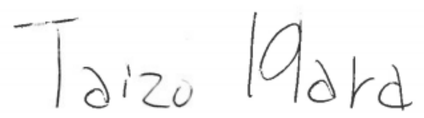
However, it is surprising to find that most of the demonstration projects of hydrogen and fuel cell applications currently source hydrogen from conventional natural gas reforming and petroleum refineries' by-products in China. Most of the demonstration projects of fuel cell electric vehicles in the country are actually running on the supply of hydrogen from fossil fuel sources. There are at least two main barriers to the development of green or clean hydrogen energy.

First, there is a lack of comprehensive and valid feasibility studies on the potential renewable or clean energy for hydrogen projects, as well as their associated energy infrastructure networks for transportation and distribution. Second, there is a lack of consensus amongst stakeholders as to who should do what to resolve the current institutional and regulatory barriers.

Hence, feasibility studies and implementation plan studies are needed to help accelerate the development of large-scale green or clean hydrogen energy demonstration. This project, titled 'Hydrogen Sourced from Renewables and Clean Energy: A Feasibility Study of Achieving Large-scale Demonstration', supported by Economic Research Institute for ASEAN and East Asia (ERIA), is timely therefore and will deliver substantial outcomes to support relevant policymaking, considering the strategic importance of developing hydrogen, especially green hydrogen in China under the country's carbon neutrality target and the 14th Five-Year Plan.

The study consisted of sub-projects covering technical, economic, financial, institutional, regulatory, and policy issues related to enabling large-scale hydrogen energy demonstration projects in China. Feasibility studies of the selected demonstration projects were conducted in collaboration with several industrial and academic entities. In the implementation plan of the feasibility studies, findings from the sub-projects provided a basis for discussion in interviews and workshops held amongst industry players, government bodies, and academic researchers. The goal of the interviews and workshops was to identify key barriers as well as proper solutions, together with an agenda for actions necessary to realise the selected demonstration projects.

The sub-projects were conducted by a working group made up of of experts from both academia and industry, such as the Institute of Energy Economics, Japan (IEEJ); China Hydrogen Alliance (CHA); University of Technology Sydney; Huazhong University of Science and Technology; Foshan University of Science and Technology; Dalian University of Technology; Grantham Institute of Imperial College London; Tokai University, Japan; Singapore University of Social Sciences; Green World Low-carbon Economy & Technology Center, China; China Energy Engineering Group Co. Ltd (CEEC); and Foshan Institute of Environment and Energy, China.



Taizo Hara

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# Table of Contents

# List of Figures

# List of Tables

# Abbreviations and Acronyms

| | |
|---|---|
| ASEAN | The Association of Southeast Asian Nations |
| AC | absorption chiller |
| AC | alternate current |
| AEC | alkaline water electrolysis |
| ANSI | American National Standards Institute |
| APS | Alternative Policy Scenario |
| ASME | The American Society of Mechanical Engineers |
| ATC | annual total cost |
| BAU | Business-As-Usual |
| Bcm | billion cubic meter |
| BG | biomass gasification |
| BloombergNEF | Bloomberg New Energy Finance |
| CAISO | California Independent System Operator |
| CAPEX | Capital Expenditure |
| CCGT | combined cycle gas turbine |
| CCHP | combined cooling, heating and power |
| CCS | carbon capture and storage |
| CCS | carbon capture and sequestration |
| CCUS | Carbon Capture, Usage, and Storage |
| CDE | carbon dioxide emission |
| CG | coal gasification |
| CHA | China Hydrogen Alliance |
| CHEI | China's Hydrogen Energy Industry |
| CLP | China Electronics Technology Group Corporation |
| CLS | Chemical Looping Reforming |
| CNIS | China National Institute of Standardization |
| CNY | Chinese Yuan |
| $CO_2$ | Carbon Dioxide |
| COM | hydrogen compressor |
| COP | coefficient of performance |
| COP | the Conference of the Parties |
| CSA | Canadian Standards Association |
| DC | direct current |
| DNV | Det Norske Veritas |
| DNV GL | Det Norske Veritas Germanischer Lloyd |
| EAS | East Asia Summit |
| EQ | ecosystem quality |
| ERIA | Economic Research Institute for ASEAN and East Asia |
| EU | European Union |

| | |
|---|---|
| EUETS | European Union Emissions Trading System |
| FCEV | fuel-cell electric vehicle |
| FCH2JU | Fuel Cells and Hydrogen 2 Joint Undertaking |
| FCV | Fuel cell vehicles |
| FEC | fossil energy consumption |
| FF | Fossil Fuel |
| GCGC | Green Credit Guarantee Corporation |
| GEIDCO | Global Energy Interconnection Development and Cooperation Organization |
| GHG | greenhouse gas |
| GJ | gigajoule |
| GO | guarantees of origin |
| GW | gigawatt |
| $H_2$ | hydrogen |
| HCNG | hydrogen enriched compreesed natural gas |
| HDV | Heavy-duty vehicle |
| HER | hydrogen evolution reaction |
| HETC | Hydrogen Energy Technical Committee |
| HFCP | Hydrogen and Fuel Cell Program |
| HH | ecosystem quality |
| HRSs | Hydrogen refueling stations |
| HySAFER | International Association for Hydrogen Safety |
| HySUT | Hydrogen Supply and Applied Technology Research Association |
| HyTReC | Hydrogen Energy Test and Research Center |
| IA-Hysafe | International Association for Hydrogen Safety |
| ICE | internal combustion engine |
| IEA | International Energy Agency |
| IRENA | International Renewable Energy Agency |
| ISES | International Solar Energy Society |
| ISO | International Organization for Standardization |
| JIS | Japanese Industrial Standards |
| JISC | Japanese Industrial Standards Committee |
| kg | kilogram |
| $kgH_2$ | kilogram hydrogen |
| km | kilometre |
| KOH | potassium hydroxide |
| kV | kilovolt |
| kW | kilowatt |
| kWh | kilowatt hour |
| kWh | kilowatt hours |
| LCA | life cycle assessment |
| LCOE | levelised cost of energy |

| | |
|---|---|
| LCOH | levelised cost of hydrogen |
| LEAP | Long-range Energy Alternative Planning System |
| m2 | square metre |
| MLIT | Ministry of Land, Infrastructure, Transport and Tourism, the Government of Japan |
| MSW | municipal solid waste |
| Mt | million tonne |
| Mt-C | million tonnes-carbon |
| Mt-$H_2$ | million tonnes-hydrogen |
| Mtoe | million tonnes of oil equivalent |
| MW | megawatt |
| NCV | net calorific value |
| NDRC | National Development and Reform Commission |
| NEA | National Energy Administration |
| NFPA2 | Technical specification for hydrogen energy |
| NG | natural gas |
| $Nm^3$ | normal cubic metre |
| $Nm^3/h$ | normal cubic metre per hour |
| NPV | Net Present Value |
| O&M | operation and maintenance |
| OER | oxygen evolution reaction |
| OPEX | Operating Expenditure |
| PEM | proton exchange membrane |
| PEM | Polymer electrolyte membrane |
| PEMFC | proton exchange membrane fuel cell |
| PGU | power generation unit |
| PV | solar photovoltaic |
| PV | photovoltaic |
| R&D | research and development |
| RD&D | Research Development and Demonstration |
| Rec | heat recovery system |
| RES | Renewable Energy Sources |
| RGGI | the Regional Greenhouse Gas Initiative |
| SAE | Society of Automotive Engineers |
| SDS | sustainable development scenario, one of the scenarios in the WEO |
| SGD | Singapore dollar |
| SMR | steam methane reforming |
| SOEC | solid oxide electrolysis |
| ST | solar thermal collector |
| STEPS | stated policy scenario, one of the scenarios in the WEO |
| SWOT | Strengths, Weaknesses, Opportunities, and Threats |
| TCH | Total cost of the Assessed H2 Production Routes |

| | |
|---|---|
| TFEC | total final energy consumption |
| toe | tonnes of oil equivalent |
| TWh | terawatt hour |
| USCAR | The United States Council for Automotive Research |
| USD | United States Dollar |
| USFA | United States Fire Administration |
| VRE | variable renewable electricity |
| WEO | World Energy Outlook, publication of IEA |
| WTW | well to wheels |

# Chapter 1
# Introduction

## 1. Background

In the past 2 years, the Economic Research Institute for ASEAN and East Asia (ERIA) has identified a significant potential for hydrogen energy supply and demand in the East Asian Summit (EAS) region. China is one of the biggest potential producers and consumers of hydrogen energy in the near future (ERIA, 2019).

As of May 2021, out of 34 Chinese provincial administrative regions, 18 (plus at least 22 municipal administrations) have published policies to develop hydrogen energy-related industries and infrastructure; this is complemented by 18 relevant policy documents issued by the central government.[1,2] Among the provincial and municipality administrations, Guangdong province issued the most policies.

There are currently over 8,000 fuel cell electric vehicles (FCEVs) operating in China, mostly supported by demonstration projects, together with over 80 hydrogen refueling stations (HRSs) (IEA, 2021). It is expected that the number of FCEVs will reach 1 million units and HRSs will increase to 1,000 units by 2030 (Li and Kimura, 2021).

Leading economies around the world have also announced or upgraded their plans about hydrogen in recent years, as summarised in Table 1 and Table 2.

**Table 1.1: Announced Plan/Estimation for Hydrogen Station Infrastructure Development**

| Country | 2020 | 2025 | 2030 |
|---|---|---|---|
| China | 100 stations | 300 stations | 1,000 stations |
| France | 100 stations (2023) | 355 stations | 1,000 stations (2028) |
| Germany | 100 stations | 400 stations | 1,000 stations |
| Japan | 160 stations | 320 stations | 900 stations |
| Rep. of Korea | 310 stations (2022) | N.A. | 1,200 stations |
| UK | 65 stations | 300 stations | 1,100 stations |
| US | 115 stations | 320–570 stations | 1,500–3,300 stations |

N.A. = not applicable.
Source: Li and Kimura (2021).

[1] Source: http://www.sohu.com/a/327206089_618917 (accessed 23 May 2021).
[2] Source: https://www.qianzhan.com/analyst/detail/220/210329-199cd898.html (accessed 23 May 2021).

**Table 1.2: Announced Plan/Estimation for Hydrogen Fuel Cell Vehicles**

| Country | 2020 | 2025 | 2030 |
|---|---|---|---|
| China | 5,000 FCEVs | 50,000 FCEVs | 1,000,000 FCEVs |
| Germany | 10,000 FCEVs | 100,000 FCEVs | 1,800,000 FCEVs |
| Japan | 40,000 FCEVs | 200,000 FCEVs | 800,000 FCEVs |
| Rep. of Korea | 80,000 FCEVs (2022) | N.A. | 6,200,000 FCEVs |
| US | 20,000 FCEVs | 90,000–200,000 FCEVs | 1,800,000–4,500,000 FCEVs |

FCEV = fuel cell electric vehicle, N.A. = not applicable.
Source: Li and Kimura (2021).

## 2. Research Questions: Barriers Faced in Developing Green or Clean Hydrogen Energy

However, it is surprising to find that most of these demonstration projects currently source hydrogen from conventional natural gas reforming and petroleum refineries' by-products. An ERIA study published in 2020 identified two main barriers to developing green or clean hydrogen energy. First, there is a lack of comprehensive and valid feasibility studies on the potential projects to produce hydrogen from renewable or clean energy sources, as well as their associated energy infrastructure network for transportation and distribution. Second, there is a lack of consensus among stakeholders regarding who should resolve the standing institutional and regulatory barriers to said projects. For example, in China, under the current regulations, power grid companies have no redundant capacity to transmit curtailed renewables, as well as nuclear energy to hydrogen production facilities near the demand market; neither do they have incentives to build dedicated new lines. Furthermore, the current power sector regulations in China do not allow onsite production of hydrogen at the renewable power stations, using the curtailed electricity.

Feasibility studies and implementation plan studies are thus called for to accelerate the development of large-scale green or clean hydrogen energy demonstration. Aiming at shaping a roadmap for stakeholders of hydrogen energy development, these studies collect information and ideas from field experts in industry, government, and academia to comprehensively identify solutions to both economic and non-economic barriers. By doing so, the studies significantly reduce the potential risks involved with the proposed large-scale renewable to hydrogen energy demonstration projects in China. They also serve to summarise the best practices and experience from existing and successful demonstrations and share the lessons in China as well as around the world.

## 3. Component Studies: Methodologies and Main Findings

This ERIA research project report covers the technical, economic, financial, institutional, regulatory, and policy issues related to enabling large-scale hydrogen energy demonstration projects in China. The research processes involve collaborations and interactions with industrial entities, government bodies, and research institutes in China, in order to identify key barriers as well as proper and practical solutions in the above-mentioned dimensions, and deliver a roadmap to realise large-scale green or clean hydrogen demonstration projects.

Chapter 2 is contributed by the Institute of Energy Economics, Japan, which provides ***a high-level outlook of the demand and supply of hydrogen as energy in China***, under the background of the carbon neutrality target recently announced by the Chinese government. Accordingly, this implies that the demand for hydrogen energy from China's road transport and power sectors will reach 58 Mtoe by 2040. On the supply side, it is estimated that green hydrogen produced using curtailed variable renewable energy could reach 140 Mtoe. Theoretically, then, green hydrogen alone has the potential to meet hydrogen energy demand in China, while the remaining potential capacity could be used to further decarbonise other sectors of the Chinese economy. However, such a vision depends on the micro-economics, namely in each hydrogen energy project, as well as how policies and institutions enable and facilitate such a transition.

Chapter 3 is contributed by a research team led by Prof. Long from Huazhong University of Science and Technology. It presents a ***technical and economic feasibility study of hydrogen sourced from renewables in Southern provinces*** such as Fujian, Jiangxi, Guangxi, and Hunan for supply to Guangdong province, an emerging demand center for hydrogen energy. It is found that small-scale liquefied hydrogen production, such as in the case of Hunan-Guangdong scenario, delivers the lowest supply cost. In the case of large-scale hydrogen production, such as in Fujian-Guangdong scenario, natural gas pipelines adapted for mixed hydrogen and natural gas offer the most cost-effective solutions. The cost of hydrogen supplied from these four provinces to Guangdong ranges between CNY31–41/kg, under the current circumstances.

Chapter 4 is contributed by a research team from Dalian University of Technology. It presents a study on the ***economic feasibility of a cooling - heating - power - hydrogen multi-generation***, applied in a specific case in an urban community of Dalian city of Liaoning province in China. The study found that the integration of renewables-to-hydrogen into a grid-connected Combined Heat and Power system could help minimise the latter's cost to meet the energy demand of the community. The costs of hydrogen production and delivery are US$2.48/kg and US$3. 35/kg, respectively, in such a case.

Chapter 5 is contributed by a research team from Guangdong Electric Power Design Institute of China Energy Engineering Group. It studies the ***technical and economic feasibility of hydrogen production from offshore wind power***, in the context of Guangdong province. The cost of hydrogen produced from offshore wind farms located in Guangdong and transported by pipeline to land ranges between CNY33–42/kg, after considering the government subsidy on offshore wind electricity at CNY0.45/kWh, about 50% of the actual cost.

Chapter 6 is contributed by a research team led by Prof. Tagizadeh-Hesary from Tokai University. This study addresses the financial feasibility of hydrogen energy projects in China to identify ***appropriate financing solutions***. Gradient sensitivity analysis was adopted to assess the impact of financial costs on the net present value of hydrogen energy projects. The method was applied to three hydrogen projects in Guangdong province (two cases) and Jiang Xi province (one case). It is found that lowering financing risk, for example, through green financing mechanisms, could improve profitability of hydrogen energy projects.

Chapter 7 is contributed by a research team lead by Dr. Sun, former executive director of the International Energy Forum. It surveys the current status, challenges, and opportunities of developing hydrogen energy in China. In doing so, lessons from leading economies around the world are also drawn. Correspondingly, a comprehensive set of ***policies and strategies*** are proposed to accelerate the development of hydrogen energy in China. Importantly, systematic demonstrations in various application fields, as well as the strategic importance of developing green hydrogen, were emphasised.

Chapter 8 is contributed by a research team lead by Dr. Wang from Green World Low-carbon Economy & Technology Center, China. It analyses the feasibility of large-scale development of the hydrogen energy industry in China from the perspective of ***safety laws and regulations***, some of which appear to be overly stringent, such as the restriction on the land property in the process of making hydrogen production. Some regulations need to be improved, such as the lack of regulatory requirements for long-distance hydrogen pipelines. International experience from the US, the European Union, Japan, and Republic of Korea is summarised. It is concluded that China should improve the top-level design as soon as possible and speed up the technical basic research to support the continuous improvement of safety standards, especially in the areas identified in this chapter.

Chapter 9 is contributed by a research team lead by Dr. Liu from Guohua Energy Investment Co., Ltd., a member of the China Hydrogen Alliance. It analyses ***key factors of the global green hydrogen standards***, and how to establish a quantitative evaluation system of low-carbon hydrogen, clean hydrogen, and renewable hydrogen by using life cycle assessment. The issue is essential in promoting the role of clean and green hydrogen and thus enabling carbon neutrality, which is the ultimate motivation of developing hydrogen energy.

Chapter 10 is contributed by a research team lead by Prof. Youngho Chang from Singapore University of Social Sciences. It ***estimates the potential of carbon emissions reduction that could be achieved*** if curtailed electricity from intermittent renewables in both the Association of Southeast Asian Nations (ASEAN) and EAS context by 2050. EAS consists of the 10 ASEAN countries, along with Australia, China, India, Japan, New Zealand, and Republic of Korea. Importantly, it is found that if carbon prices are higher than

US$20/tonne of $CO_2$, then producing hydrogen from curtailed electricity from renewables via electrolysis could be cost effective, even under a low electrolyser utilisation rate, such as 1,000 hours per year.

Chapter 11 is contributed by a research team led by Dr. Shi from University of Technology Sydney. ***Strategies and policy frameworks leading to a shift to green or low-carbon hydrogen*** have not been explored in depth nor identified clearly in the context of China. This study aims at bridging such gaps. A survey method and roadmapping technique have been applied to survey experts on hydrogen energy from government bodies, industries, and academia and achieve basic consensus on strategically enabling large-scale green hydrogen demonstration, followed by commercialisation in China. A strategic roadmap is thus derived based on these findings, with recommendations on policy principles and tools at each phase of the development of hydrogen energy in China.

## 4. Conclusions and Policy Recommendations

With the above-mentioned studies, in the context of China, this report concludes the following:

First, as hydrogen and fuel cell technologies are maturing commercially, it is important to identify scenarios and applications that could make these technologies cost-competitive as low-hanging fruits to enable initial penetration of the technologies. More studies on the technical and economic feasibility of large-scale renewable and clean energy to hydrogen projects in such scenarios and applications are thus called for, so as to comprehend whether any technical and economic barriers and gaps exist.

Second, technical and economic feasibility of hydrogen infrastructure and supply chains is equally important, especially in the sense of determining what kind and scale of infrastructure network and supply chain capacity should be developed to enable large-scale development of green and clean hydrogen energy in China.

Third, on the one hand, the safety of large-scale hydrogen energy projects is a precondition and thus calls for updated or newly developed legislation, regulation, and standards; on the other hand, the existing institutional and regulatory system may not be a good match with the characteristics of the new hydrogen and fuel cell technologies, especially as technologies are still developing fast. Therefore, continuous research in this regard is called for.

Fourth, systematic and comprehensive policy frameworks are called for in order to develop the abovementioned dimensions. In the meantime, it is important that policies help forge a series of market mechanisms for large-scale renewable and clean hydrogen energy projects, such as those in the power market, the carbon market, and green financing. In this regard, this report contributes a strategic roadmap for policies, as well as other stakeholders' strategies and actions in line with the proposed policies.

Lastly, international cooperation is critical in achieving accelerated adoption of hydrogen and fuel cell technologies and the development of green and clean hydrogen energy. There are at least three major dimensions of international collaboration: (1) international coordination in policy support for hydrogen energy, especially in market creation and international trade of hydrogen energy, with special emphasis on green and clean hydrogen; (2) international collaboration in hydrogen and fuel cell supply chains, with lowering trade barriers in technologies and equipment, transfer of and joint research and development in technologies being the key in this regard; and (3) sharing best practices and lessons from existing and ongoing hydrogen energy demonstration projects globally.

With these, this study thus presents a high-level strategic overview and assessment on the feasibility of green and clean hydrogen energy in China. It is hoped that this project serves as a starting point for research institutes and experts in and outside of China to look further into more details of the issue of how to implement and accelerate the development of green and clean hydrogen energy in China.

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# Chapter 2

# Hydrogen Energy Demand and Supply Potential in China

Ichiro Kutani[3] and Mitsuru Motokura[4]

## 1. Hydrogen Demand Potential

Future hydrogen demand potential is difficult to estimate due to many uncertainties, including promotion policies. In addition, the absence of transparent and comprehensive statistics for hydrogen energy disables us from adopting econometric modeling approaches to estimate future hydrogen demand. Therefore, the study creates assumptions and scenarios to estimate China's hydrogen demand potential in 2040.

### 1.1. Basic assumptions for hydrogen demand estimation

The study assumes the following:

- No nation-wide hydrogen pipeline will be developed before 2040.
  - A stational fuel cell that consumes natural gas as a source of hydrogen is not counted as a demand.
- Focus on the transport sector and power generation
  - Fuel-cell vehicles
  - Fuel-cell power generation
  - Hydrogen-fuelled combined cycle gas turbine (CCGT)
- The following technologies are excluded from the analysis:
  - Fuel-cell ships, trains
  - Synthetic fuels produced from hydrogen, e.g. ammonia and methanol

### 1.2. Target sector and assumed fuel switch

The study considers the sustainable development scenario (SDS) in the World Energy Outlook (WEO) 2020 of the International Energy Agency (IEA) as a reflection of China's recently announced ambition to become carbon neutral by 2060, since the scenario assumes the world will become net zero by 2070.

The estimation time is set at 2030 and 2040 considering the availability of data, i.e. the WEO 2020 shows their outlook data only until 2040.

Fuel-cell electric vehicles (FCEVs) can substitute passenger vehicles and diesel-run heavy-duty vehicles, such as buses and trucks, in the transport sector.

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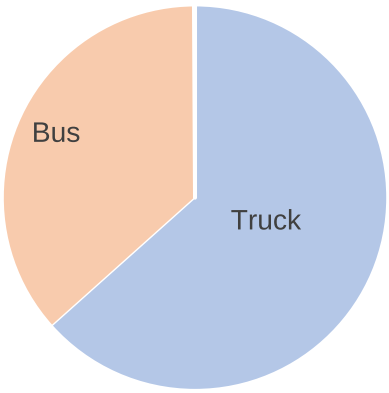
[4] Senior Coordinator, The Institute of Energy Economics, Japan.

In the power generation sector, the study assumes two types of power generation: (i) fuel-cell power generation using 'otherwise curtailed' electricity from variable renewable electricity (VRE) and (ii) combined-cycle gas turbine power generation, which runs with pure hydrogen fuel or natural gas–mixed fuel.

### 1.3. Hydrogen demand potential in transport

As of September 2019, China's stocks totalled 3,518 FCEVs, of which trucks and buses share 2,230 (64%) and 1,285 (36%), respectively. Passenger vehicles numbered only three.

**Figure 2.1: Fuel-Cell Electric Vehicles, as of September 2019**




Source: NEDO (2020).

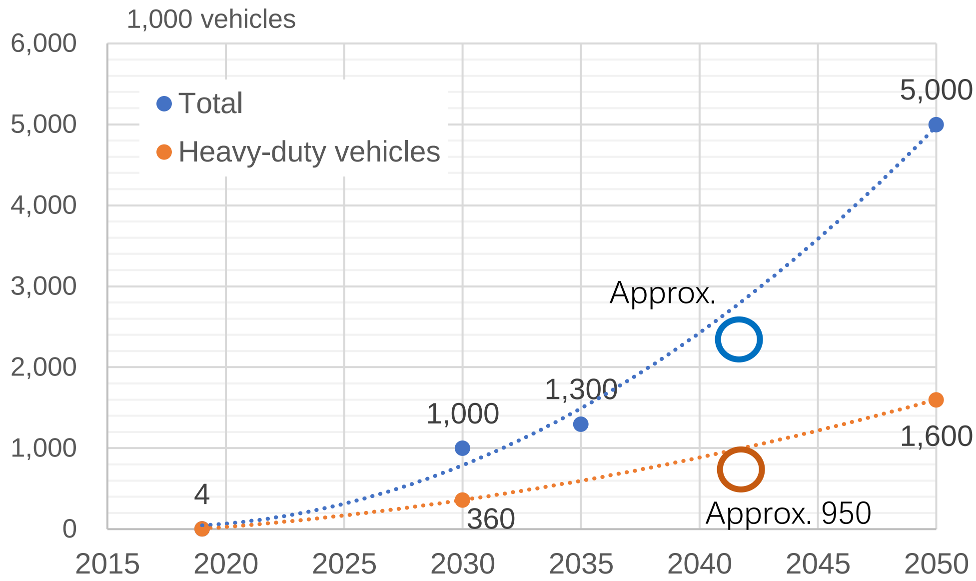
The study assumed FCEV stock, average fuel economy, and average driving distance to estimate hydrogen demand.

$$\begin{aligned} Hydrogen\ demand \\ &= Vehicle\ stock \\ &\div Average\ fuel\ economy\ [km/L] \\ &\times Annual\ average\ driving\ distance\ [km] \end{aligned}$$

1) Vehicle stock

Total FCEV stocks are targeted to reach 1.0 million in 2030, 1.3 million in 2035, and 5.0 million in 2050 (China Hydrogen Alliance, 2018). Heavy-duty vehicles (HDVs) will be 0.36 million in 2030 and 1.6 million in 2050. From this date, the study assumes a total FCEV stock in 2040 of 2.4 million and heavy-duty FECV stock of 0.95 million.

**Figure 2.2: Target of FCEV Stock**




FCEV = fuel-cell electric vehicle.
Source: China Hydrogen Alliance (2018).

From the data, we could estimate vehicle stocks in 2030 and 2040. We assumed the HDV stock consists of 35% buses and 65% trucks (Table 2.1).

**Table 2.1: Assumed FCEV Stock**

| | | 2030 | 2040 |
|---|---|---|---|
| Passenger vehicles | thousand | 640 | 1,450 |
| Hevy-duty vehicles | thousand | 360 | 950 |
| of which buses | thousand | 126 | 333 |
| of which trucks | thousand | 234 | 618 |
| Total | thousand | 1,000 | 2,400 |

Source: Created from China Hydrogen Alliance (2018).

2) Fuel economy

We assumed a difference in fuel economy between internal combustion engine (ICE) vehicles and FCEVs to calculate hydrogen demand.

For passenger vehicles, we selected Toyota Crown as ICE vehicle and Toyota Mirai as FCEV as these are similar in body size and weight. Table 2.2 compares the two vehicles; the estimate shows that the fuel economy of FCEVs is 1.8 times better than ICE vehicles.

**Table 2.2: Fuel Economy of a Passenger Vehicle**

| | | Toyota Crown | Toyota Mirai |
|---|---|---|---|
| | |  |  |
| Dimension | L | 4,910 | 4,890 |
| (cm) | W | 1,800 | 1,815 |
| | H | 1,455 | 1,535 |
| Weight (kg) | | 1,590–1,650 | 1,850 |
| Displacement | | 2,000 cc | - |
| Driving mile/full load | | - | 650 km |
| Full load | | - | 85.68 m3 |
| Fuel economy | | 12.8 km/L | 7.59 km/m3 |
| | | 16,853 km/toe | 29,645 km/toe |

Note: MIRAI's fuel tank capacity is 122.4 L at a pressure of 70 MPa >> 85.68 m3-H2/full load
Source: Toyota Motor Corporation (2007).

For the HDVs, we first surveyed the fuel economy of major vehicles sold in Japan. Though the manufacturer differs, the average fuel economy is concentrated in a narrow range. Therefore, we assumed 4 kilometre (km)/L for ICE trucks and 5 km/L for ICE buses.

**Table 2.3: Fuel Economy of ICE Heavy-Duty Vehicles**

| Type of Vehicle | | | Manufacturer | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Isuzu | | Hino | | Fuso | |
| Truck | 10 tonne class | km/L | 6.50 | 6.70 | 5.70 | 6.30 | 5.00 | 6.00 |
| | 20 tonne class | km/L | 4.15 | 4.45 | 3.80 | 4.40 | 3.75 | 4.40 |
| | 25 tonne class | km/L | 4.05 | 4.25 | 4.05 | 4.45 | 3.75 | 4.25 |
| | 35 tonne class | km/L | 3.15 | 3.30 | | 3.25 | 3.15 | 3.40 |
| | 60 tonne class | km/L | 1.92 | 1.98 | 1.92 | 1.98 | 1.86 | 1.94 |
| | Average | km/L | 4.05 | | 3.98 | | 3.75 | |
| Bus | 10 tonne or more | km/L | 3.95 | 6.00 | 3.95 | 6.00 | 3.95 | 5.90 |
| | Average | km/L | 4.98 | | 4.98 | | 4.93 | |

Note: A value indicates the minimum and maximum ranges.
Source: MILT (2020).

Toyota conducted a long-term FECV bus pilot project in Tokyo and Chubu airport in 2007 (Toyota, 2007). The result showed that fuel economy of the FCEV bus is 1.6 times to 2.0 times better than the ICE bus. Therefore, we assumed that the fuel economy of the FCEV HDV is 1.8 times better than the ICE HDV, which is coincidentally the same as that of passenger vehicles.

3) Driving distance

According to MILT (2004), in Japan, the average annual driving distance is 10,000 km for passenger vehicles; 55,000 km for buses; and 68,000 km for trucks. Meanwhile, in China, passenger vehicles' average monthly driving distance is 1,272 km (Sun et al., 2011), i.e. approximately 15,000 km per annum, 1.5 times longer than in Japan. From this, we assume 1.5 times longer driving distance for buses and trucks as well.

**Table 2.4: Annual Average Driving Distance**

| | China | Japan |
|---|---|---|
| Passenger vehicle | 15,000 km | 10,000 km |
| Bus | 80,000 km | 55,000 km |
| Truck | 100,000 km | 68,000 km |

Source: MILT (2004), Sun et al. (2011).

4) Estimated hydrogen demand

Table 2.5 shows the estimated hydrogen demand of 4.1 Mtoe in 2030 and 10.6 Mtoe in 2040 in the road transport sector.

**Table 2.5: Estimated Hydrogen Demand for Transport**

| | | 2030 | | | 2040 | | |
|---|---|---|---|---|---|---|---|
| | | Passenger Vehicle | Bus | Truck | Passenger Vehicle | Bus | Truck |
| Fuel economy of ICE vehicle | km/L | 12.8 | 5.0 | 4.0 | 12.8 | 5.0 | 4.0 |
| Fuel economy of FCEV (oil equivalent) | km/L | 23.0 | 9.0 | 7.2 | 23.0 | 9.0 | 7.2 |
| Annual average driving distance | km | 15,000 | 80,000 | 100,000 | 15,000 | 80,000 | 100,000 |
| Annual average fuel consumption per vehicle | toe | 0.5 | 7.6 | 11.9 | 0.5 | 7.6 | 11.9 |
| FCEV stock | | 640,000 | 126,000 | 234,000 | 1,450,000 | 332,500 | 617,500 |
| Hydrogen demand | Mtoe | 0.3 | 1.0 | 2.8 | 0.7 | 2.5 | 7.4 |
| Total hydrogen demand | Mtoe | | 4.1 | | | 10.6 | |

FCEV = fuel-cell electric vehicle.
Source: Author.

### 1.4. Hydrogen demand potential for fuel cell sourced from curtailed electricity

When the VRE capacity substantially increases in a power generation mix, curtailment of excess electricity will become necessary to maintain the frequency and voltage of the power grid. The curtailment rate would reach as high as 20% to 30% (Chang and Han, 2021). This 'otherwise curtailed' electricity can be stored or converted into other types of energy to be used when necessary. One option of such an application is to convert curtailed electricity into hydrogen by water electrolysis. Produced hydrogen can be supplied to a fuel cell as a distributer electricity and heat generator.

1) Assumptions

The study assumes the following:

- 25% curtailment rate, by referring to Chang and Han (2021)
- 50% of curtailed electricity will be converted into hydrogen (the remaining 50% goes to a storage battery)
- Apply 5 kWh/Nm3-H2 of production efficiency by referring to some catalogue data of alkaline water electrolysers.

2) Estimated demand

Since demand depends on the amount of curtailed electricity, the study firstly calculated the amount of curtailed electricity. The amount of VRE power generation is referred to as SDS of IEA's WEO 2020.

The estimated hydrogen demand is 18.1 Mtoe in 2030 and 33.5 Mtoe in 2040.

**Table 2.6: Estimated Hydrogen Demand for Fuel Cell**

| | | 2030 | 2040 |
|---|---|---|---|
| VRE power generation | TWh | 2,827 | 5,230 |
| Curtailment rate | | 25% | 25% |
| Hydrogen storage rate | | 50% | 50% |
| VRE power for hydrogen production | TWh | 353 | 654 |
| Hydrogen production efficiency | kWh/Nm3-H2 | 5 | 5 |
| Hydrogen production (= consumption) | Bcm | 70.7 | 130.7 |
| | Mtoe | 18.1 | 33.5 |

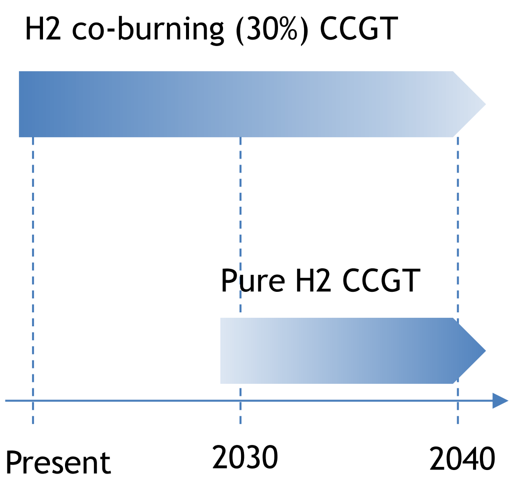
VRE = variable renewable energy.
Source: Author.

### 1.5. Hydrogen demand potential in CCGT

1) Available technology

Currently, technology is already commercially available to burn a 30% hydrogen-mixed fuel in a natural gas CCGT.5 The technology can also retrofit to existing CCGT by replacing a burner. While utility-scale pure hydrogen CCGT is being developed, the study assumes the technology will become available after 2030 (Figure 2.3).

**Figure 2.3: Assumed Technology**



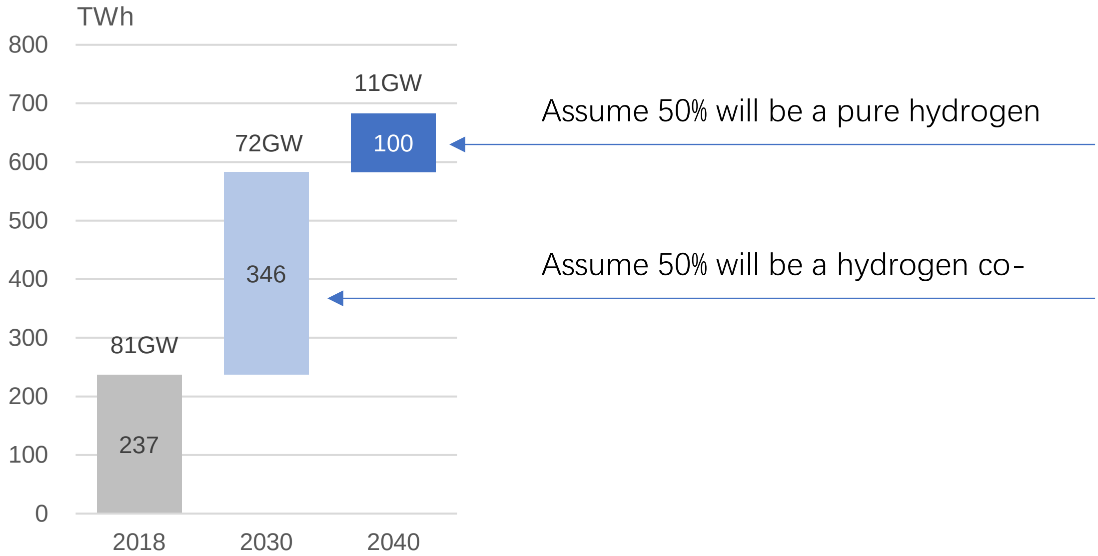

CCGT = combined cycle gas turbine.
Source: Author.

2) Scenario

In 2018, an 81 GW gas power generator in China generated 237 TWh of electricity (Figure 2.4). WEO 2020 estimated that 583 TWh of electricity will be supplied by a 153 GW gas power plant in 2030 and 683 TWh of electricity by a 164 GW capacity in 2040. The study assumes half of added power generation capacity between 2018 and 2030 will become a hydrogen co-burning fleet in 2030. After 2030, the study assumes half of the added capacity will become pure hydrogen CCGT in 2040.

5 Interview of Mitsubishi Heavy Industries staff.

**Figure 2.4: Outlook of Natural Gas Power Generation and Assumption of Fuel Switch**




Source: Created from IEA (2020a).

3) Estimated hydrogen demand

Table 2.7 shows the estimated hydrogen demand of 7.1 Mtoe in 2030 and 13.9 Mtoe in 2040 in the power generation sector.

**Table 2.7: Estimated Hydrogen Demand for CCGT**

| | | 2030 | Change between 2030–2040 | 2040 |
|---|---|---|---|---|
| Additional natural gas power generation | TWh | 346 | 100 | - |
| Conversion ratio to H2 generation | | 50% | 50% | - |
| Converted generation | TWh | 173 | 50.2 | - |
| | Mtoe | 14.9 | 4.3 | - |
| Thermal efficiency | | 63% | 63% | - |
| Required energy input | Mtoe | 23.6 | 6.85 | - |
| Hydrogen content ratio in a fuel | | 30% | 100% | - |
| Hydrogen demand | Mtoe | 7.1 | 6.8 | 13.9 |

Source: Author.

### 1.5. Summary of hydrogen demand potential and avoided CO2 emission

The total estimated hydrogen demand is 29.2 Mtoe in 2030 and 58.0 Mtoe in 2040. They are equivalent to 1.4% in 2030 and 2.9% in 2040 of total final energy consumption (TFEC) in the respective years (Table 2.8). However, the share of hydrogen to the TFEC is small because the use of hydrogen energy has just started. Thus, even in 2040, it is too early to expect the total penetration of hydrogen technologies in society. Besides, the study does not count industry demand due to its complexity and the need for pipelines for supplying hydrogen.

**Table 2.8: Total Hydrogen Demand**

| | 2030 | | 2040 | |
|---|---|---|---|---|
| | Amount (Mtoe) | % of TFE | Amount (Mtoe) | % of TFE |
| Transport | 4.1 | 0.2% | 10.6 | 0.5% |
| Fuel cell | 18.1 | 0.8% | 33.5 | 1.7% |
| Power generation | 7.1 | 0.3% | 13.9 | 0.7% |
| **Total** | **29.2** | **1.4%** | **58.0** | **2.9%** |

TFEC = total final energy consumption from the SDS scenario in IEA (2020a).
Source: Created from IEA (2020a).

Fuel switch from fossil fuel to hydrogen can reduce CO2 emissions. Table 2.9 shows the avoided CO2 emission amount. But again, the share of reduced CO2 emission to total CO2 emission is small even in 2040.

**Table 2.9: Avoided CO2 Emission**

| | 2030 | | 2040 | |
|---|---|---|---|---|
| | Amount (mil. tonne-CO2) | % of total CO2 | Amount (mil. tonne-CO2) | % of total CO2 |
| Motor gasoline | 0.11 | 0.00% | 0.25 | 0.01% |
| Diesel oil | 1.21 | 0.02% | 3.20 | 0.10% |
| Natural gas | 10.71 | 0.16% | 20.17 | 0.66% |
| **Total** | **12.03** | **0.17%** | **23.62** | **0.77%** |

Note: Carbon content of fossil fuel: Motor gasoline = 18.9 kg-C/GJ, Diesel oil = 20.2 kg-C/GJ, Natural gas = 15.3 kg-C/GJ.
Source: Created from IEA (2020b).

## 2. Hydrogen Supply Potential

### 2.1. Hydrogen production technologies and their cost

The hydrogen production process has long been developed for synthetic or city gas. Industrial hydrogen production processes developed to date include steam reforming of light hydrocarbons, partial oxidation, coal gasification, and water electrolysis.

Hydrogen hardly exists in hydrogen molecules in nature but exists in oxides or carbides (H2O, CnHm). Therefore, to obtain hydrogen from water, hydrocarbons, etc., energy should be applied, resulting in a chemical reaction that breaks the H-O or C-H bond. Heat and electricity are generally used as energy input, but there are also light and radiation methods (Table 2.10).

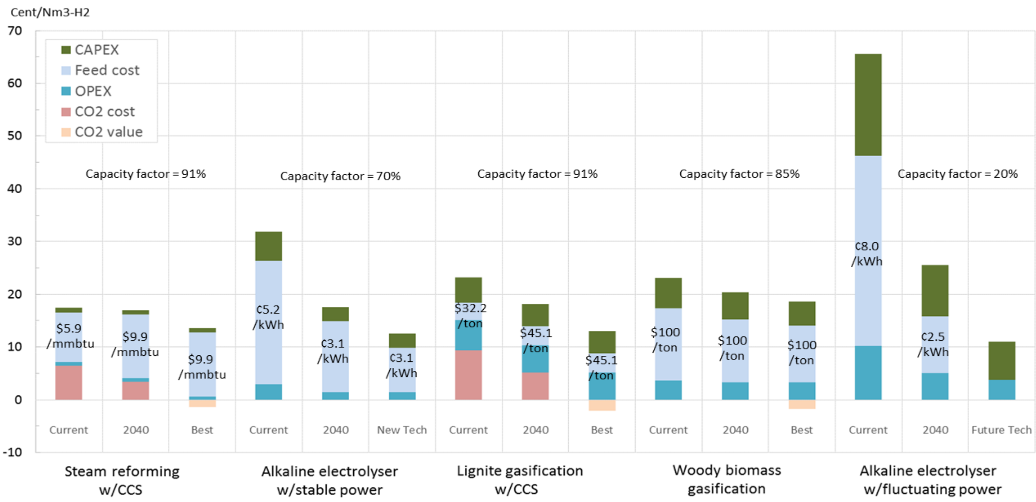
**Table 2.10: Technologies to Produce Hydrogen**

| | | Input Energy | | |
|---|---|---|---|---|
| | | **Heat** | **Electricity** | **Others** |
| Feedstock | Hydrocarbon | ● **Steam reforming**<br>● **Partial oxidation**<br>● **Autothermal reforming**<br>● **Thermal cracking** | - | - |
| | Water | ● **Thermochemical water splitting** | ● **Alkaline electrolysis**<br>● **Polymer electrolyte membrane**<br>● **High-temperature stream reforming** | ● **Photolytic**<br>● **Biological**<br>● **Radiation** |

Source: Created from US DOE (https://www.energy.gov/eere/fuelcells/hydrogen-production-processes).

Steam reforming of natural gas is currently the cheapest, while alkaline water electrolysis using VRE is the most expensive method (Kimura and Li, 2019). The latter is costly because the electric power supply for water electrolysis is not stable. Thus, the capacity factor of the water electrolysis device is low. Therefore, the hydrogen production cost is halved if a high operating rate can be ensured with stable power. In the future, technological improvements may reduce the cost of alkaline water electrolysis, making it possibly the most economical hydrogen production method.

**Figure 2.5: Cost of Large-Scale Hydrogen Production**




**1 : Feed Cost of Lignite gasification is based on FOT price in Intra-regional Group Countries.*
**2 : CCS cost is based on $70/t-CO2 for current and $48/t-CO2 for 2040 (CCS/Utilization Singapore Perspectives).*

Source: Kimura and Li (2019).

The following sections estimate China's hydrogen supply potential using coal gasification, steam reforming of natural gas, and water electrolysis.

## 2.2. Coal gasification

### 1) Method

China uses coal in all sectors, such as industry, buildings, and power generation. However, recently, China has curbed coal use to mitigate severe air pollution. In addition, China announced its ambition to become carbon neutral by 2060, accelerating the move away from coal.

On the other hand, China's coal self-sufficiency rate in 2019 was a high 96%, implying a surplus of coal supply capacity if domestic coal demand declines in the future. Therefore, in this study, the difference between the future outlook of 'coal production under the WITHOUT carbon-neutral scenario' and 'coal demand under the WITH carbon-neutral scenario' is the amount of coal supply that can be used to produce hydrogen. The stated policy scenario (STEPS) in IEA (2020a) will be adopted for the former and the SDS in IEA (2020a) will be adopted for the latter.

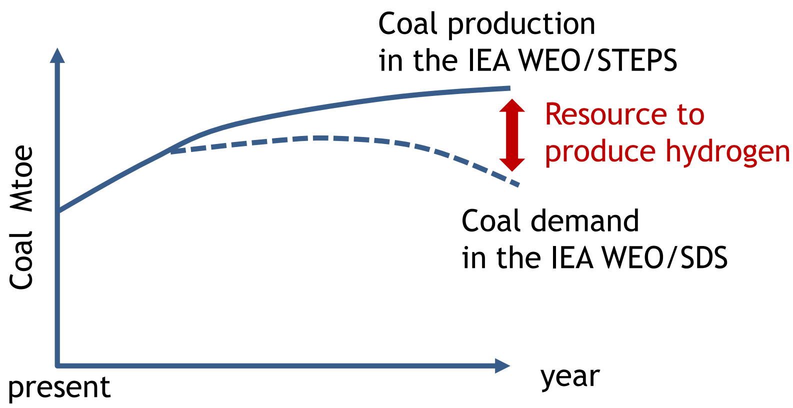
$$\text{Available coal for H2 production} = \text{Coal production under the WITHOUT carbon} - \text{neutral scenario} - \text{Coal demand under the WITH carbon} - \text{neutral scenario}$$

where:

the WITHOUT carbon-neutral scenario = Stated policy scenario (STEPS) in IEA (2020a)

the WITH carbon-neutral scenario = Sustainable development scenario (SDS) in IEA (2020a)

**Figure** Error! Use the Home tab to apply 0 to the text that you want to appear here.**2.6: Available Coal to Produce Hydrogen**




SDS = sustainable development scenario, WEO = world economic outlook.
Source: Author.

2) Assumptions

It is necessary to determine the gasification efficiency of coal to estimate the amount of hydrogen production. Thus, this study adopted an analysis of JST (2019), which estimates the amount of hydrogen produced from the two types of coal: lignite coal and bituminous coal.

3) Estimated hydrogen supply potential

Table 2.11 shows the big difference in hydrogen production efficiency per calorific value between lignite coal and bituminous coal. Therefore, the hydrogen production amount is similar regardless of coal type.

**Table 2.11: Estimated Hydrogen Production Potential from Coal**

| | | 2018 | 2030 | 2040 |
|---|---|---|---|---|
| Coal production/STEPS | Mtoe | 1,860 | 1,854 | 1,693 |
| Coal demand/SDS | Mtoe | 1,986 | 1,366 | 732 |
| Available coal to produce H2 | Mtoe | | 488 | 961 |
| | | | | |
| *If produced from lignite coal* | | | | |
| Production efficiency | ton-coal/tonne-H2 | | 21 | 21 |
| Lignite coal (NCV) | MJ/kg | | 11.5 | 11.5 |
| Production efficiency | toe-coal/toe-H2 | | 2.0 | 2.0 |
| H2 production | Mtoe | | 242 | 477 |
| | Bcm | | 947 | 1,866 |
| *If produced from bituminous coal* | | | | |
| Production efficiency | ton-Coal/ton-H2 | | 8.7 | 8.7 |
| Bituminous coal (NCV) | MJ/kg | | 26.2 | 26.2 |
| Production efficiency | toe-coal/toe-H2 | | 1.9 | 1.9 |
| H2 production | Mtoe | | 257 | 506 |
| | Bcm | | 1,004 | 1,977 |

NCV = net calorific value, SDS = sustainable development scenario, STEPS = state policy scenario.
Source: Created from IEA (2020a), JST (2019).

4) Potential of carbon capture and storage (CCS)

The process of gasifying coal inevitably generates CO2. Since using hydrogen aims to decarbonise the energy supply, the generated CO2 should be captured and stored. Therefore, the study evaluates the potential of applying the CCS technology in China.

The GCCSI (2020) estimated China's CCS potential at 3,077 gigatonnes. However, storage potential is currently rarely used, and most of it classified undiscovered.

**Table 2.12: Potential of CCS in China**

| Classification | CO2 Storage Resource (Gt) Project and no project | CO2 Storage Resource (Gt) Project specified only |
|---|---|---|
| Stored | 0.0003 | 0.0003 |
| Capacity | 0 | 0 |
| Sub-Commercial | 105 | 0.031 |
| Undiscovered | 3067 | 0 |
| Aggregated* | 3077 | 0.03 |

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.
Capacity = economically viable resources; Sub-commercial = discovered but economic viability uncertain and some may inaccessible; Undiscovered = geographically unconfirmed resource.
Source: GCCSI (2020).

By assuming the realisation rate, we can obtain the usable CCS potential. We assume three different rates for sub-commercial resources: 25%, 50%, and 75%. For undiscovered resources, we assume a 5% realisation rate since there is enormous uncertainty to commercialise.

Then the study estimates an expected life of usable CCS capacity by dividing an available CCS capacity by CO2 emission from coal gasification. Table 2.13 shows the evaluated results – that CCS capacity may be satisfactory to produce necessary blue hydrogen in 2040.

However, we need to remind that CCS capacity is not infinite. Thus, the supply of blue hydrogen is physically limited.

**Table 2.13: Available Capacity and Life of CCS in China**

| **Storage Capacity** | | | | | |
|---|---|---|---|---|---|
| Sub-commercial | | | | | |
| Potential | Gt-$CO_2$ | 105 | 105 | 105 | 105 |
| Realisation rate | % | 25% | 50% | 75% | 75% |
| Available capacity | Gt-$CO_2$ | 26 | 53 | 79 | 79 |
| Undiscovered | | | | | |
| Potential | Gt-CO2 | 3,067 | 3,067 | 3,067 | 3,067 |
| Realisation rate | % | 0% | 0% | 0% | 5% |
| Available capacity | Gt-$CO_2$ | 0 | 0 | 0 | 153 |
| Toral available capacity | Gt-$CO_2$ | 26 | 53 | 79 | 232 |

| **Life of CCS** | | | | | |
|---|---|---|---|---|---|
| Carbon content of 'Other bituminous coal' | kg-C/GJ | 25.8 | | | |
| CO2 content of 'Other bituminous coal' | ton-CO2/toe | 3.96 | | | |
| Consumable coal amount to produce blue H2 under each available CCS capacity | Mtoe | 6,628 | 13,255 | 19,883 | 58,601 |
| Life of CCS | | | | | |
| If coal consumption is 55 Mtoe/yr (able to supply for H2 demand in 2030) | year | 121 | 241 | 362 | 1,065 |
| If coal consumption is 100 Mtoe/yr (able to supply for H2 demand in 2040) | year | 60 | 121 | 181 | 533 |

Source: Created from GCCSI (2020).

## 2.3. Natural Gas Steam Reforming

The demand for natural gas, clean fossil energy, is growing in China. Fuel shift from coal to natural gas effectively reduces air pollution and CO2 emissions. Thus, demand is expected to continue increasing in the future.

Meanwhile, the dependence on natural gas supply for import is increasing in China. The self-sufficiency rate fell below 100% in 2007 and had continued to decline, reaching 59% in 2019. When applying the same method as coal to estimate the available amount, no natural gas resource is available in China to produce hydrogen in the future.

This import dependence will continue in the future despite the prospect of domestic natural gas production increasing. Therefore, valuable domestic natural gas should first be used to meet natural gas demand. Also, it is economically irrational to produce hydrogen from expensive imported natural gas. Therefore, in this study, the hydrogen production potential from steam reforming of natural gas is set to zero.

For reference, the following chemical formula expresses the steam reforming of natural gas; theoretically, 4 mol of hydrogen can be obtained from 1 mol of methane. The formula assumes that 70% of reforming efficiency in high heat value basis (Iseki, 2012) uses the pressure swing adsorption technique.

$$CH_4 + 2H_2O = 2CO_2 + 4H_2$$

**Table 2.14: Estimated Hydrogen Production Potential from Natural Gas**

| | | 2018 | 2030 | 2040 |
|---|---|---|---|---|
| Natural gas production/STEPS | Mtoe | 135 | 202 | 234 |
| Natural gas demand/SDS | Mtoe | 233 | 356 | 411 |
| Available natural gas suppy to produce H2 | Mtoe | | -154 | -177 |
| | | | | |
| Production efficiency | Mtoe/Mtoe-H2 | | 0.70 | 0.70 |
| H2 production | Mtoe | | 0 | 0 |
| | Bcm | | 0 | 0 |

SDS = sustainable development scenario, STEPS = stated policy scenario.
Source: Created from IEA (2020a), Iseki (2012).

## 2.4. Alkaline Water Electrolysis

1) Potential of renewable energy

Although the use of renewable energy is increasing in China, the development potential remains. For example, producing hydrogen by water electrolysis is possible by using it as input energy.

Therefore, first, the study surveys the potential of renewable energy that to produce hydrogen. Table 2.15 estimates the remaining renewable energy resources to produce hydrogen.

**Table 2.15 Remaining Potential of Major Renewable Energy Sources to Produce Hydrogen**

| | Technical Potential (IRENA) | Prospected Power Generation Capacity in 2040 (IEA WEO, SDS) | Estimated Remaining Potential in 2040 |
|---|---|---|---|
| Hydropower | 400–700 GW (average 550 GW) | 563 GW | - |
| Wind/onshore | 1,300–2,600 GW (average 1,950 GW) | 929 GW | 1,000 GW |
| Wind/offshore | 200 GW | | |
| Solar PV/utility | 2,200 GW | 2,124 GW | 500 GW |
| Solar PV/rooftop | 500 GW | | |

PV = photovoltaic, SDS = sustainable development scenario, WEO = world energy outlook.
Source: IRENA (2014), IEA (2020a).

In the SDS, which assumes a significant reduction of CO2 emission, the hydropower capacity in 2040 will be 563 GW, almost the same as the hydropower potential estimated by IRENA (2014). In other words, the possibility to generating additional hydropower will be nearly exhausted by 2040. Thus, there is no remaining potential for producing hydrogen.

For wind power, when comparing the combined potential of on-shore and off-shore with the prospected power generation capacity in 2040, 1,000 GW of surplus capacity remains. Similarly, solar photovoltaic (PV) power generation will result in 500 GW of surplus capacity in 2040. This way, while aiming for decarbonisation, renewable energy would mostly be used to decarbonise electricity. Thus, the amount left for hydrogen production is limited.

In China, part of the generated electricity is being curtailed. It is possible to produce hydrogen by using the 'otherwise curtailed' electricity.

2) Assumptions

The study assumes the following:

- Able to commercialise 75% of the remaining potential
- Apply average capacity factor in 2018, i.e. 55% for wind and 28% for solar PV
- Apply 5 kWh/Nm3-H2 of production efficiency (from a few catalogue data).

3) Estimated hydrogen supply potential

Table 2.16 shows the estimated results.

**Table 2.16. Estimated Hydrogen Production Potential from Renewable Energy**

| | | 2018 | 2030 | 2040 |
|---|---|---|---|---|
| *Wind power* | | | | |
| Potential | GW | 2,150 | 2,150 | 2,150 |
| Capacity/SDS | GW | 184 | 614 | 929 |
| Generation/SDS | TWh | 366 | 1,360 | 2,256 |
| Remaining development potential | GW | | 1,221 | 1,221 |
| Realisation rate | | | **75%** | **75%** |
| Capacity factor | | | **55%** | **55%** |
| Production efficiency | kWh/Nm3-H2 | | **5.0** | **5.0** |
| H2 production | Bcm | | 882.3 | 882.3 |
| | Mtoe | | 225.8 | 225.8 |
| | | | | |
| *Solar PV* | | | | |
| Potential | GW | 2,700 | 2,700 | 2,700 |
| Capacity/SDS | GW | 175 | 1,106 | 2,124 |
| Generation/SDS | TWh | 177 | 1,466 | 2,974 |
| Remaining development potential | GW | | 576 | 576 |
| Realization rate | | | **75%** | **75%** |
| Capacity factor | | | **28%** | **28%** |
| Production efficiency | kWh/Nm3-H2 | | **5.0** | **5.0** |
| H2 production | Bcm | | 212.1 | 212.1 |
| | Mtoe | | 54.3 | 54.3 |
| | | | | |
| *Otherwise curtailed electricity from wind power and solar PV* | | | | |
| VRE power generation | TWh | 543 | 2,827 | 5,230 |
| Curtailment rate | | | **25%** | **25%** |
| Hydrogen storage rate | | | **50%** | **50%** |
| VRE power for hydrogen production | TWh | | 353 | 654 |
| Hydrogen production efficiency | kWh/Nm3-H2 | | **5.0** | **5.0** |
| Hydrogen production (= consumption) | Bcm | | 70.7 | 130.7 |
| | Mtoe | | 18.1 | 33.5 |

PV = photovoltaic, SDS = sustainable development scenario, VRE = variable renewable energy.

Source: Created from IEA (2020a), various catalogue data of manufacturers.

## 2.5. Supply and Demand Balance

When combining the estimated hydrogen demand and supply potential, a sufficient supply seems to meet the demand until 2040.

**Table 2.17: Summary of Estimated Results**

| | | 2030 | 2040 |
|---|---|---|---|
| **Total demand** | **Mtoe** | **29** | **58** |
| Transport | Mtoe | 4 | 11 |
| Fuel cell | Mtoe | 18 | 33 |
| Power generation | Mtoe | 7 | 14 |
| | | | |
| **Total supply** | **Mtoe** | **548** | **805** |
| Coal gasification | Mtoe | 250 | 492 |
| Natural gas steam reforming | Mtoe | 0 | 0 |
| Water electrolysis using REs | Mtoe | 298 | 314 |

RE = renewable energy.
Source: Author.

However, we need to be reminded of two points. First, the available CCS capacity to produce blue hydrogen is uncertain and limited. Although CCS has potential, significant geological and economic uncertainties in actual development exist. In addition, the amount that can be stored is finite; therefore, the supply of blue hydrogen is limited.

Second, the potential of VRE is also limited. Decarbonisation of electricity is essential to achieve the ambitious carbon-neutrality target; a large amount of VRE is also required for this application. Therefore, optimisation of VRE use will be necessary for the future, i.e. balancing between direct use as electricity and fuel to produce hydrogen.

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# Chapter 3

# Technical and Economic Feasibility of Renewable Energy to Hydrogen Projects in Southern Provinces for Supply to Guangdong

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 LaNi5, Mg2Ni, 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.

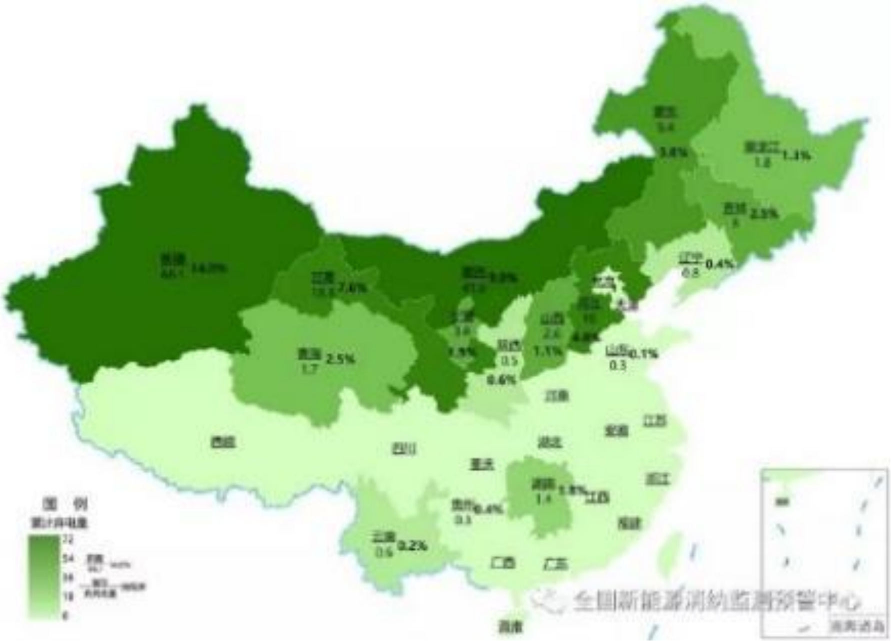
The total solar radiation of the national land average horizontal plane is 1,470.5 kWh/m$^2$, of which 1,400–1,750 kWh/m$^2$ is in western Sichuan, most of Yunnan, and Hainan, and 1.050–1.400 kWh/m$^2$ is in Jiangnan and most of South China (China Meteorological Administration’s Wind and Solar Resources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

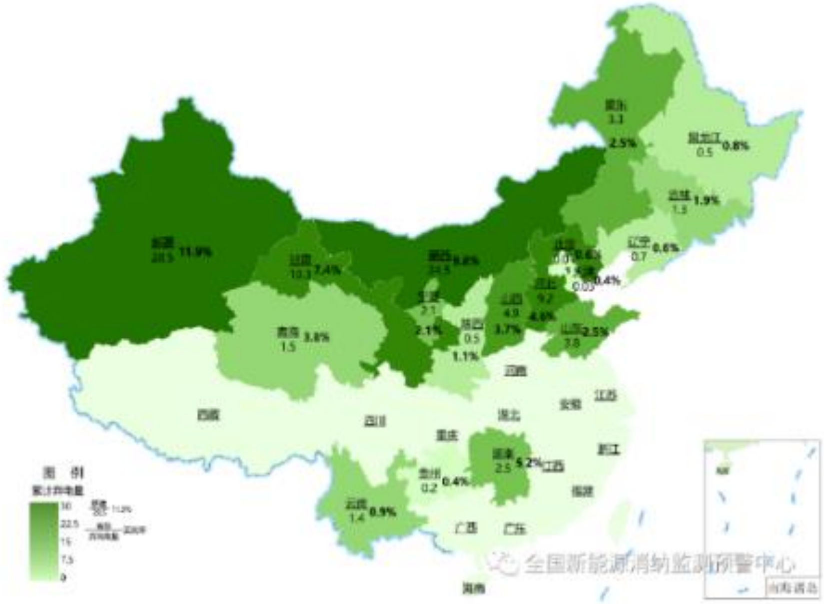

Source: China New Energy Consumption Early Warning Center (2020).

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<br>5.2% | Yunnan 1.4<br>0.9% | Guizhou 0.2<br>1.1% | Yunnan 0.2<br>0.6% |
| **March 2020** | Hunan 1.4<br>6.7% | Yunnan 1.6<br>1.8% | Guizhou<br>0.4% | Yunnan 0.1<br>0.7% |
| **December 2019** | Hunan 1.4<br>1.8% | Yunnan 0.6<br>0.2% | Guizhou 0.1<br>0.4% | Yunnan 0.2<br>0.4% |
| **September 2019** | Hunan 1.4<br>2.4% | Yunnan 0.6<br>0.3% | Guizhou 0.1<br>0.5% | Yunnan 0.1<br>0.3% |
| **June 2019** | Hunan 1.1<br>2.9% | Yunnan 0.5<br>0.7% | Guizhou 0.1<br>0.7% | Yunnan 0.1<br>0.3% |
| **March 2019** | Guizhou 0.3<br>1.3% | Yunnan 0.3<br>0.3% | Guizhou 0.1<br>1.4% | Yunnan 0.02<br>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/N$m^3$, and the total cost is about 75,400 yuan.

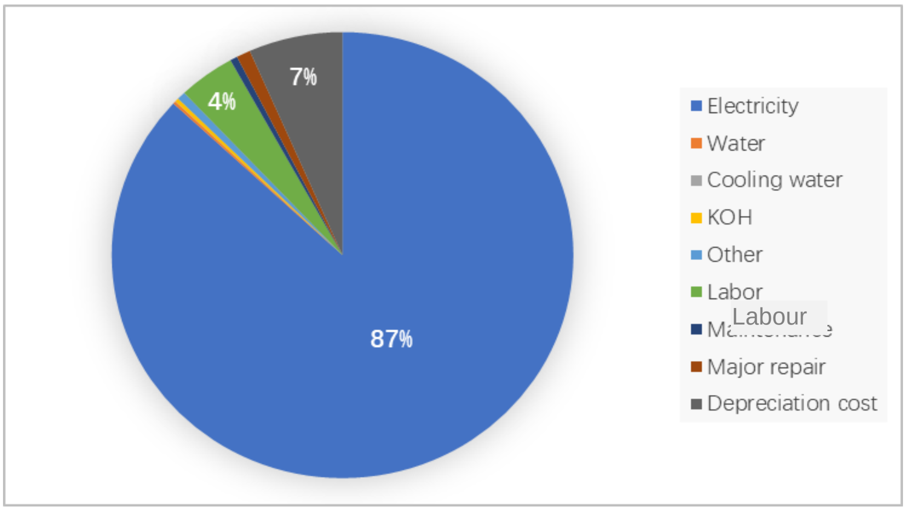
Table 3.8 summarises the cost items of hydrogen production. Figure 3.5 shows the proportion of each part.

**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.

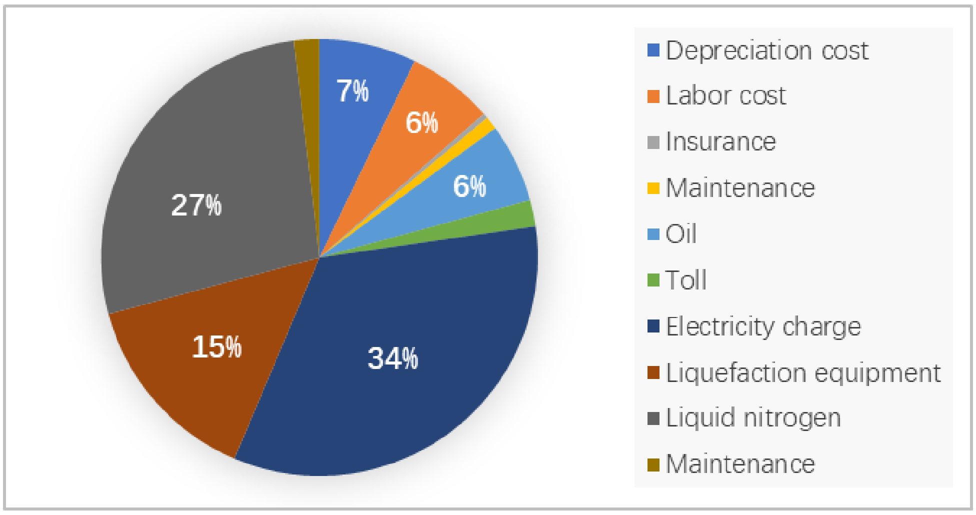
Table 3.12 summarises the liquid hydrogen storage and transportation cost items.

**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**

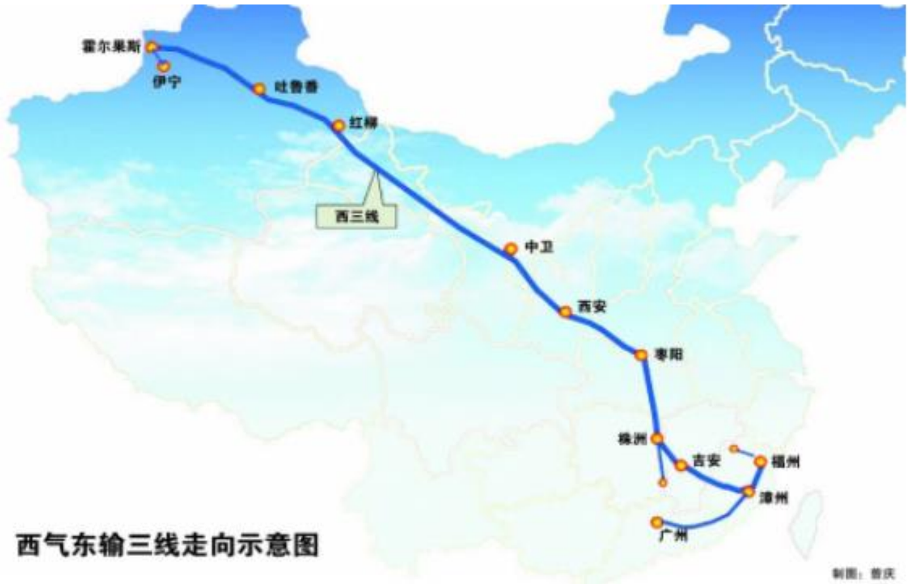
| Cost Item | Lower Item | Cost (yuan/kg) |
|---|---|---|
| Compression | Electricity | 0.39 |
| Fixed charge | Depreciation cost | 7.33 |
| | Labour | 0.89 |
| | Maintenance | 0.58 |
| **SUM** | | **9.2** |

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**

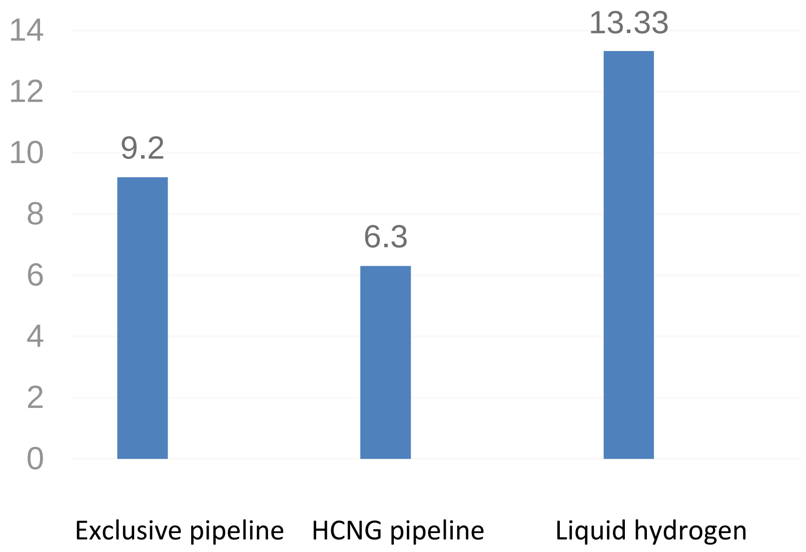
| Cost Item | Cost (yuan/kg) |
|---|---|
| Pipeline toll | 1.85 |
| Refining | 4.47 |
| **SUM** | **6.3** |

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)**

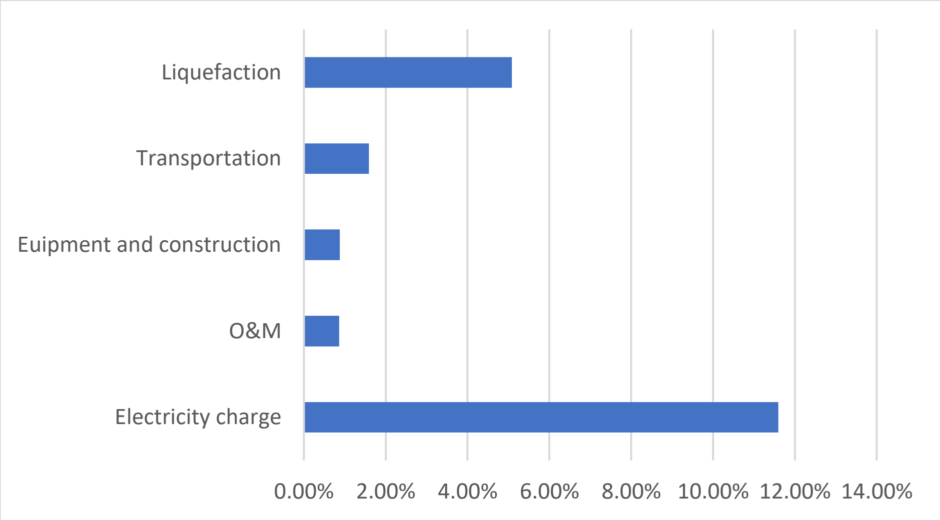



Source: Authors.

### 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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# Chapter 4

# Hybrid Energy Systems for Combined Cooling, Heating, and Power and Hydrogen Production Based on Solar Energy: A Techno-Economic Analysis

Nan Li and Yujia Song

In this chapter, solar energy, the hydrogen production system and the combined cooling, heating, and power (CCHP) system are combined to realise cooling–heating–power hydrogen multi-generation. Taking the total cost as the objective function, the configurations of the system with the lowest unit energy supply cost is obtained. The simulation work of the hybrid system based upon public buildings in Dalian, China is carried out to find an appropriate design scheme. The optimal system is analysed and described in detail. The results show when the daily hydrogen production is 700 kilograms (kg), the unit energy cost is the lowest, which is \$0.0615/kilowatt hours (kWh). The total cost of the system is about \$3.49 million and the annual carbon dioxide emissions of the system is about 8,570 tons. The fossil energy consumption of the system is about 42,100 megawatt hours (MWh). Therefore, 700 kg/day hydrogen supply is the best choice from the economic point of view. By comparing the total cost, carbon dioxide emissions and primary energy consumption with three existing systems, it is concluded that this system performs the best in three aspects.

Keywords: Hydrogen production; solar energy; combined cooling, heating, and power; total cost; carbon dioxide emissions; fossil energy consumption

## 1. Project Basis

### 1.1. Background

With the rapid development of the economy and the continuous consumption of fossil energy, the realisation of low-carbon and environmental protection development has become the goal of the power generation industry of all countries in the world. The new energy generation technologies have become the development direction of the power industry. Amongst them, wind power and photovoltaic (PV) power generation, due to their superior natural resource endowment, rapid development, and flexible installation, are more mature and more efficient than other new energy power generation technologies. They can well replace fossil energy power generation. According to statistics, the world's PV installed capacity grew rapidly from 2010 to 2012 and the growth rate has gradually slowed. At the end of 2016, the global PV installed capacity was about 76 gigawatts (GW), with the cumulative installed capacity exceeding 300 GW. Amongst them, China, the United States, and Japan ranked the top three with 34.54 GW, 14.1 GW, and 8.6 GW, respectively. From the perspective of regional distribution, Asia is still the world's most important PV power generation market, and China, the United States, and India have a strong driving force for PV power generation industry development.

Despite the rapid development of China's renewable energy, there are also shortcomings. Wind energy and PV are easily affected by seasons, climate, and time, which can lead to unstable power output of new energy systems. Grid connection will have a great impact on the voltage and stability of the power grid. The phenomenon of wind and PV power curtailment is still prominent in China. In 2019, China's wind and light abandonment capacity was16.9 billion kWh and 4.6 billion kWh, with a total of more than 20 billion kWh. Therefore, how to effectively use renewable energy and reduce wind and photovoltaic power curtailment has great significance to improve the utilisation rate of renewable energy and promote the energy revolution in China. With the rapid development of society, great importance has been attached to the efficient and clean power generation technology of renewable energy (wind energy and solar energy) and widely used by countries all over the world. Wind power generation and PV power generation are the main forms of renewable energy utilisation. Their rapid and large-scale development makes it difficult for the power grid to absorb the electricity.

To develop PV power generation more widely, two major problems need to be solved. The first problem is due to the instability of photovoltaic power generation which will have a greater impact on the grid. In order to avoid this impact, the grid will not accept unstable electricity, which will cause a waste of power. The second problem is the difficulty in storing energy from PV power generation. Traditional electrochemical energy storage, electromagnetic energy storage, and physical energy storage technologies cannot meet the needs of massive energy storage and the development of pure green energy in the future. Green storage is one of the key problems to solve the difficulty of connecting wind power and PV power.

Pumped storage and compressed air storage are relatively mature technical schemes, but they are limited by specific conditions, such as a large amount of water, reasonable terrain, dependence on fossil fuels, etc. The electrochemical battery is another way, but in the short term, lead-acid batteries, nickel-metal hydride batteries, lithium-ion batteries, or all-vanadium REDOX flow batteries will be limited by cost, scale, and technology maturity. Other energy storage methods such as flywheel energy storage cannot readily meet the challenge of large-scale application due to their low efficiency and small capacity. As a clean energy source, hydrogen has the characteristics of high energy density, large capacity, long life, and easy storage and transmission. It has become one of the optimal plans for large-scale comprehensive green development, storage, and utilisation of wind power and PV power. Using electrolysis of water to produce hydrogen for energy storage, PV power generation can integrate hydrogen as a clean and high-energy fuel into the existing gas supply network to realise the complementary conversion of electricity to gas. It can also be directly and efficiently used. Especially with the development of efficient and clean technologies such as fuel cells, hydrogen generation by PV power generation can provide clean hydrogen fuel for fuel cell vehicles and form them into green energy vehicles in the true sense.

To achieve 'the peak of China's carbon dioxide emissions by 2030, and strive to achieve carbon neutrality by 2060', the government requires traditional enterprises to offset their carbon dioxide emissions in the form of energy conservation and emissions reduction, to achieve zero emissions of carbon dioxide. Therefore, traditional enterprises have a strong desire to invest in the construction of clean energy power generation projects to balance carbon dioxide emissions. However, due to a large number of light-discarding phenomena in northeast China, the government controls the clean energy power generation to prevent a large number of wind and light-discarding phenomena. Therefore, the combined use of light-discarding and distributed energy can realise the combined supply of cold, heat, electricity, and hydrogen, which not only solves the problem of carbon neutralisation of traditional enterprises but also solves the problem of light discarding for the government. In this chapter, the solar energy, hydrogen production system and CCHP system are combined to realise the system of the cold–heat–electricity–hydrogen combined power supply. Taking the total system cost as the objective function, the configuration of the system with the lowest unit energy supply cost is obtained. The optimal system is analysed and described in detail. When the daily hydrogen supply is 700 kg, the unit energy cost is the lowest, which is \$0.0615/kWh. The total cost of the system is \$3,491,080, and the annual carbon dioxide emission of the system is 8,574,791 kg. The primary energy consumption of the system is 42,135,860 kWh. Therefore, from the economic point of view, 700 kg/day hydrogen supply is the best choice. By comparing the total cost, carbon dioxide emissions, and primary energy consumption with the three reference systems, it is concluded that the CCHP system performs the best in three aspects.

In recent years, China's primary energy consumption structure has been dominated by traditional fossil fuel energy represented by coal and oil, which causes serious problems of energy security and environmental pollution. Therefore, it is imperative to promote energy reform and develop 'green, low-carbon, clean, efficient, and safe' energy technology. By the end of 2019, the installed capacity of renewable energy power generation in China was 794 million kW, accounting for 39.5% of the total power capacity, including 210 million kW of wind power and 204 million kW of PV power generation. At the same time, distributed energy has also been vigorously developed due to its environmental protection and flexibility. From 2015 to 2019, the cumulative installed capacity of distributed photovoltaic power generation in China has increased year by year, reaching 50.6 GW in 2018. By the first three quarters of 2019, the cumulative installed capacity of distributed PV power generation in China had reached 58.7 GW. Despite the rapid development of renewable energy in China, there are still some shortcomings. Wind energy and light energy are easily affected by the seasons, climate, and time, which leads to the instability of the output power of the new energy system. If the grid is connected, the voltage and stability of the power grid will be greatly affected. At present, the phenomenon of 'abandoning wind' and 'abandoning light' is still prominent in China. In 2019, China's abandoned wind power was 16.9 billion kWh, and the abandoned light power was 4.6 billion kWh, with a total of more than 20 billion kWh. Therefore, how to effectively use renewable energy and reduce the rate of abandoned wind and light power is of significance to improve the utilisation rate of renewable energy and promote the energy revolution.

The task of national energy conservation and emissions reduction is important, which is related to the people's livelihoods. There is an urgent need to control air pollution. In the coming years, the task of controlling air pollution in provinces and cities will be a challenge, forcing governments at all levels to address their responsibilities and strive to achieve energy conservation and emissions reduction targets. The development of renewable energy has become an important measure to achieve energy conservation and emissions reduction. As one of the renewable energy sources, solar energy is also a key field of development.

At present, domestic and foreign scholars generally believe that hydrogen technology is an important part and key technical support of renewable energy systems and the energy internet. As the most ideal energy carrier and clean energy internationally recognised, hydrogen is known as ‘the ultimate energy of the 21st century’. Today, with the increasingly serious problems of environmental pollution and greenhouse gas emissions, hydrogen energy has become the focus of the international community with its unique advantages of high heat and being clean and efficient. We need to reach a consensus on development. The 973 and 863 plans of the Ministry of Science and Technology have funded several plans on hydrogen energy. Local governments have issued policies on the hydrogen energy industry, and Sichuan, Guangdong, Beijing, Shanghai, Tianjin, amongst others, have implemented nearly 20 projects. How to use hydrogen energy efficiently to solve the increasingly serious problems of energy security and environmental pollution has become the current research focus.

Due to the serious problem of light discarding in China, the national government wants to reduce the light discarding rate of PV power generation. If the problem of the light discarding rate cannot be solved, the government will no longer approve the investment and construction of new energy power generation projects to prevent the increase of the light discarding rate. On the other hand, China will enhance its national independent contribution and adopt more powerful policies and measures to achieve the peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. The government requires traditional enterprises to offset their carbon dioxide emissions by energy conservation and emissions reduction, to achieve zero emissions of carbon dioxide. Therefore, traditional enterprises have a strong desire to invest in the construction of clean energy power generation projects to balance the carbon dioxide emissions and reduce the pressure of survival. To solve the problem of carbon neutralisation in traditional enterprises, and at the same time to prevent a large number of new energy projects from abandoning light, we use the excess electricity generated by PV power generation for the CCHP system. In this system, the electricity generated by PV cells is used to supply power for the community, and the surplus electricity is converted into hydrogen through the proton exchange membrane electrolyser to provide hydrogen for the community or for electric cars. The purpose of this study is to optimise the scale of the proposed combined cooling, heating, power, and hydrogen supply system to meet the load requirements of selected buildings. This, in turn, will reduce electricity purchases from the grid by increasing building self-sufficiency, lower energy costs, and lower peak load limits.

### 1.2. Literature Review

Hydrogen as a new way of energy storage, combined with wind and PV will improve the utilization rate of power generation. In remote areas (weak power grid system), conventional energy cannot guarantee the quality of the power supply and the investment is high. As a multi-purpose energy carrier, hydrogen has obvious advantages such as heat, electricity, and hydrogen generation, and the integrated construction of pure green energy vehicles in hydrogen refuelling stations, which can effectively solve the above problems.

The production and utilisation of hydrogen energy are attracting the attention of many scholars and research institutions all over the world. The comprehensive analysis of the current research situation in China and abroad shows that the utilisation of electrolytic aquatic hydrogen is a good way to improve energy efficiency. Scholars have conducted a large number of studies on energy cost optimisation, net cost optimisation, system reliability, economy, optimal system configuration, optimisation algorithm, and optimal system scheduling of hydrogen energy systems. Ma, Yang, and Lu (2014) obtained the optimal solar wind battery system configuration by calculating the optimal net cost and energy cost, and analysed and described the optimal system in detail. Javed and Ma (2019) estimated the scale of a hybrid solar–wind battery system based on energy cost and system reliability. A genetic algorithm is used to optimise the proposed system, and the results are compared with those of the Homer Pro software. Singh, Baredar, and Gupta (2017) proposed hydrogen fuel cell and solar PV hybrid energy systems for independent application. Through the fuzzy logic method to calculate the best equipment cost and replacement cost, and the best equipment cost is applied to the Homer Pro software to calculate the best performance of the hybrid energy system. Singh, Chauhan, and Singh (2020) conducted technical and economic analysis on the hybrid energy system based on the solar PV fuel cell. Artificial bee colony algorithms, particle swarm optimisation algorithms, and hybrid algorithms were used to optimise the net cost of the proposed system. The results of the three algorithms are compared in terms of cost effectiveness. Mokhtara et al. (2020) reduce carbon dioxide emissions by providing electricity for buildings and hydrogen for public transport through solar energy. The HRES-$H_2$ system uses solar PV cells to power the university campus building, and converts the surplus power into hydrogen through the proton exchange membrane electrolyser, which is then used to power the trams in Valgara, Algeria. Assaf et al. (2018) used the multi-objective optimisation of the genetic algorithm to calculate the size of the main equipment of the solar hydrogen coupling system. The goal is to maximise the overall reliability of the system, minimise the energy cost, and minimise the percentage of unused excess energy in PV power generation. Bornapour et al. (2017) established a microgrid model composed of a proton exchange membrane fuel cell combined heat and power, wind turbine, and PV units, and determined the optimal scheduling state of these units by considering the uncertainty of renewable energy. Guinot et al. (2015) studied the operation of a PV cell system with independent application. The optimal system configuration is determined by optimising the size of components and the parameters of power management strategy, and the power consumption of auxiliary equipment and the aging of components (battery, electrolyser, and fuel cell) is considered. The purpose of the study by Akhtari, Shayegh, and Karimi (2020) was to analyse the hybrid renewable energy system including wind energy, hydrogen energy, and solar energy, to improve the efficiency and reliability of the system, and provide users with power and heat demand. Luta and Raji (2018) made a comparative analysis on the power grid expansion and the implementation of the renewable off-grid hybrid power system. The purpose of the study was to determine the best feasible scheme. Ghenai, Salameh, and Merabet (2020) designed an off-grid solar PV fuel cell hybrid power generation system. The main objective is to optimise the design and development dispatching control strategy of the independent hybrid renewable power system to meet the power load of residential quarters in desert areas. Jahangiri et al. (2019) modelled and quantified the actual electricity production and cost-effective hydrogen based storage systems in several cities in Chad. Xu et al. (2020) proposed a two-stage data-driven multi-criteria decision-making framework to study the optimal configuration of an off-grid wind–light–hydrogen system. In the first stage, a set of Pareto solutions is determined based on the improved non-dominated sorting genetic algorithm. The objective is to simultaneously minimise the average cost of energy, the possibility of power supply loss and the rate of power abandonment. In the second stage, the weights of the three objectives are determined by the importance cross-correlation method, and the unique optimal solution is selected from the Pareto solutions by the similarity ranking technique of ideal solutions. Mehrjerdi (2020) conducted modelling and research on peer-to-peer energy management in buildings. The optimal power of the solar system, power line, fuel cell, and electrolyser, the optimal capacity of the hydrogen storage tank, and the optimal operation mode (charge-discharge mode) of the hydrogen storage system is obtained. Ruiming (2019) proposed an integrated energy system composed of wind turbines, photovoltaic cells, electrolytic hydrogen, fuel cells and hydrogen storage units, and discussed the construction of multi-objective day power dispatching of integrated energy system considering operation and environmental costs. Xu et al. (2018) proposed a multi-objective optimisation model for the configuration of wind power and/or energy storage and/or a local user hybrid energy storage system. A wind farm in Hebei Province is studied and discussed. Through scenario analysis, sensitivity analysis, and comparative analysis, the advantages of the model are demonstrated. Zhang et al. (2020) used a branch cutting algorithm to obtain the minimum annual total cost of the system satisfying different combinations of power load and thermal load: photovoltaic–thermal load–battery, photovoltaic–thermal load–hydrogen, and photovoltaic–thermal load–battery–hydrogen. The influence of heat load on the comprehensive energy efficiency of fuel cell cogeneration is considered. Kikuchi et al. (2018) conducted technical and economic analysis on hydrogen production from photovoltaic power generation using a battery assisted electrolyser. The installed capacity of each module technology is optimised for various unit costs of photovoltaic, battery, and proton exchange membrane electrolyser.

Loisel et al. (2015) evaluated the economics of a hybrid power plant consisting of offshore wind farms and hydrogen production storage systems in the Loire River region of France. Sultan et al. (2020) studied the optimisation design of hybrid renewable energy systems dependent on the power grid and off-grid. The system consists of PV cells, a wind turbine, and a fuel cell with hydrogen tanks to store energy in the chemical form. A new meta-heuristic optimisation technique is used to achieve the optimal component size of the proposed hybrid power system. Zhang et al. (2019) proposed a new hybrid optimisation algorithm for the optimal sizing of a stand-alone hybrid solar and wind energy system based on three algorithms: chaotic search, harmony search, and simulated annealing. Diab et al. (2019) proposed a simulation model to describe the operation of a PV–wind–diesel hybrid microgrid system. Optimal sizing of the proposed system has been presented to minimise the cost of energy supplied by the system while increasing the reliability and efficiency of the system presented by the loss of power supply probability.

As for the CCHP system, many scholars combine solar energy and a CCHP system to add energy storage system, apply new operation strategy, and use a double-layer optimisation algorithm to study. Romero Rodríguez et al. (2016) combined solar energy with a cogeneration system to analyse the configuration of natural gas internal combustion engine, photovoltaic and other equipment, and made a detailed analysis of life cycle cost, emissions, and primary energy consumption. Yang and Zhai (2018) established a mathematical model of the CCHP system mixed with photovoltaic panels and solar collectors. A particle swarm optimisation algorithm is used to find the optimal value of design parameters. Five operation strategies are used in the hybrid system, and the performance of the hybrid system under different operation strategies is analysed. The hybrid system is compared with the conventional system. Yang and Zhai (2019) modelled the CCHP system with a PV system and solar system, and applied the particle swarm optimisation algorithm to find the optimal value of design parameters. Besides, the solar hybrid CCHP systems of three different buildings in seven climate regions of the United States were simulated. Based on the simulation results, the energy output characteristics and operation performance of the solar hybrid CCHP system were studied. Zheng et al. (2019) proposed a new heat storage strategy for the CCHP system, which determines the operation state of a power generation unit according to the power demand, heat demand, and the state of the heat storage device. The working principle of heat storage strategy is introduced and compared with traditional strategy. Taking a hospital in Shanghai as an example, the system performance under different storage strategies is evaluated and compared. Xi et al. (2018) proposed a two-layer optimisation method to optimise the combination of desalination and an independent CCHP system, which is assumed to be installed on a remote South China Sea island. The universal method and branch and bound method are used to solve mixed-integer linear programming optimisation problems in design and operation stages, respectively. Yang et al. (2017) proposed a CCHP and solar thermal coupled compressed air energy storage (S-CAES) system based on the gas turbine. The off-design model of the gas turbine based on CCHP and S-CAES is established. The advantages and disadvantages of two different control strategies are analysed. Ebrahimi and Keshavarz (2015) studied the optimal orientation and size of the solar collector integrated with the basic CCHP system. The optimum conditions of the solar collector are determined under five different climatic conditions, and the advantages of using the hybrid CCHP system instead of the basic CCHP system are discussed. Wang et al. (2018) proposed a CCHP system combining solar energy and compressed air energy storage. Solar energy and cool storage air conditioning system are combined to heat the high-pressure air in the gas storage. From the perspective of investment cost and efficiency, the multi-objective optimisation method based on a non-dominated sorting genetic algorithm is adopted to obtain the optimal performance of the CCHP system. Ren, Wei, and Zhai (2020) proposed a hybrid CCHP system, and two different solar energy utilising systems are evaluated. The NSGA-II algorithm is used to search for the Pareto front solution of the multi-objective optimisation model considering economic, energy and environmental performance. Li et al. (2020) proposed an improvement strategy following balanced heat-electrical load (FBL) for the CCHP system with a heat pump. The proposed FBL strategy is applied to the CCHP system of a high-speed railway station, and the performance of the FBL strategy is compared with that of the following hybrid electric-heating load (FHL) strategy. Ren et al. (2019) optimised the integrated performance of a hybrid combined cooling, heating, and power system driven by natural gas as well as solar and geothermal energy resources from the energy, economy, and emission perspectives. Li et al. (2019) proposed a combined cooling, heating, and ground source heat pump system with a heat exchanger to improve the comprehensive performance, and compared it with a CCHP–GSHP system without a heat exchanger.

In this chapter, the solar energy, hydrogen production systems, and CCHP systems are combined to realise the system cold–heat–electricity–hydrogen combined power supply. Taking the total system cost as the objective function, the configuration of the system with the lowest unit energy supply cost is obtained. The optimal system is analysed and described in detail. A reference system was introduced to compare the total cost of the system, primary energy consumption and carbon dioxide emissions. The novelty of this study is that it solves the problem of high light dissipation in China, reduces the survival pressure for traditional enterprises, and reduces a large amount of carbon dioxide emissions. Connecting the building energy system to the public transportation sector by producing hydrogen, providing it to hydrogen-filling stations for hydrogen fuel cell vehicles, to increase the share of renewable energy, and make it feasible from a technical, economic, and environmental perspective.

### 1.3. Project Overview

Energy conservation, emissions reduction, and environmental protection are China's basic state policies. The Outline of the 12th Five-Year Plan for National Economic and Social Development sets clear targets: ‘By 2020, the Chinese government promises that non-fossil energy will account for about 15% of primary energy consumption, and the carbon dioxide emissions per unit of GDP will be reduced by 40 to 45% compared with 2005 levels’. On 10 September 2013, the State Council issued the notice of the State Council on the action plan for the prevention and control of air pollution. In the document, clear requirements are put forward for the concentrations of inhalable particulate matter and fine particulate matter (PM) reduction index in the Beijing Tianjin Hebei region, Yangtze River Delta, and Pearl River Delta to the end of 2017. By 2017, the PM10 concentration in regional and the abovementioned cities in China will be reduced by more than 10% compared with 2012. The concentrations of fine particles in the Beijing Tianjin Hebei region, the Yangtze River Delta region, and the Pearl River Delta region decreased by 25%, 20%, and 15%, respectively. The average annual concentration of fine particles in Beijing is about 60 microgram per cubic metre of air ($\mu g/m^3$).

In order to implement the notice of the State Council on printing and distributing the action plan for the prevention and control of air pollution, the government has strengthened the prevention and control of air pollution and the improvement of air quality in Beijing, Tianjin, and Hebei and the surrounding areas. In addition, according to the requirements of the State Council, the Ministry of Environmental Protection and the State Energy Administration issued a guide for the implementation of the action plan for the prevention and control of air pollution in Beijing, Tianjin, Hebei, and surrounding areas.

In recent years, the national economy of Panjin City has achieved rapid development. Its comprehensive strength has been significantly enhanced, the urban and rural outlook has been continuously improved, and people's living standards have been significantly improved. The Panjin municipal government actively implements the macro-control policies of the central government, closely combines the actual situation of Panjin City, and strives to speed up the development in the adjustment and take the lead in the competition. A series of strong measures have been taken actively, scientifically, and decisively to maintain the steady and healthy economic development of Panjin City, and to increase the income of urban and rural residents year by year.

From the existing problems in the national economic and social development of Panjin City, it can be seen that the contradiction between environmental capacity, energy resource carrying capacity, and accelerating development is sharp, the rigid constraint of energy resources and environment on economic development is prominent, and the need to adjust the industrial structure and transform the mode of economic development is urgent. Therefore, we should follow the development path of ‘scientific development, green rise’, develop renewable energy, cultivate and strengthen related industries, form new economic growth points, and promote the transformation of economic development mode from resource-dependent to multi-support At present, the utilization of solar energy resources is one of the important development directions of national energy strategy. The rational development of solar energy resources in Panjin City can promote the development of related industries and provide strong support for Panjin Economic Development.

Solar energy is a renewable, clean source of energy. Solar power is the process of converting local natural solar energy into electricity. The production process does not emit any harmful gas and does not pollute the environment. The Law on the Prevention and Control of Air Pollution of the People's Republic of China sets clear limits on pollutant emission standards or total volume control targets for newly built or expanded thermal power plants that emit sulphur dioxide. With the gradual increase of the enforcement of this law, the investment cost of the new thermal power plant, and the cost of the technical transformation of the existing thermal power plant will increase greatly. In this case, the use of solar energy to generate power will be no fuel consumption and no 'three wastes' emissions. The solar power station will implement greening projects at the same time, these play a role in promoting the development of the local vegetation and trees, protecting land resources, adjusting the ecological environment, as well as improving the regional climate environment.

Panjin area is rich in solar energy resources in Liaoning Province. The development and construction of the Gada Lou Reservoir PV project have a good demonstration role for the construction of photovoltaic power station projects in the region. The construction of the reservoir PV project not only has good economic benefits, but also has significant social benefits. The planned PV power station is located in Dawa, Panjin City, Liaoning Province, and the planning level year is 2021.

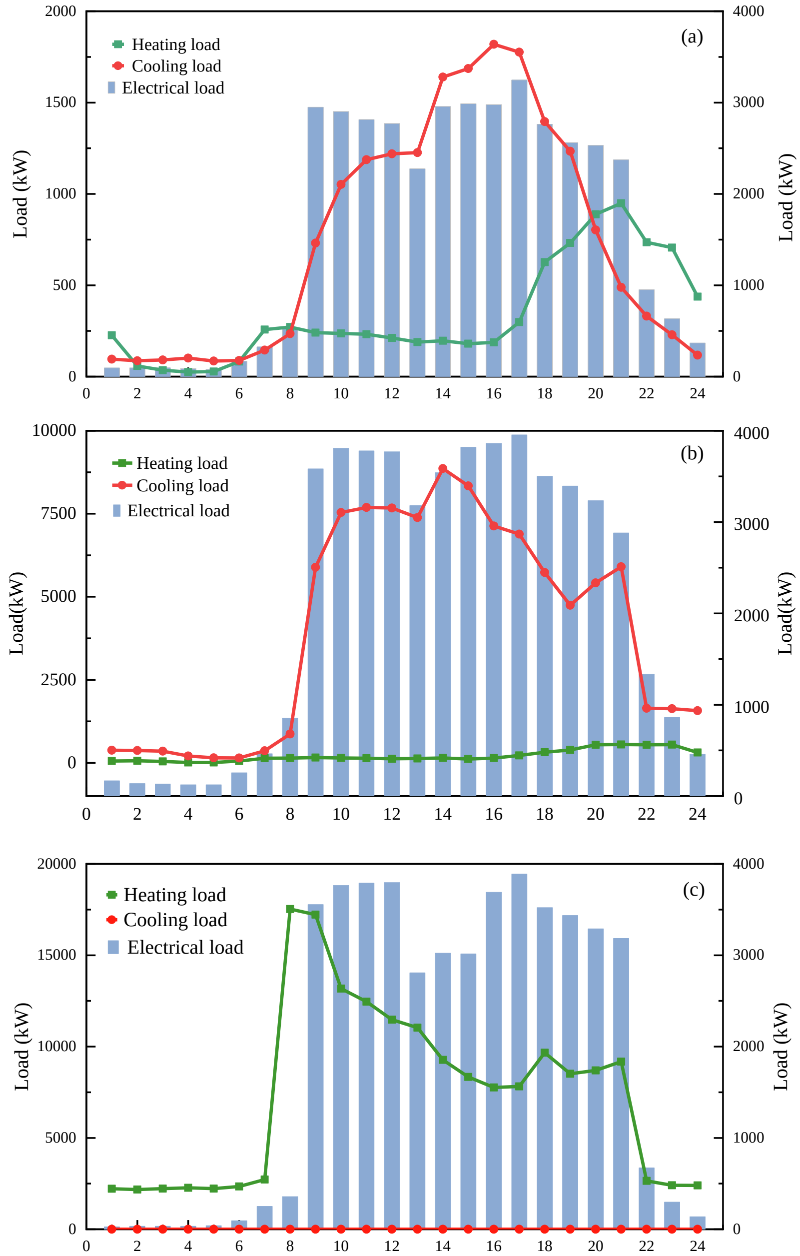
Panjin City is a prefecture-level city under the jurisdiction of Liaoning Province. It is located in the central area of the Liaohe River Delta and on the estuary of the Liaohe River. Topographic features are higher in the north and lower in the south, and gradually incline from north to south. Panjin is located in the north temperate zone, it has a warm temperate continental subhumid monsoon climate. The main characteristic of the climate is four distinct seasons. Wind and rain are less in spring. The climate is dry. Liaoning Province has jurisdiction over one county and three districts. The total area is 4,102.9 square kilometres.

## 2. Research

### 2.1. Building Description and Climate Description

According to the climate of Panjin, the whole year is divided into three parts: winter (November–February), transition season (March–June, October), and summer (June–September). Three typical days are selected from the three parts, and each typical day is divided into 24 periods. Regional buildings are selected to simulate the change of cooling and heating load, including hotels, office buildings, and shopping malls. The building area of each type is 50,000m$^2$. The hourly variation of cooling, heating, and power load of each typical day is shown in Figure 4.3. The power demand of the three typical days is relatively stable, the demand for cooling and electricity is dominant in summer, and the demand for heating and electricity is dominant in winter. The data source is from Hua Dianyuan software.

## Figure 4.1: Typical Daily Cooling, Heating, and Power Load

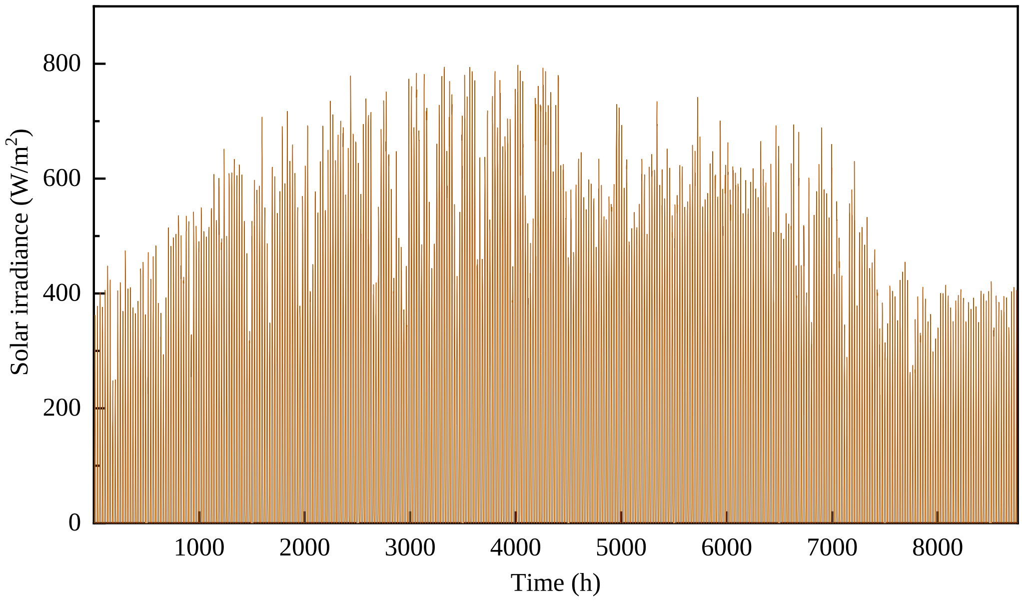


Building electrical, heating,cooling load ：
(a)Typical day of transition season (b)Typical summer day (c)Typical winter day

kW = kilowatt.

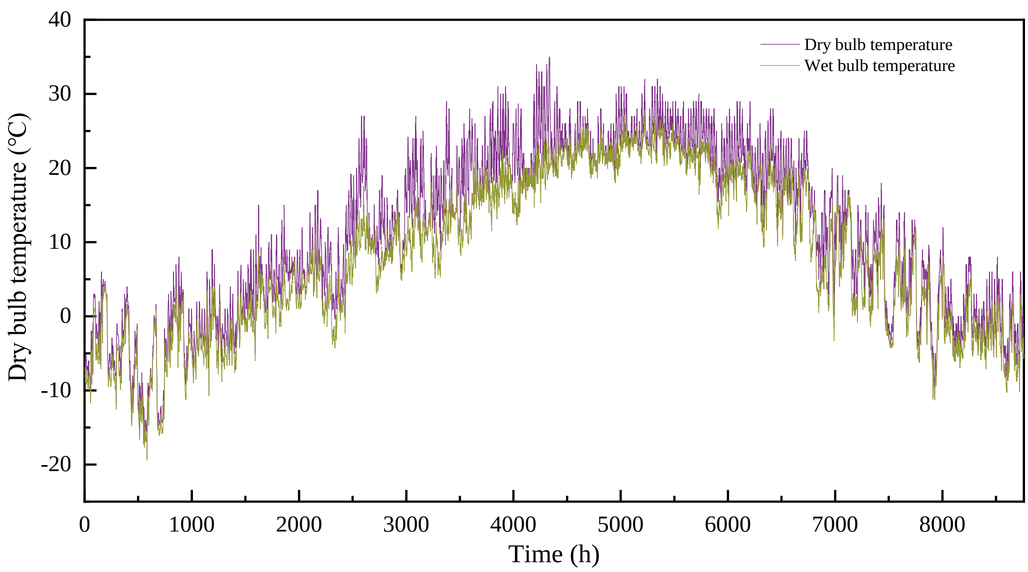
Source: Hua Dianyuan software.

**Figure 4.2: Annual Hourly Solar Radiation in Panjin**




W/m² = watts per square metre.
Source: Hua Dianyuan software.

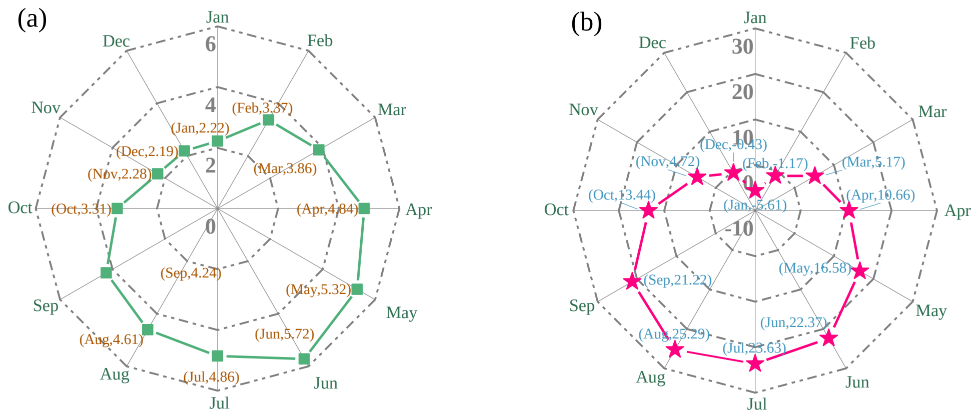
**Figure 4.3: Dry Bulb Temperature and Wet Bulb Temperature**




Source: Hua Dianyuan software.

Annual hourly solar radiation in Panjin is shown in Figure 4.2. Dry bulb temperature and wet bulb temperature are shown in Figure 4.3. The average monthly light intensity in Dalian is shown in Figure 4.4a. The light intensity is very high from April to August. It can be seen that the solar radiation intensity reaches the maximum in June and the minimum in December. The average temperature over 12 months is shown in Figure 4.4b. The temperature is above 20°C from June to September, with the highest monthly average temperature of 25.29°C in August, and below zero in January, February, and December. The lowest temperature is –5.61°C in January.

**Figure 4.4. Monthly Average Light Intensity in Dalian**



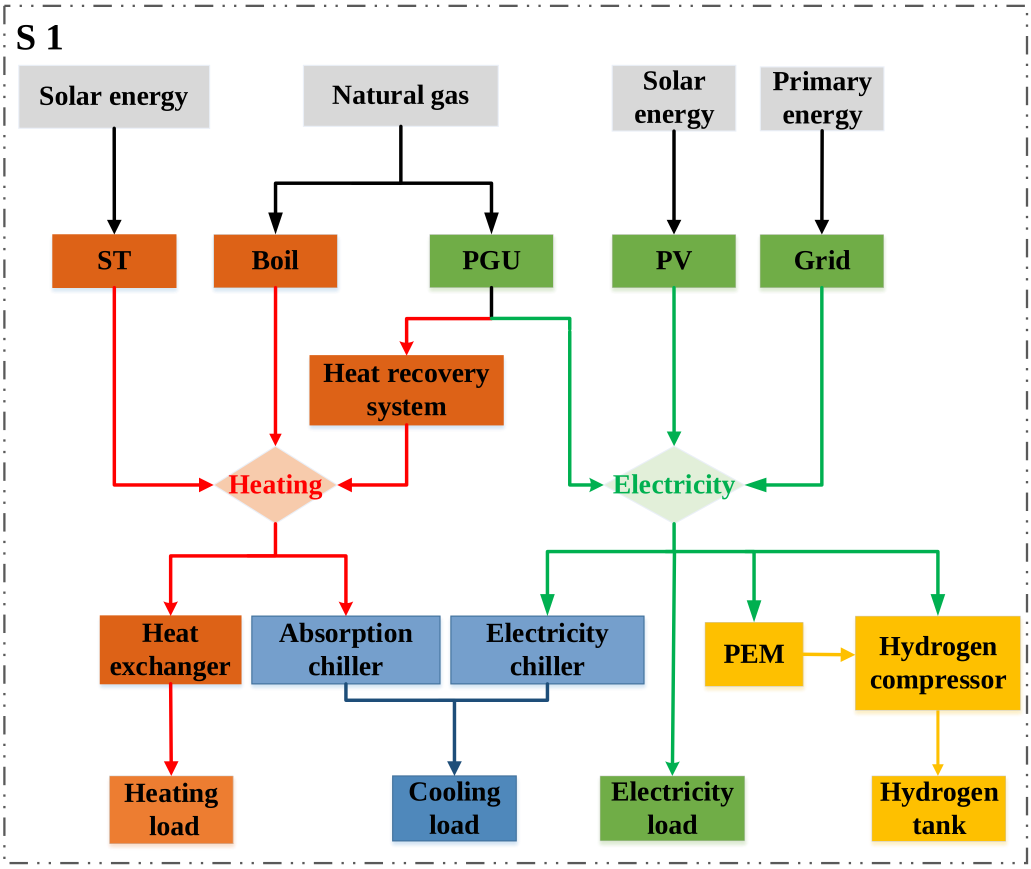

Monthly average solar radiation (kW/m²/day) Monthly average temperature (°C)

kW/m² = kilowatts per square metre.
Source: Hua Dianyuan software.

## 2.2. System Description

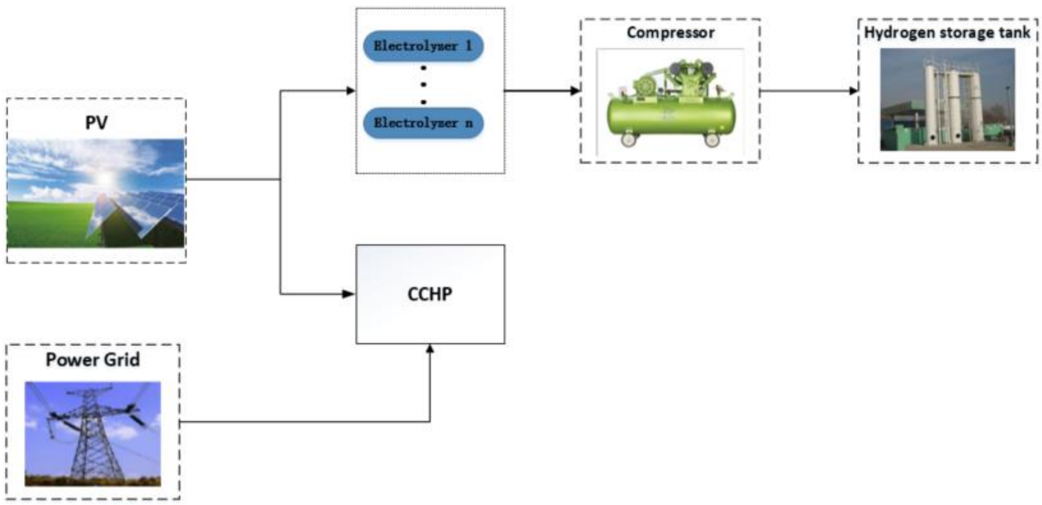
Dalian is rich in renewable energy, but wind energy is not suitable for large-scale use in urban areas. In contrast, PV panels have broad development prospects in urban high-rise buildings due to their flexible and reliable layout and other natural and technical advantages. Therefore, in this study, a hybrid energy system driven by solar energy and natural gas is proposed and modelled and optimised. The system structure is shown in Figure 4.5. The main demands of buildings include power, hydrogen, heating, and refrigeration. The main power generation equipment in the system are gas turbines and PV cells. When the power of the system cannot meet the load demand of users, the grid supplies power to users. When the light intensity is zero, the system does not produce hydrogen. The generated hydrogen passes through a nearby hydrogenation station to charge the hydrogen fuel cell buses to meet the hydrogen demand. Fuel cell vehicles can be recharged from 9 p.m. to 5 a.m., and the amount of hydrogen required for each fuel cell vehicle is 25 kg/day. This can effectively solve the problem of abandoned light. Absorption chillers and compression chillers provide cooling loads for users, and heat collectors and waste heat recovery systems provide heat energy for users. When the generated heat cannot meet the load demand of users, the auxiliary boiler supplies heat energy to users.

**Figure 4.5: CCHP System Flow Chart**




CCHP = combined cooling, heating, and power, PEM = proton exchange membrane, PGU = power generation unit, PV = photovoltaic, S = System 1, ST = solar thermal collector.
Source: Prepared by author.

**Figure 4.6: System Diagram**




CCHP = combined cooling, heating, and power, PV = photovoltaic.
Source: Prepared by author.

The equipment parameters of the system and their costs are shown in Table 4.1 and Table 4.2.

**Table 4.1. Equipment Costs of the System**

| Facility | Unit | Price |
|---|---|---|
| Absorption chiller | $/kW | 216 |
| Electricity chiller | $/kW | 134 |
| Boiler | $/kW | 25 |
| Heat exchanger | $/kW | 22 |
| Power generation unit | $/kW | 584 |
| PEM | $/kW | 353 |
| Hydrogen tank | $/kg | 400 |
| Compressor | $/kW | 83 |
| PV | $/kW | 250 |
| Solar thermal collector | $/kW | 200 |

kW = kilowatt, PEM = proton exchange membrane, PV = photovoltaic,
Sources: Obara and Li (2020); Ma, Fang, and Liu (2017).

**Table 4.2: Equipment Parameters of the System**

| Parameter | Symbol | Value |
|---|---|---|
| Gas turbine efficiency | $\eta_{pgu,e}$ | 35% |
| Coefficient of performance of electricity chiller | $COP_{ec}$ | 3.00 |
| Efficiency of the heat recovery system | $\eta_{rec}$ | 80% |
| Heat exchanger efficiency | $\eta_{he}$ | 80% |
| Coefficient of performance of absorption Chiller | $COP_{ac}$ | 0.7 |
| Gas-fired boiler | $\eta_{b}$ | 79% |
| Generation efficiency of the power grid | $\eta_{e}$ | 35% |
| Transmission efficiency of the power grid | $\eta_{grid}$ | 92.2% |
| Efficiency of solar collector | $\eta_{ST}$ | 75% |
| Solar photovoltaic efficiency | $\eta_{PV}$ | 16% |
| PEM efficiency0 | $\eta_{el}$ | 90% |

PEM = proton exchange membrane.
Source: Akhtari, Shayegh, and Karimi (2020).

**Photovoltaic**

Extensive solar power generation is the current mainstream of a form of new energy power generation, but also the world's key planning of the development of content. This power generation method is mainly based on the principle of PV effect to directly convert ground solar energy into electric energy. The whole process is noise-free and pollution-free, and is not limited to regional distribution, with small volumes and a long service life. It is a new energy power generation form vigorously promoted by countries around the world. In the process of power generation, the photovoltaic array panel is the basis of the system and the core of energy conversion. In practical application, in order to improve the capacity of the PV array, multiple PV cells are connected in series to form the corresponding square array, which is convenient for the expansion and specification design of the system. In this chapter, the area of each PV plate is 1.6m$^2$, and the total area of the PV system is expressed by Eq.1.

$$A_{PV} = 1.6 N_{PV} \tag{1}$$

The total output of the PV array is expressed by Eq.2 **Error! Reference source not found.**.

$$P_{PV}(t) = A_{PV}\eta_{PV}(t)G(t) \tag{2}$$

where $\eta_{PV}$ is the efficiency of PV panel, $G(t)$ is the solar radiation intensity in kW/m$^2$/h.

**Proton exchange membrane**

The traditional electrolytic cell operates with a constant hydrogen production rate under the condition of stable electric energy, while the wind power and PV in the integrated energy power generation system are intermittent and random, so the electrolytic cell should be able to produce hydrogen safely and reliably under the condition of unstable electric energy. At present, basic electrolytic cells and proton exchange membrane electrolysers are widely used in integrated energy power generation systems in the world, because these two kinds of electrolysers can operate stably under intermittent fluctuating power, high pressure, high current density and low voltage.

The working principle of the electrolyser is to electrolyse water to produce hydrogen and oxygen. The hydrogen produced is stored in a hydrogen storage tank for sale.

The mass flow rate of hydrogen generated per second (kg/s) is calculated by Eq.3 0.

$$\dot{m}_{H_2} = \frac{E_{el} \times \eta_{el}}{LHV} \tag{3}$$

The amount of hydrogen produced per hour (kg/h) in the mathematical model is shown in Eq.4 0.

$$\Delta H = \frac{E_{el} \times \eta_{el} \times 3600}{LHV} \tag{4}$$

where, LHV is the calorific value of hydrogen, 143 MJ/kg 0.

**Power generation unit**

The gas turbine is widely used in the microgrid because of its small size, long life, high reliability and low environmental pollution. By burning natural gas, the micro gas turbine drives the generator to provide power loads for the system. At the same time, the waste gas with a large amount of heat generated by the micro gas turbine can be recycled by the waste heat recovery system of the CCHP system, which can directly provide the heating load demand for the system, and can also provide the cooling load demand for the system through the absorption refrigeration mechanism. The power generation efficiency of the gas turbine varies with the change of equipment load rate. Low load rate $f$ will lead to a decrease in equipment efficiency. To avoid the prime mover running with too low efficiency, the switching coefficient of the equipment is set, α = 25%(as the Eq. 5)

$$E_{pgu} = \begin{cases} 0 & 0 \le f < 25\% \\ F_{pgu} \times \eta_{pgu,\mathrm{e}} & 25\% \le f < 100\% \\ P_{pgu} & f \ge 100\% \end{cases} \tag{5}$$

**Power grid**

When the power generated by photovoltaic and prime mover is not enough to meet the power consumption of users, insufficient power is provided by the grid. The power of the grid is shown in Eq. 6.

$$E_{grid} = F_e \times \eta_e \times \eta_{grid} \tag{6}$$

where $\eta_e$ is the generation efficiency of the grid, $\eta_{grid}$ is the transmission efficiency of the power grid.

**Heat recovery system**

The temperature of waste heat flue gas produced by the gas turbine is as high as 450–550°C, which can be recycled by the waste heat recovery system. After the waste heat generated by the gas turbine is recovered by the waste heat recovery device, it can be used step by step. The heat recovered from the waste heat recovery system is shown in Eq. 7.

$$Q_{rec} = F_{pgu} \times \left(1 - \eta_{pgu,e}\right) \times \eta_{rec} \tag{7}$$

where $\eta_{rec}$ is the efficiency of the heat recovery system.

**Boiler**

The gas boiler is different from the micro gas turbine to generate electric energy after burning natural gas, but after burning natural gas to generate high temperature steam, to provide users with hot load and cold load requirements. When the heat generated by a board and waste heat recovery device cannot meet the cold and hot demand of users, the gas boiler will supplement the insufficient heat, as Eq.8 shows.

$$Q_b = F_b \times \eta_b \tag{8}$$

**Heat exchanger**

The heat is provided to the user through the heat exchanger, and the efficiency relationship of the heat exchanger as Eq.9 shows.

$$Q_h = Q_{he} \times \eta_{he} \tag{9}$$

**Absorption chiller**

In the hybrid energy system, an absorption chiller is introduced into the system to provide cooling loads for the system by using the high temperature exhaust gas produced by various power generation equipment. It can not only improve the comprehensive energy utilisation efficiency of the system but also effectively improve the operation mode of the system. At present, waste heat drive technology mainly includes absorption refrigeration technology and adsorption refrigeration technology, amongst which absorption refrigeration technology has been widely used in practice. At present, the most widely used absorption chillers are mainly based on ammonia or lithium bromide. By using the evaporation characteristics of the refrigerant and the absorption and heat dissipation characteristics of the absorbent, the waste heat in the exhaust gas is converted into the cooling load required by the system. Due to the large volume, high cost and corrosive ammonia water, ammonia-water absorption chiller is gradually replaced by lithium bromide absorption chiller with low cost, simple equipment and high reliability, as shown in Eq.10.

$$Q_{ac} = Q_{acr} \times COP_{ac} \tag{10}$$

where $COP_{ac}$ is the coefficient of performance of the absorption chiller.

**Electricity chiller**

The electricity chiller drives the compressor to work by consuming electric energy, generating the cooling capacity required by the system and supplying the cooling loads of the system. The system consists of a compressor, condenser, refrigeration heat exchanger, throttling mechanism, and some auxiliary equipment. The electricity chiller compacts the gas through the compressor, releases the heat after condensing in the condenser, and then reduces the pressure and temperature through the throttling mechanism. After that, the gas absorbs the heat from the refrigerant and evaporates into steam, which continues to enter the compressor and so on.

When the cooling capacity produced by the absorption refrigerator is not enough to meet the cooling load of users, the insufficient cooling capacity is supplemented by the compression refrigerator. The compression refrigerator drives the compressor to work through the consumption of electric energy, to generate the cooling capacity required by the system and supply the cooling load of the system. Cooling load from a compression refrigerator is calculated by Eq.11.

$$Q_{ec} = E_{ec} / COP_{ec} \tag{11}$$

where, $Q_{ec}$ is the cooling capacity produced by the compression refrigerator, $COP_{ec}$ is the coefficient of performance of a compression refrigerator, $E_{ec}$ is the power consumption of the compression refrigerator.

**Hydrogen compressor**

The power consumed by the hydrogen compressor is shown in Eq.12,

$$E = m_{h2} \times n \times \frac{k}{k-1} \times R \times T \times \left[ \left( \frac{P_{n+1}}{P_1} \right)^{\frac{k-1}{nk}} - 1 \right] \times \frac{1}{3600} \tag{12}$$

where, the specific heat ratio $k$ =1.4, the gas constant of hydrogen $R$=4.157 (KJ/kg.K), the inlet gas temperature $T$=290K, the absolute pressure $P_1$=1.5MPa, the outlet pressure $P_{n+1}$=20MPa, the order $n$=1.

**Solar thermal collector**

The total output of the ST is shown in Eq.13.

$$Q_{ST}(t) = A_{ST} \eta_{ST}(t) G(t) \tag{13}$$

where, $\eta_{ST}$ is the efficiency of solar thermal collector, $G(t)$ is the solar radiation intensity in kW/m$^2$/h.

## 2.3. Equilibrium Equation

**Electric balance**

According to the energy balance, the sum of PV power generation, generator power generation, and grid power generation should be equal to the sum of the user's power loads, power consumption of refrigerators, and electrolysers. As shown in Eq.14.

$$E_{pgu} + E_{PV} + E_{grid} = E + E_{ec} + E_{el} + E_{com} \tag{14}$$

**Heat balance**

The sum of the heat recovery system, the heat of the photovoltaic and the heat of the boiler is equal to the sum of the heat required by the absorption refrigerator and the heat of the heat exchanger, as Eq.15 shows.

$$Q_{pgu,r} + Q_{ST} + Q_b = Q_{acr} + Q_{he} \tag{15}$$

**Cold balance**

The refrigeration capacity of the absorption refrigerant and compression refrigerator should meet the cooling load required by users. As shown in Eq.16.

$$Q_{ec} + Q_{ac} = Q_c \tag{16}$$

In the optimisation analysis of the hybrid energy system, some important assumptions are as follows.

(a) It is assumed that the hybrid energy system is completely reliable.

(b) The tilt angle of PV is equal to the local dimension.

### 2.4. Objective Function

In this chapter, the annual cost of the optimal objective function to optimise so it is given as Eq. (17).

$$ATC = C_{ini} + C_{O,M} + C_{fule} \tag{17}$$

where, $C_{ini}$ is the annual capital recovery cost, including equipment costs, engineering costs and some indirect costs. $C_{ini}$ can be obtained from Eq.18. $C_{O,M}$ is the operation and maintenance cost of the system, as shown in Eq.20. $C_{fule}$ is the cost of raw materials consumed by the system, as shown in Eq.21.

$$C_{ini} = \left( \sum_{i=1}^{n} P_{rated,i} \Phi_i \right) \left(1 + f_{other}\right) f_{cr} \tag{18}$$

where, $f_{other}$ is the conversion factor of other costs, including other auxiliary equipment costs, engineering costs and indirect costs. The capital recovery coefficient $f_{cr}$ is shown in Eq.19. $\Phi_i$ is the unit cost of the equipment. The value of $f_{other}$ is shown in Table 4.3.

$$f_{cr} = \frac{r\left(1+r\right)^m}{\left(1+r\right)^m - 1} \tag{19}$$

where, the superscript $m$ is the lifetime of the system, which is assumed to be 20 years.

$$C_{O,M} = \left( \sum_{i=1}^{n} P_{rated,i} \Phi_i \right) f_{O,M} \tag{20}$$

$$C_{fule} = \sum_{t=1}^{8760} \left( F_{s,t} C_g + E_{grid} C_e \right) \tag{21}$$

The value of $f_{O,M}$ is shown in Table 4.3. The value of $C_g$ and $C_e$ are shown in Table 4.4.

The cost and replacement cost can be calculated by Eq.22–25**Error! Reference source not found.** .

$$C_{ele} = PAF\left(P_{ele} \times C_{ele}\right) \tag{22}$$

$$C_{re,ele} = PAF\left[P_{ele} \times C_{ele} \times FPF\left(10\right)\right] \tag{23}$$

$$FPF\left(k\right) = \left(1+j\right)^{-k} \tag{24}$$

$$PAF = \frac{j(1+j)^n}{(1+j)^n - 1} \quad (25)$$

where PAF represents the factor of converting present value to annual value, *j* and *n* are the annual interest rate and the electrolyser lifetime which in this chapter are assumed as 5% and 10 years, *FPF(k)* denotes the factor of convert final value to present value, where *k*=10.

### 2.5. Evaluating Indicator

Unit energy cost is used to evaluate the economic feasibility of the system. According to different hydrogen demands, the equipment configuration with the lowest unit energy cost is selected. Unit energy cost ($/kWh) can be calculated by Eq.26.

$$UEC = \frac{ATC}{E_{served} + C_{served} + H_{served} + H_{2served}} \quad (26)$$

Primary energy consumption (*PEC*) is the primary energy consumption of the system, including natural gas consumption and coal consumption of the power grid, as Eq.27 shows. To meet the strategic requirements of national energy utilisation, the lower the consumption of primary energy, the better.

$$PEC = F_{b,tot} + E_{grid,tot} + F_{en,tot} = \sum_{t=1}^{8760} \left( F_{b,tot} + \frac{E_{grid}}{\eta_e \times \eta_{grid}} + F_{en} \right) \quad (27)$$

China's commitment is to reach the peak of carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060. Therefore, carbon dioxide emissions (*CDE*) is an important indicator to measure whether the system is in line with the goal of energy and environmental friendliness, as Eq.28 shows. The value of $f_e$ and $f_g$ is shown in Table 4.3.

$$CDE = F_{b,tot} \times f_g + E_{grid,tot} \times f_e + F_{en,tot} \times f_g \quad (28)$$

**Table 4.3: Main Parameters in the Optimisation Calculation**

| Parameter | Symbol | Value |
|---|---|---|
| Proportion factor of other costs | $f_{other}$ | 0.5 |
| Proportion coefficient of operation and maintenance | $f_{O,M}$ | 0.02 |
| Carbon emission coefficient of natural gas | $f_g$ | 0.2(kg/kWh) |
| Carbon emission coefficient of the power grid | $f_e$ | 0.977(kg/kWh) |

Source: Li (2017), Benefits Evaluation of Building-scale and District-scale Cooling Heating and Power System [D]. Dalian University of Technology.

**Table 4.4: Natural Gas and Electricity Prices in Dalian Area**

| | Electricity | | | Natural gas |
|---|---|---|---|---|
| Time | (8:00-11:00)<br>(17:00-22:00) | (0:00-5:00)<br>(22:00-24:00) | (5:00-8:00)<br>(11:00-17:00) | |
| Unit price ($/kWh) | 0.1736 | 0.08673 | 0.1158 | 0.03262 |

kWh = kilowatt hour.

Source: Li (2017), Benefits Evaluation of Building-scale and District-scale Cooling Heating and Power System [D]. Dalian University of Technology.

### 2.6. Operation Strategy

The generation capacity of PV cells and the heating capacity of collectors give priority to meet the electricity demand and heat demand of users. When the power consumption is insufficient, generators will supplement the insufficient power. When the heat is insufficient, boilers will supplement the insufficient heat. When there is sufficient PV power, it is used for the electrolysers and the compressors to produce hydrogen and compress hydrogen. When there is no light intensity and PV power is not generated, the electrolysers and the compressors will not operate, as Eq.10 shows. The system produces different kilograms of hydrogen (from 100 kg/day to 1000 kg/day), and the corresponding equipment capacity is different. The optimal hydrogen supply of the system is determined by comparing the unit energy cost, primary energy consumption, carbon dioxide emission and total cost.

$$\begin{cases} E_{pgu} + E_{PV} = E + E_{ec} + E_{el} + E_{com} & E_{PV} > 0 \\ E_{pgu} + E_{grid} = E + E_{ec} & E_{PV} = 0 \end{cases} \tag{29}$$

The main restriction is that the power and heat output of all installed equipment should not exceed the rated power, and the daily hydrogen production should be greater than or equal to the demand, as Eq.30 shows.

$$\begin{aligned} &Q_{i,t} \le Q_{i,rated} \quad \forall i,t \\ &E_{i,t} \le P_{i,rated} \quad \forall i,t \\ &H_2 \ge W \quad W = 100kg/d \sim 1000kg/d \end{aligned} \tag{30}$$

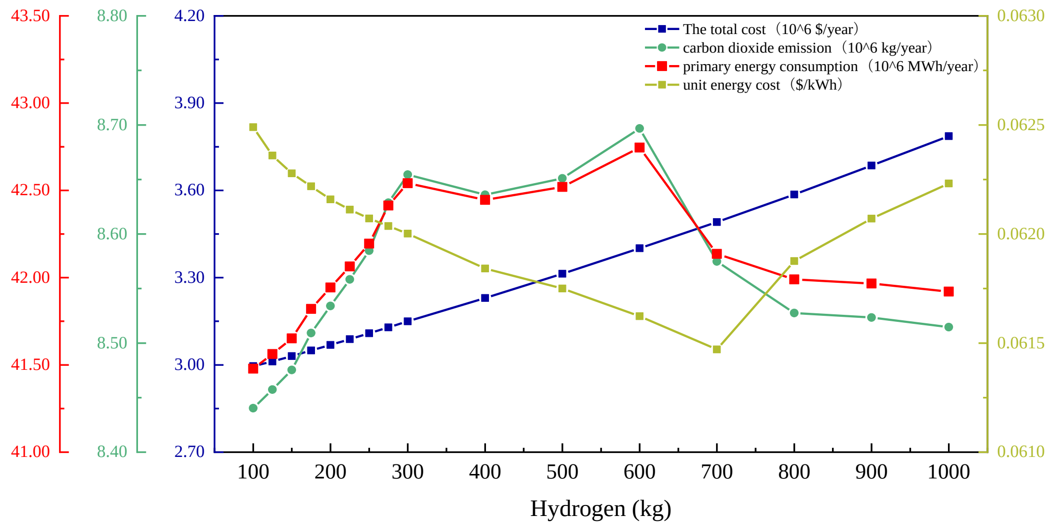
## 3. Results and Discussion

### 3.1. Comparative Analysis of Operation Results

The hydrogen production of the system varies from 100 kg/day to 1000 kg/day. The total cost, unit energy cost, primary energy consumption, and carbon dioxide emissions of the system are shown in Figure 4.7 and Table 4.5. It can be seen that the total cost of the system increases steadily with the increase of hydrogen production. Carbon dioxide emissions and primary energy consumption have a similar trend because the carbon dioxide emitted by the system is mainly produced by the combustion of primary energy.

Carbon dioxide emissions and primary energy consumption increased rapidly with the increase of hydrogen production before 300 kg/day, and reached the extreme value at 300 kg/day and 600 kg/day, with slight fluctuation between them. Carbon dioxide emissions and primary energy consumption of the system with hydrogen production of 700 kg/day decreased rapidly, and then decreased slowly and tended to be stable. At the same time, the unit energy cost decreases with the increase of hydrogen production, reaches the lowest value at 700 kg/day, and then increases rapidly. When the daily hydrogen production of the system is 700kg, the unit energy cost is the lowest, and the primary energy consumption and carbon dioxide emissions are relatively low. Therefore, the optimal hydrogen production of the system is 700 kg/day.

**Figure 4.7: Total Cost, Unit Energy Cost, Primary Energy Consumption, and Carbon Dioxide Emissions of the System**




kg = kilogram, kWh = kilowatt hour, MWh = megawatt hour.
Source: Prepared by authors.

The optimal configuration of the system is shown in Table 4.5 when the amount of hydrogen produced by the system is from 100 kg/day to 1000 kg/day.

**Table 4.5: Optimal Configuration of the System for Different Hydrogen Production**

(The unit of $H_2$ is kg per day and the rest is kW)

| $H_2$ | PV | PEM | ST | PGU | AC | Boil | WHRS | Com |
|---|---|---|---|---|---|---|---|---|
| 100 | 5972 | 514 | 11008 | 3640 | 7655 | 13615 | 5,408 | 21 |
| 200 | 6429 | 1054 | 10809 | 3635 | 7516 | 13639 | 5,400 | 44 |
| 300 | 7086 | 1600 | 10522 | 3627 | 7315 | 13675 | 5389 | 66 |
| 400 | 8966 | 2141 | 9767 | 3605 | 6786 | 13771 | 5357 | 89 |
| 500 | 9462 | 2692 | 9912 | 3600 | 6888 | 13767 | 5348 | 112 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 600 | 10320 | 3284 | 9738 | 3590 | 6766 | 13796 | 5333 | 136 |
| 700 | 12072 | 3849 | 9475 | 3570 | 6582 | 13848 | 5303 | 160 |
| 800 | 13160 | 4528 | 9329 | 3557 | 6480 | 13879 | 5285 | 188 |
| 900 | 14482 | 5245 | 9007 | 3542 | 6255 | 13929 | 5262 | 217 |
| 1000 | 15804 | 5962 | 8712 | 3527 | 6048 | 13977 | 5240 | 247 |

PV = photovoltaic, PEM = proton exchange membrane, ST = solar thermal collector, PGU = power generation unit, AC = absorption chiller, WHRS = waste heat recovery system, Com = hydrogen compressor.
Source: Prepared by authors.

### 3.2. Comparative Analysis of Reference System

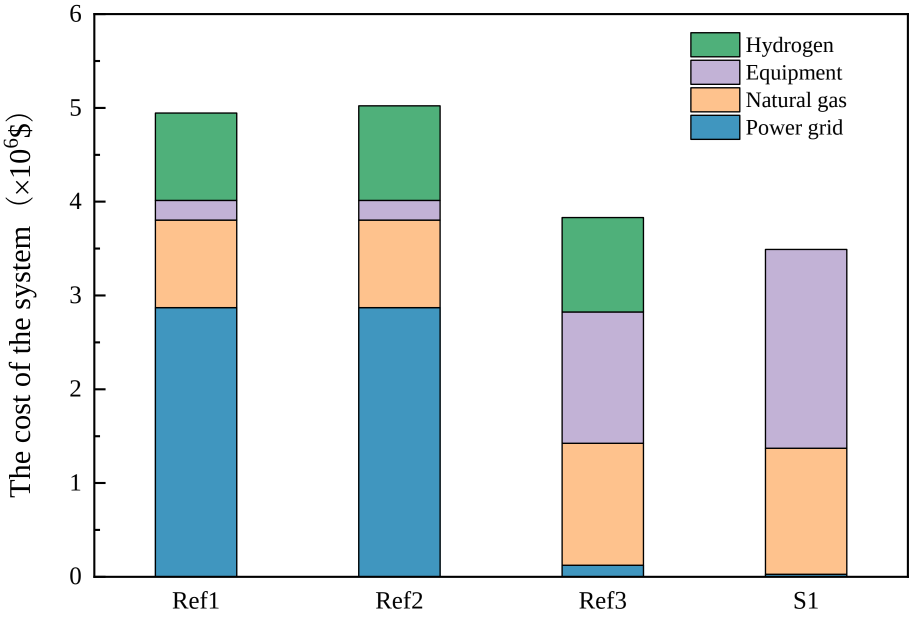
Reference system 1 (Ref 1): the power demand of users is met by the power generation of local thermal power plants and transmitted to the power grid. The cold demand is met by the compression chiller, and the power of the compression chiller is provided by the power grid. The heat demand is met by gas boilers. Hydrogen is produced by coal gasification and transported to hydrogenation stations by storage and road transportation.

Reference system 2 (Ref 2): compared with Ref 1, the supply mode of cooling, heating and power is the same. Hydrogen is provided by the centralised hydrogen production plant of natural gas and transported to the hydrogenation station through storage and transportation and road transportation.

Reference system 3 (Ref 3): it is composed of a CCHP system and centralised hydrogen production mode of the natural gas plant. The electricity demand of users is provided by photovoltaic power generation, internal combustion engine power generation and the power grid. Heat demand is provided by solar collectors, boilers, and heat recovery systems of internal combustion engines. Cold demand is provided by absorption chillers and compression chillers. The mode of hydrogen supply is the same as that of Ref 2.

The cost comparison between the reference system and the design system is shown in Figure 4.8. It can be seen from the figure that the electricity cost, natural gas cost, and equipment cost are the same in the proportion of Ref 1 and Ref 2 costs. Since the cost of centralised hydrogen production from natural gas is higher than that of coal, the total cost of Ref 2 is slightly higher than that of Ref 1. In the total cost of Ref 1 and Ref 2, electricity cost accounts for the largest proportion. In Ref 3 and System 1 (S1), the power cost accounts for a small proportion, because the power demand is mainly provided by internal combustion engine power generation and photovoltaic power generation, and only a small part of the power is supplied by the grid. Overall, the total cost of system S1 is the lowest, in which the equipment cost accounts for a relatively high proportion, followed by the natural gas cost.

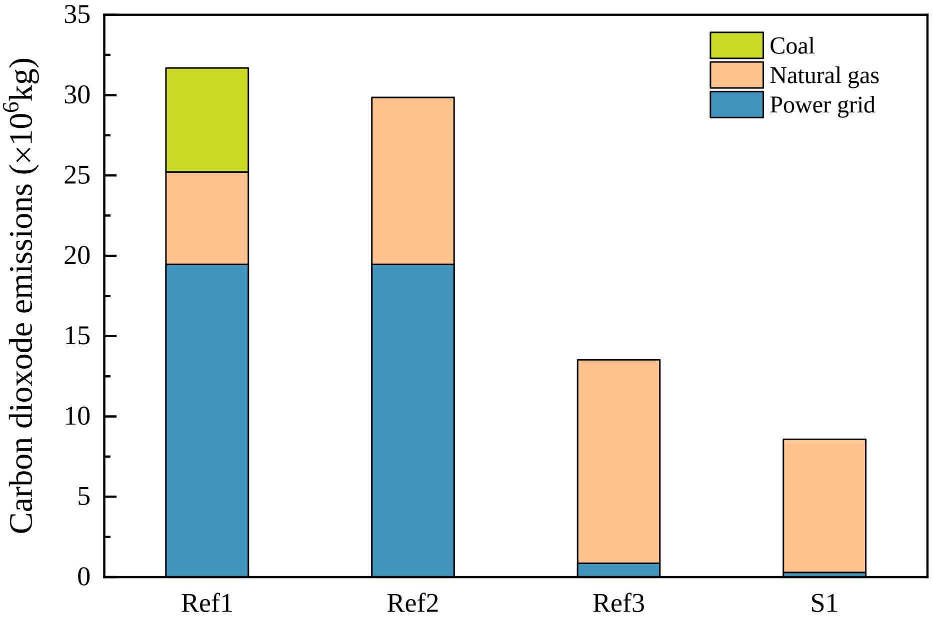
**Figure 4.8: Cost Comparison Between the Reference System and the Design System**




S1= System 1.
Source: Prepared by authors.

The comparison of carbon dioxide emissions between the reference system and the design system is shown in Figure 4.9. As can be seen from Figure 4.9, Ref 1 and Ref 2 have high carbon dioxide emissions. This is because the power of Ref 1 and Ref 2 is provided by the power plant, which will produce a lot of carbon dioxide when generating electricity. Because the hydrogen in Ref 1 is produced from coal, the carbon dioxide emission of Ref 1 is higher than that of Ref 2. Since the electricity of Ref 3 and S1 is provided by the internal combustion engine and PV, PV power generation does not produce carbon dioxide, so the overall carbon dioxide emission of the system is low. Because the hydrogen of the S1 system is produced by electrolyser, and no carbon dioxide is produced in the process, compared with the Ref 3 system, hydrogen is produced by concentrated hydrogen production from natural gas, so the carbon dioxide emission of the S1 system is the lowest.

**Figure 4.9: Comparison of Carbon Dioxide Emissions Between the Reference System and the Design System**

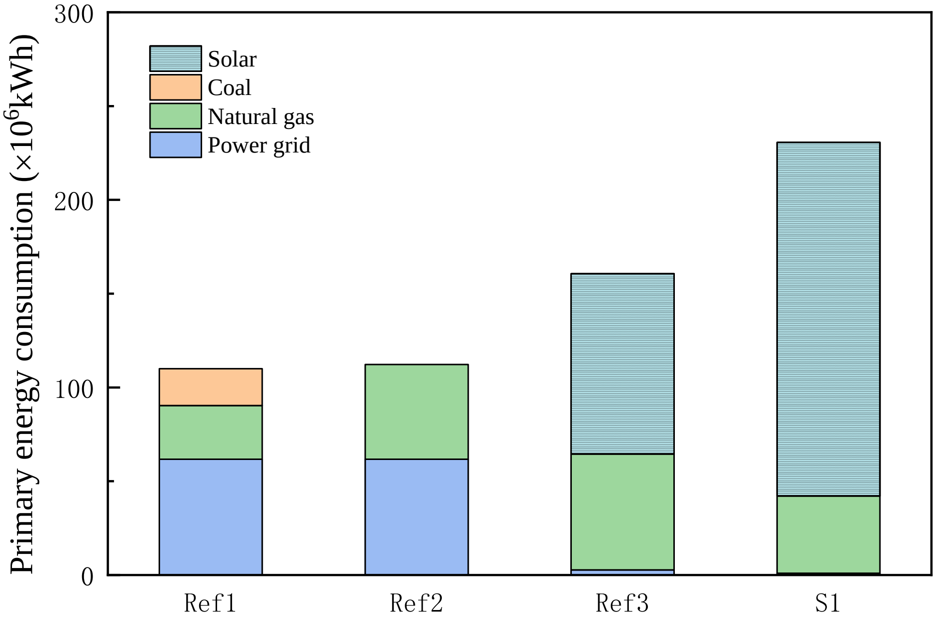



kg = kilogram.
Source: Prepared by authors.

The primary energy consumption of the reference system and the design system is shown in Figure 4.10.

It can be seen from Figure 4.10 that the main primary energy consumption of Ref 1 and Ref 2 is the energy consumption of the power grid. The main primary energy consumption of Ref 3 and Ref 4 is solar energy. Due to the low efficiency of photovoltaic power generation, more solar energy is needed to generate the same power. But solar energy is renewable energy and clean energy, so in general, S1 system energy use is cleaner and more sustainable.

**Figure 4.10: Primary Energy Consumption of the Reference System and the Design System**




kWh = kilowatt hour.

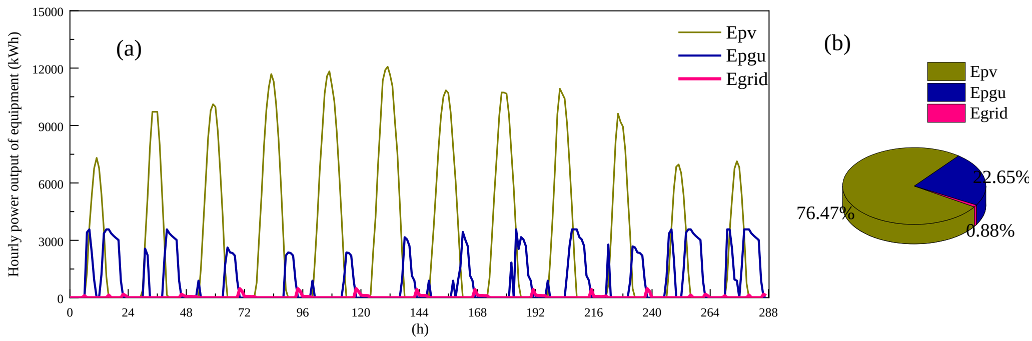
Source: Prepared by authors.

### 3.3. Optimal System Analysis

#### 3.3.1. Analysis of Annual Total Energy Supply of the System

As shown in Figure 4.11(a), in the system with daily hydrogen production of 700 kg/day, the hourly power generation curves of the photovoltaic, gas engine, and power grid in 12 typical days are shown. It can be seen that in the typical days of January, February, November, and December, the gas engine has two obvious peaks in a day, just because the light intensity is weak, and the light time is short in winter. In the morning and evening, the PV power generation is not enough to meet the power consumption of the system, and the engine power generation is needed to supplement the insufficient power. When the demand is small, the internal combustion engine will not run when the power is small due to the start-stop constraint, and the insufficient power will be made up by the power grid. In winter and transition season, the power generated by an internal combustion engine is more. In summer, due to the strong light intensity and more photovoltaic power, the power generated by the internal combustion engine is less. Figure 4.11(b) shows the proportion of photovoltaic, internal combustion engine, and power grid in the total power supply of the system in a year. It can be seen that photovoltaic power generation accounts for 76.47%, internal combustion engine power generation accounts for 22.65% of the total power generation, and power grid power generation accounts for only 0.88%.

**Figure 4.11: Annual Power Supply of the System**

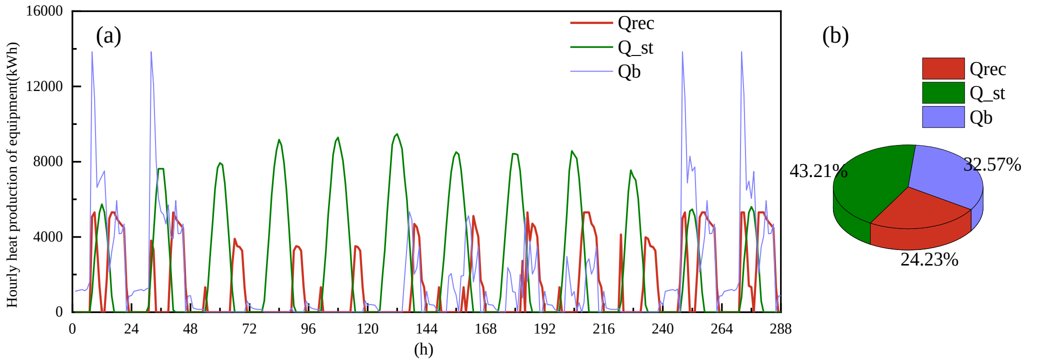



Epv = electricity of photovoltaic, Epgu = electricity of power generation unit, Egrid = electricity of grid, h = hour, kWh= kilowatt hour.

Source: Prepared by authors.

In the system with daily hydrogen production of 700 kg/day, the hourly heating capacity of solar collectors, internal combustion engine waste heat recovery systems, and boilers in 12 typical days is shown in Figure 4.12(a). In January, February, November, and mid-December of winter, the heat output of the boiler is significantly higher than that in other seasons. This is due to the weak light intensity and short light time in winter, and the heat generated by solar collectors is not enough to meet the heat demand of the system, so boilers are used to supplement the insufficient heat. In the typical days of June, July, August, and September in summer, boilers provide heat for the absorption chiller to cool. In the transition season, the demand for heat and cooling capacity is low, so the solar collectors and waste heat recovery systems can meet the needs of users' cooling and heating load, and the calorific value of the boiler is low. As shown in Figure 4.12(b), the annual total calorific value of the solar collectors, waste heat recovery system, and boilers is relatively balanced. The calorific value of solar collectors is the highest, accounting for 43.21% of the total calorific value, followed by boilers, accounting for 32.57% of the total calorific value, and the calorific value of the waste heat recovery system accounts for 24.23% of the total calorific value.

**Figure 4.12: Annual Heating Supply of the System**

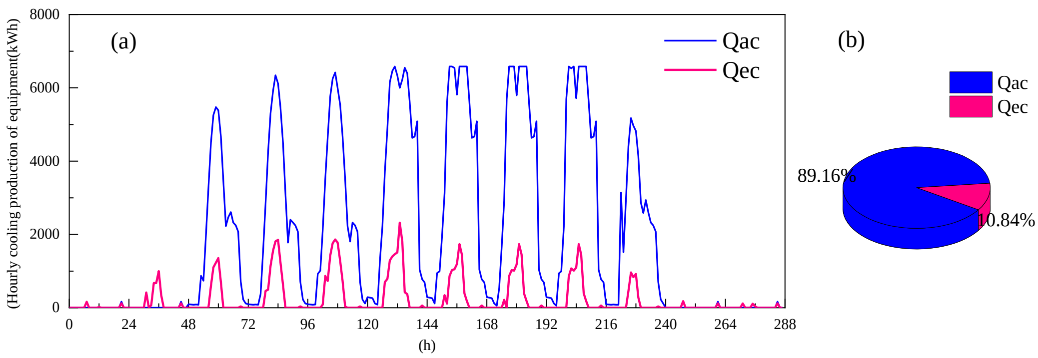



h = hour, kWh = kilowatt hour, Qrec = heat of heat recovery system, Q_st = heat of solar thermal collector, Qb = heat of boiler.

Source: Prepared by authors.

In the system with daily hydrogen production of 700 kg/day, the hourly cooling capacity of the absorption refrigerator and compression refrigerator in 12 typical days is shown in Figure 4.13(a). In winter, there is no cooling load demand, so the cooling capacity of the system is almost zero. As shown in Figure 4.13(b) the cooling capacity provided by the absorption chiller accounts for 89.16% of the total cooling capacity, and the cooling capacity provided by the compression chiller accounts for 10.84% of the total demand.

**Figure 4.13. Annual Cooling Supply of the System**




h = hour, kWh = kilowatt hour, Qac = cooling of absorption chiller, Qec = cooling of electricity chiller.

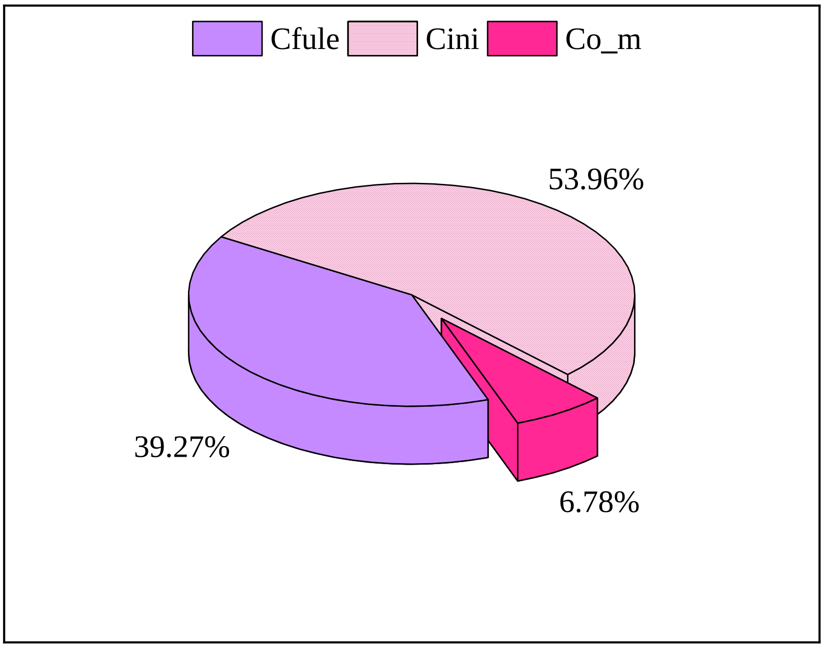
Source: Prepared by authors.

Due to the obvious seasonality, a typical day is selected in winter, summer, and the transition season, respectively for detailed load analysis. Figure 4.14 shows the load balance of cooling, heating, and power in summer.

### 3.3.2. Cost Analysis

The total cost of the system is composed of capital recovery cost, operation and maintenance cost and fuel cost. As shown in Figure 4.14, the highest proportion of capital recovery cost is 53.96%. Fuel cost accounted for 39.27%, and the lowest operation and maintenance cost was only 6.78%.

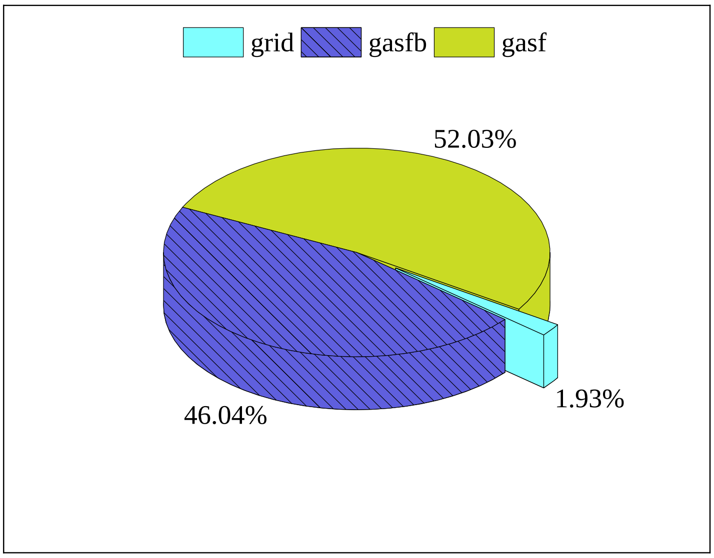
**Figure 4.14: The Total Cost of the System**




Cfule = fuel cost, Cini = capital recovery cost, Co_m = operation and maintenance cost.
Source: Prepared by authors.

Fuel cost includes the cost of natural gas burned by the internal combustion engine, the cost of natural gas burned by the gas-fired boiler and the cost of buying electricity from the power grid. As shown in Figure 4.15, the cost of natural gas consumed by the internal combustion engine is the most, accounting for 52.03%. The gas-fired boiler also accounts for a large proportion, accounting for 46.04%, while the cost of purchasing electricity in the power grid is only 1.93%.

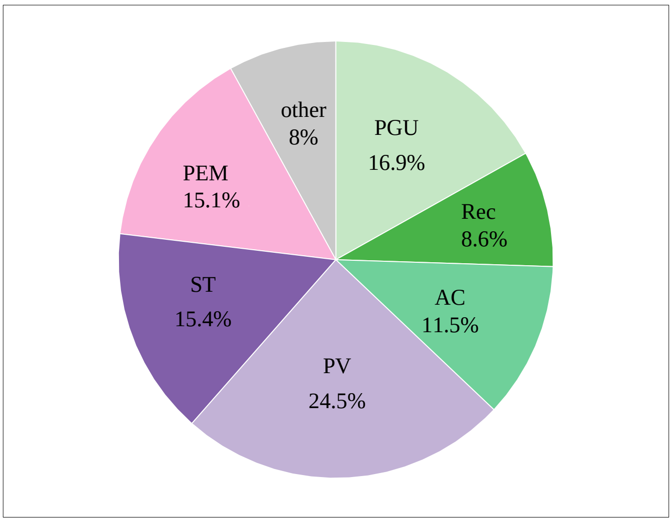
**Figure 4.15: Fuel Cost of the System**




Gasfb = gas fired boiler, gasf = natural gas.
Source: Prepared by authors.

The cost of each piece of equipment in the annual capital cost is shown in Figure 4.16. The cost of photovoltaic is the highest, accounting for 24.48%, the cost of the internal combustion engine is 16.91%, and the cost of solar collector and the electrolytic cell is similar, accounting for 15.37% and 15.08%, respectively. Absorption chillers also account for a large proportion. The cost of heat exchanger, hydrogen storage tank, and boiler accounts for about 2%.

**Figure 4.16: Cost of Each Piece of Equipment in the Annual Capital Cost**




AC = absorption chiller, PEM = proton exchange membrane, PGU = power generation unit, ST = solar thermal collector, Rec = heat recovery system.
Source: Prepared by authors.

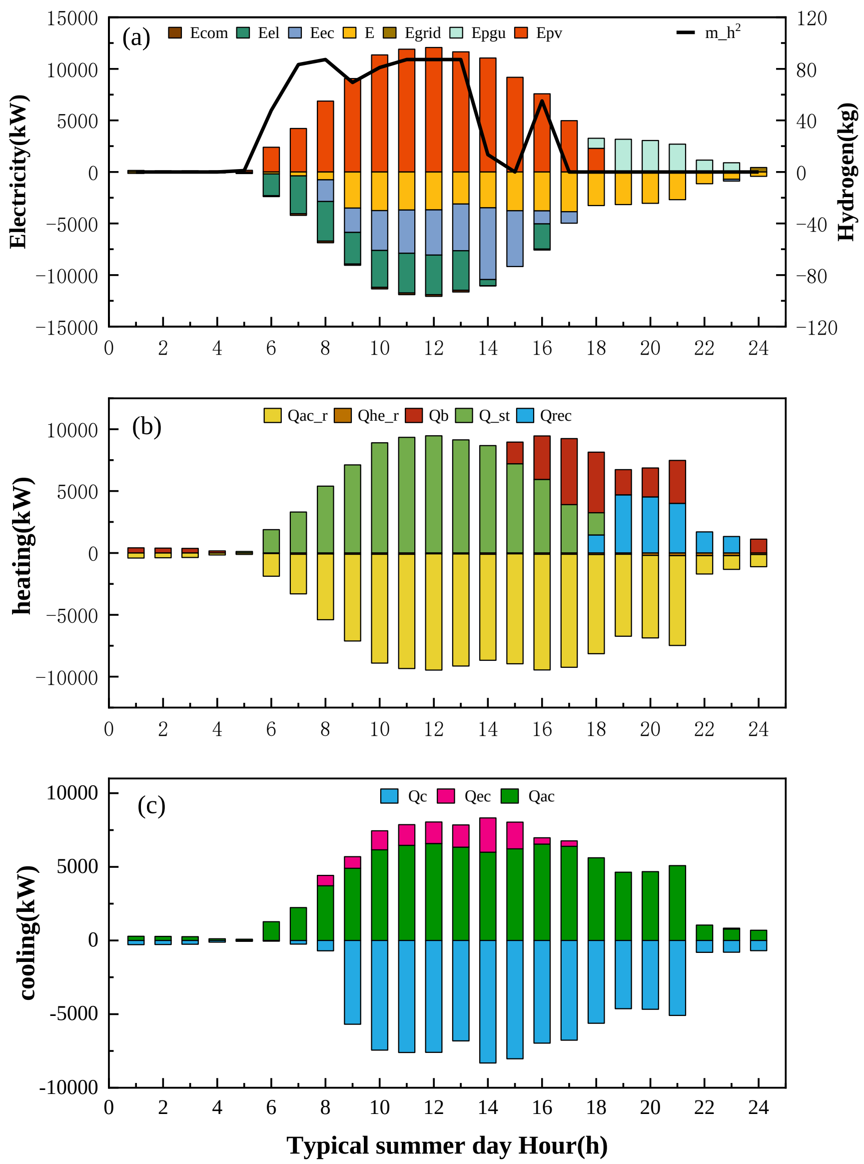
### 3.3.3. Typical Daily Load Analysis

The power output of PV, generator, and the power grid depends on the characteristics of the electric load. The power load, power supply, and hydrogen production of regional public buildings are shown in Figure 4.17(a). The top of the horizontal axis shows the output of the PV, generator, and power grid. The lower part of the horizontal axis indicates the power consumption of the user, the power consumption of the compression refrigerator, the electrolytic cell, and the hydrogen compressor. The black line represents the production of hydrogen at each moment. In summer, the power generation of the system is mainly used for the power load demand of users, followed by the compression chiller and electrolytic cell, and the power consumption of hydrogen compressor accounts for a small part of the total power supply. It can be seen that the amount of hydrogen generated is relatively large from 7:00 to 13:00 on typical days in summer. From 13:00 to 15:00, the power consumption of the compression refrigerator increases greatly, while the user's power consumption still maintains a relatively large demand, which makes the available power of the electrolyser decrease greatly during this period. The hydrogen gas production keeps the same with the change of the power consumption of the electrolyser, and there is no surplus at 15:00 Electricity is used to produce hydrogen for the electrolyser, so the hydrogen production is 0 at this time, and the power consumption of the compressor is also 0. At 16:00 with the decrease of power consumption of the compression refrigerator, the hydrogen production increases again. Then, with the decrease of light intensity, when there is no extra point for hydrogen production, the electrolyser and compressor stop working.

The heat load and heat supply of regional public buildings are mainly provided by solar collectors, heat recovery systems of gas turbines and boilers. As shown in Figure 4.17(b), the heat load and heat supply of a typical day in summer. Above the horizontal axis is the heating capacity of the heating equipment. It can be seen that due to the strong light intensity in summer, the heat supply of solar collectors accounts for a large proportion. The second is the heat recovery system of the gas-fired boiler and internal combustion engine, whose heating period is mainly concentrated in the afternoon when the light intensity is weak and in the evening. Below is the heat required by the absorption refrigerator and the heat exchange of the heat exchanger, that is, the heat load of the user. Since there is a large demand for cooling capacity in summer, we can see that the heat under the horizontal axis is mainly supplied to the absorption chiller for cooling. The heat supplied to the heat exchanger accounts for a small part of the total heat.

The cooling load of regional public buildings is mainly provided by compression chillers and absorption chillers. As shown in Figure 4.17(c), above the horizontal axis is the cooling capacity generated by the compression chiller and absorption chiller, and below the horizontal axis is the cooling capacity required by the regional building. As shown in Figure 4.17, since the solar collector generates a lot of heat, most of the cooling capacity is provided by the absorption chiller. The cooling capacity provided by the compression refrigerator only accounts for 13% of the total cooling capacity.

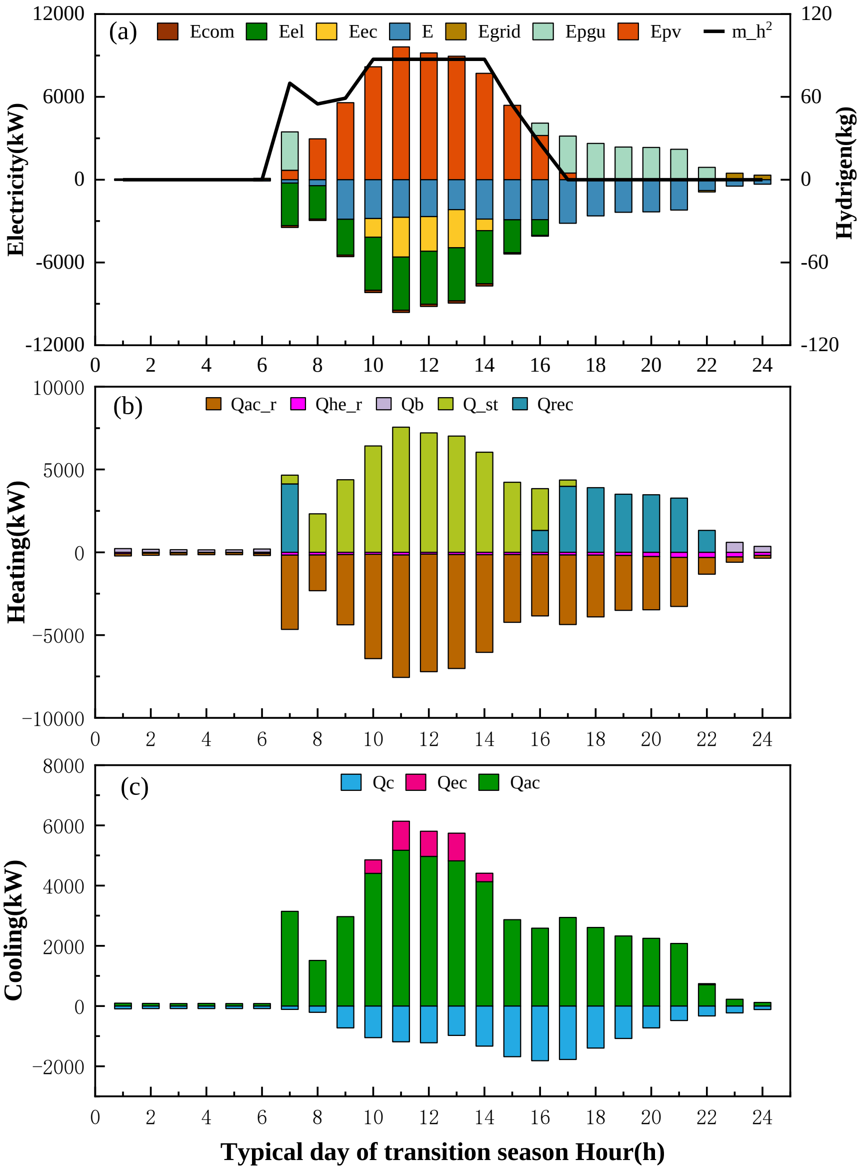
**Figure 4.17. Analysis of Typical Daily Load in Summer**




kg = kilogram, kW = kilowatt, Ecom = electricity of compressor, Eel= electricity of electrolyser, Eec = electricity of chiller, E = electrical load, Egrid = electricity of gird, Epgu = electricity of power generation unit, Epv = electricity of photovoltaic, m_h$^2$ = hydrogen production, Qac_r = heat of absorption chiller, Qhe_r = heat of heat exchanger, Qb = heat of boiler, Q_st = heat of solar thermal collector, Qrec= heat of heat recovery system, Qc = cooling load, Qec = cooling of electricity chiller, Qac = cooling of absorption chiller.
Source: Prepared by authors.

The changing trend of the transition season is similar to that of summer, as shown in Figure 4.18(a). In the transition season, the light intensity is not as high as that in summer, and the corresponding photovoltaic power generation is not as high as that in summer. Therefore, the power generation of the corresponding gas-fired internal combustion engine is increased to meet the demand of the electric load. Due to the low demand for cooling load in the transition season, we can see that the power consumption of the compression refrigerator is greatly reduced, which is less than that of the electrolytic cell. As shown in Figure 4.18(b), the main heating equipment in the transition season is the solar collector and the heat recovery system, and the boiler only provides a small part of the heat. We can see that the main heat is used in the absorption refrigerator. As shown in Figure 4.18(c), in the transition season, due to the small cooling load, a part of the cooling capacity is wasted.

**Figure 4.18: Analysis of Typical Daily Load in the Transition Season**



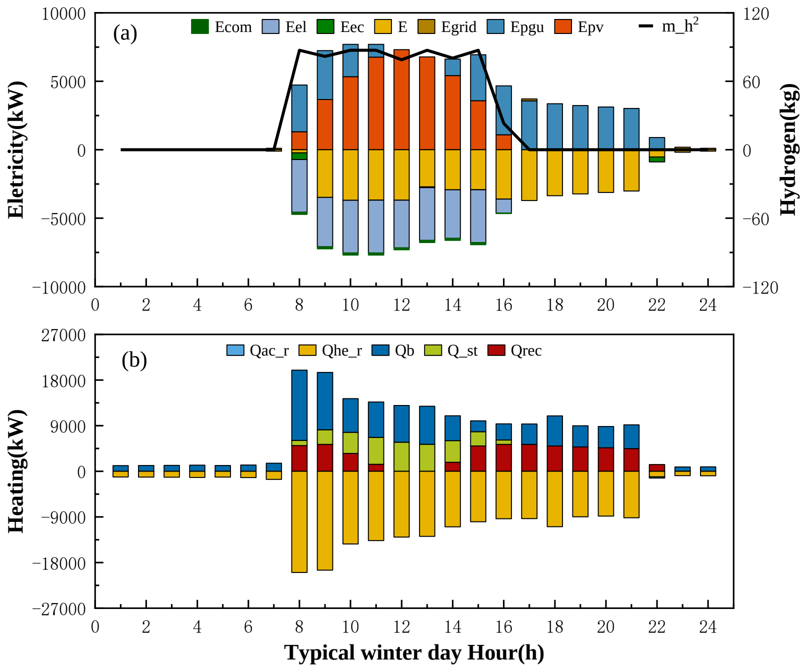

kg = kilogram, kW = kilowatt, Ecom = electricity of compressor, Eel= electricity of electrolyser, Eec = electricity of chiller, E = electrical load, Egrid = electricity of gird, Epgu = electricity of power generation unit, Epv = electricity of photovoltaic, m_h² = hydrogen production, Qac_r = heat of absorption chiller, Qhe_r = heat of heat exchanger, Qb = heat of boiler, Q_st = heat of solar thermal collector, Qrec= heat of heat recovery system, Qc = cooling load, Qec = cooling of electricity chiller, Qac = cooling of absorption chiller.
Source: Prepared by authors.

In winter, as shown in Figure 4.19(a) due to the weakening of light intensity and light time, the photovoltaic power generation is not enough to meet the power load of users. Therefore, it can be seen that when the photovoltaic power is not generated, the gas turbine has been working, and a small part of the power is provided by the grid. At 8 a.m., due to the weak light intensity, the photovoltaic power generation is not enough to meet the power load demand of users, so gas turbine power generation is used to make up for the shortage of electricity, and the excess electricity is used to produce hydrogen. At 9 a.m., with the increase of light intensity, the power of the gas-fired internal combustion engine decreases, and there is no surplus electricity to the electrolytic cell at this time, so the production of hydrogen is 0. In winter, the electric load of users accounts for a large proportion of the total power consumption. The second is the compression refrigerator and electrolyser.

Due to the weak illumination intensity and short illumination time in winter, as shown in Figure 4.19(b), the main heating equipment is the boiler, followed by the heat recovery system of the gas turbine. This is because the cost will be reduced by using the boiler for heating, so when the solar collector does not supply heat, most of the heat is provided by the boiler. Because there is no cold demand in winter, the absorption chiller does not work.

Since there is no cooling load in winter, it is not listed in Figure 4.19.

**Figure 4.19: Analysis of Typical Daily Load in Winter**




kg = kilogram, kW = kilowatt, Ecom = electricity of compressor, Eel= electricity of electrolyser, Eec = electricity of chiller, E = electrical load, Egrid = electricity of gird, Epgu = electricity of power generation unit, Epv = electricity of photovoltaic, m_h² = hydrogen production, Qac_r = heat of absorption chiller, Qhe_r = heat of heat exchanger, Qb = heat of boiler, Q_st = heat of solar thermal collector, Qrec= heat of heat recovery system, Qc = cooling load, Qec = cooling of electricity chiller, Qac = cooling of absorption chiller.
Source: Prepared by authors.

### 3.3.4. Calculation and Analysis of Hydrogen

The cost of hydrogen mainly comes from three parts: the cost of hydrogen production, the cost of hydrogen compression, and the cost of hydrogen storage. Since the distributed energy system is close to the user, the selected hydrogenation station is very close to the user. Therefore, hydrogen does not need to be transported.

$$CC_{H_2} = C_{H_2} + \mathrm{Cos}\,t_{kgH_{2,com}} + \mathrm{Cos}\,t_{kgH_{2,store}} \tag{31}$$

$CC_{H2}$—Total cost of hydrogen, $/kgH$_2$

$C_{H2}$—Cost of hydrogen production, $/kgH$_2$

$Cost_{kgH2,com}$—Cost of hydrogen compression, $/kgH$_2$

$Cost_{kgH2,store}$—Hydrogen storage cost, $/kgH$_2$

***Cost of hydrogen production***

The cost proportion of hydrogen in the system is calculated by Eq.32, and further the cost of hydrogen in the total cost of the system can be solved. The calculation method of hydrogen production cost is as follows:

$$C_{H_2} = \frac{\dfrac{q_{H_2}}{q_{power} + q_{heat} + q_{cool} + q_{H_2}} \cdot ATC}{H_{2,gen}} \tag{32}$$

$q_{H2}$—Hydrogen calorific value, kWh

$q_{power}$—Calorific value of electrical load, kWh

$q_{heat}$—Heating load calorific value, kWh

$q_{cool}$—Calorific value of cooling load, kWh

The total cost of the system is \$3,491,080.19, the annual total functional capacity 56,792,661.71 kWh, and the annual total hydrogen supply 10,283,337.20 kWh. According to the calculation, the unit hydrogen production cost of the system is \$2.48/kg.

***Cost of hydrogen compression***

The cost of hydrogen compression is mainly composed of three parts: the cost of the compressor, the cost of electricity consumed by hydrogen compression, and the cost of water consumed by hydrogen compression. The cost of compressor accounts for the highest part. The power needed to compress the gas is provided by the system, which need not be considered here. Hydrogen compressors are designed to compress hydrogen gas, ensuring it is pressurised enough to be stored in hydrogen storage tanks, where it can be transported over long distances and sold throughout the country.

$$\mathrm{Cost}_{kgH_{2},com}=\frac{H_{2,compower}\times price_{electric}+H_{2,coolwater}\times price_{water}+H_{2,comcost}}{H_{2,gen}} \quad (33)$$

$H_{2,compower}$—Power consumption when compressing hydrogen, kWh

$price_{water}$—Water price, \$/Lit

$H_{2,coolwater}$—Cooling water volume, Lit

$H_{2,comcost}$—Compressor cost consumption, \$

Water cost for compressed hydrogen

$$H_2CoolWater=\frac{H_2ComPower\cdot 50}{2.2} \quad (34)$$

$$H_2ComPower=H_2GenCap\cdot NStages\cdot(\frac{\gamma}{\gamma-1})\cdot R\cdot T\cdot(\frac{H_2Com\Pr}{Gen\Pr})^{(\frac{\gamma-1}{NStages\cdot\gamma}-1)} \quad (35)$$

$H_2CoolWater$—Water for compressed gas, Lit

$\gamma$—Adiabatic index=1.4

$R$—Gas constant= 4124J/kg.K

$T$—Temperature=290K

*GenPr*—Hydrogen production pressure

$H_2ComPr$—Hydrogen storage pressure, MPa

*NStages*—Compressor stage

1.$H_2ComPr<0.5MPa$

2.$0.5MPa<H_2ComPr<5MPa$

3. $H_2ComPr>5MPa$

The calculated compressor cost is \$1.34/kg.

The water cost for compressed hydrogen is \$0.077/kg.

The total compression cost is \$1.417/kg.

***Hydrogen storage cost***

The cost of hydrogen tank is the main cost in the stage of hydrogen storage.

$$\text{Cost}_{kgH_{2,store}} = \frac{c_{\text{tank}} \cdot p_{\text{tank}} \cdot (n+2) \cdot b}{H_{2,gen}} \qquad (36)$$

$c_{tank}$—Unit cost of hydrogen storage tanks, \$/kg

$p_{tank}$—Capacity of hydrogen storage tank, kg

$n$—Number of hydrogen storage tanks

$b$—Conversion factor

The cost of hydrogen storage is \$1.93/kg. Therefore, the total cost of hydrogen supply is \$5.827/kg.

| Total cost \$/kg | Cost of hydrogen production \$/kg | Cost of hydrogen compression \$/kg | Cost of hydrogen storage \$/kg |
|---|---|---|---|
| 5.827 | 2.48 | 1.417 | 1.93 |

## 4. Conclusion

To solve the urgent problem of large-scale surplus and demand growth of solar power generation in China, this chapter proposes a solution of CCHP, and analyses the economy, energy, and environment based on the application scenarios. The optimal system configuration for hydrogen supply is selected.

The optimal matching hydrogen load of the system is 700 kg/day, and the unit energy cost of the system is the smallest, which is \$0.0615/kWh. The total cost of the system is \$3,491,080. The annual carbon dioxide emission of the system is 8,574,791 kg, and the primary energy consumption of the system is 4,213,5860 MWh. The capacity of photovoltaic equipment is 12,072 kW, that of the gas turbine is 3,570 kW, and that of an electrolytic cell is 3,849 kW.

In comparison with the reference system, it can be concluded that the total cost, carbon dioxide emissions, and fossil energy consumption of S1 are the lowest amongst the four systems. S1 is more economical and sustainable.

In the system with hydrogen production of 700 kg/day, photovoltaic power generation accounts for 76.47% of the total power generation, internal combustion engine power generation accounts for 22.65% of the total power generation, and power grid power generation accounts for only 0.88%. The calorific value of the solar collector is the highest, accounting for 43.21% of the total calorific value, followed by the boiler, accounting for

32.57% of the total calorific value, and the heat of waste heat recovery system accounts for 24.23% of the total calorific value. The cooling capacity provided by the absorption chiller accounts for 89.16% of the total cooling capacity, and the cooling capacity provided by the compression chiller accounts for 10.84% of the total demand.

In the analysis of typical days, the operation time of the gas engine is short because of the strong illumination intensity and long illumination time in summer. When there is no illumination, the gas turbine will run. In the transition season and winter, especially in winter, due to the weak light intensity and the constraints of daily hydrogen production, the photovoltaic power generation cannot fully meet the power load demand of users, and the internal combustion engine needs to supplement the insufficient power.

In the cost analysis, the capital recovery cost of the system accounts for 53.96%, the fuel cost accounts for 39.27%, and the operation and maintenance cost of equipment accounts for 6.77%. The cost of natural gas in the fuel cost is 98.07% of the fuel cost. In the equipment cost, PV accounted for the highest proportion, which was 24.48%, followed by solar collector and electrolyser, which were 15.37% and 15.08%, respectively.

The part of the system to be improved is that during the transition, most of the cold energy generated by the system is wasted, and further optimisation design is needed to achieve the standard of supply and demand balance.

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| Nomenclature | |
| --- | --- |
| **AC** | absorption chiller |
| **ATC** | annual total cost |
| **CCHP** | combined cooling, heating and power |
| **CDE** | carbon dioxide emission |
| **COP** | coefficient of performance |
| **COM** | hydrogen compressor |
| **PEC** | primary energy consumption |
| **PGU** | power generation unit |
| **PEM** | proton exchange membrane |
| **PV** | photovoltaic |
| **Rec** | heat recovery system |
| **ST** | solar thermal collector |
| **Symbols** | |
| $A$ | area ($m^2$) |
| $C$ | cost (\$/kWh) |
| $E$ | electricity (kWh) |
| $F$ | fuel consumption (kWh) |
| $G$ | the solar radiation intensity($kW/m^2/h$) |
| $Q$ | thermal energy (kWh) |
| $\eta$ | efficiency |
| $P$ | installed capacity of equipment (kW) |
| $\Phi$ | equipment costs (\$/kW ) |
| $\dot{m}$ | mass flow rate of hydrogen generated(kg/s) |
| **Subscripts** | |
| ***PV*** | photovoltaic |
| ***ST*** | solar thermal collector |
| ***ac*** | absorption chiller |
| ***b*** | boil |
| ***com*** | hydrogen compressor |
| ***e*** | electricity |
| ***el*** | electrolyser |
| ***ec*** | electricity chiller |
| ***grid*** | electricity grid |
| ***g*** | natural gas |
| ***H*** | heat load |
| ***He*** | heat exchanger |
| ***Pgu*** | power generation unit |
| ***Rec*** | heat recovery system |

# Chapter 5
# Hydrogen Production from Offshore Wind Power in South China

Zhibin Luo, Xiaobo Wang, and Aiguo Pei

Wind power hydrogen production converts the electricity generated by wind power directly into hydrogen through water electrolysis hydrogen production equipment and produces hydrogen that is convenient for long-term storage through water electrolysis. With the development of offshore wind power from offshore projects, construction costs continue to rise. Turning power transmission into hydrogen transmission will help reduce offshore wind power construction costs. This chapter analyses ways of producing hydrogen from offshore wind power, including alkaline water electrolysis, proton exchange membrane electrolysis of water, and solid oxide electrolysis of water. In addition, the chapter outlines economic and cost analyses of offshore wind power hydrogen production. In the future, with the development and progress of water electrolysis hydrogen production technology, hydrogen production from offshore wind power will be more economical and more practical.

Keywords: Hydrogen production, water electrolysis, offshore wind power

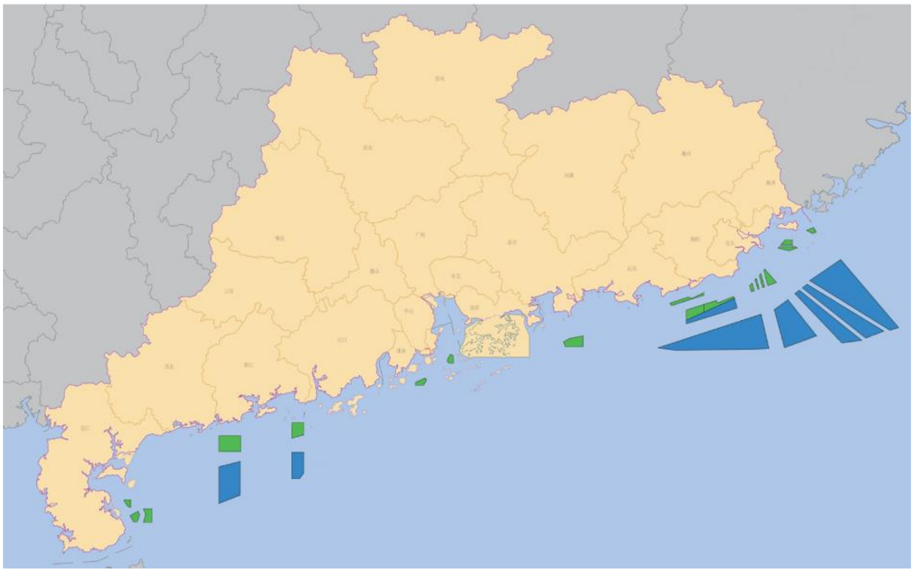
## 1. Introduction

In 2010, the first phase of the Shanghai Donghai Bridge Offshore Wind Farm, China's first domestic demonstration project of large-scale offshore wind farms, was officially put into operation. In the following years, the construction of offshore wind farms in coastal provinces such as Guangdong, Jiangsu, Zhejiang, and Fujian has gradually accelerated. Take Guangdong Province, which has a relatively large-scale offshore wind power development as an example. In 2012, the National Energy Administration approved the 'Guangdong Province Offshore Wind Farm Project Plan'. In 2016, the Guangdong Provincial Energy Administration initiated the revision of the 'Guangdong Province Offshore Wind Power Development Plan (2017–2030). According to the distribution of wind energy resources (Figure 5.1), taking into consideration factors such as construction conditions, industrial base supporting facilities, and project economics, the province plans to build 23 offshore wind farm sites with a total installed capacity of 66.85 million kilowatts (kW), including 15 sites in shallow offshore areas (within 35 metres of water depth), with an installed capacity of 9.85 million kW, of which 4.15 million kW is in eastern Guangdong seas, 1.5 million kW in Pearl River Delta seas, and 4.2 million kW in western Guangdong seas. Eight offshore deep water (35–50 metres water depth) wind farm sites are planned, with an installed capacity of 57 million kW, distributed in the eastern and western waters of Guangdong. Offshore deep water sites will be mainly used as reserve sites for the long-term development and construction of offshore wind power in the province. After the technology matures and the development and construction cost decreases, the development of offshore deep water sites will be promoted within reason.

While offshore wind power is developing rapidly, it is also facing several problems (Fernández-Guillamón et al., 2019; Babarit et al., 2018).

1) The plant site in the shallow offshore area is limited, with a capacity of 9.85 million kW, accounting for only 14.7%. Most of the wind farms in offshore shallow water areas with good wind resources have started construction, and the stock of offshore shallow water areas is limited.
2) Planning is mostly concentrated in deep water areas, with a capacity of 57 million kW, accounting for 85.3%. In the deep sea areas, offshore wind power construction costs are high, and construction is difficult. The construction costs of submarine cables, sea booster stations, and wind turbine foundations have doubled.
3) With the popularisation of offshore wind power, feed-in tariff policy subsidies have gradually reduced. According to the 'Notice of the National Development and Reform Commission on Improving the Policy of Wind Power Feed-in Tariff (Development and Reform Price [2019] No. 882)' issued by the National Development and Reform Commission in May 2019, onshore wind power will achieve parity on the grid in 2021. It is an inevitable trend to reduce subsidies for offshore wind power.
4) Irregular intermittent fluctuations of offshore wind power have a great impact on the grid.
5) In order to cope with the high proportion of new energy structures, grid companies will have higher requirements for the quality of new energy power connected to the grid, and management will become more stringent. The 'Implementation Rules for the Grid-connected Operation and Auxiliary Service Management of Wind Power Farms in the Southern Region' has been issued. The grid-connected wind power needs to pay auxiliary service fees to subsidise peak shaving costs (Franco et al., 2021).

**Figure 5.1: Distribution of Planned Offshore Wind Power Plants in Guangdong Province (2017–2030)**



The green areas indicate the shallow offshore areas, and the blue areas indicate the deep offshore areas.
Source: Guangdong Provincial Development and Reform Commission.

Hydrogen energy is a clean secondary energy, which has the advantages of wide source, high calorific value, high energy density, storable, renewable, electric and combustible, zero pollution, and zero carbon emission, amongst others (Veers et al., 2019; Kojima, 2019). It is known as controlling the earth temperature rise in the 21st century, the 'ultimate energy' to solve the energy crisis (Yan 2018; Abdin et al., 2020). The scientific and industrial circles recognise that hydrogen energy is the best solution to control the earth temperature rise and solve the energy crisis (Dincer and Acar, 2018; Dawood, Anda, and Shafiullah, 2020; Kovač, Paranos, and Marciuš, 2021). It is not only because hydrogen has a wide range of uses and involves all aspects of traditional energy, but also comes from its excellent storage properties. Hydrogen energy can effectively make up for the shortcomings of poor electrical energy storage and support the development of a high proportion of renewable energy (Liu, Feng et al., 2020; Liu, Wang et al., 2020).

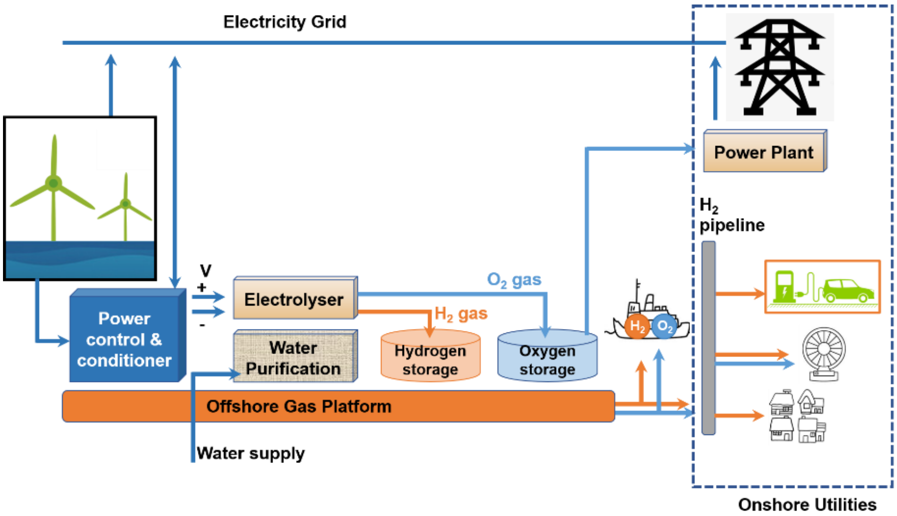
The hydrogen energy industry has developed rapidly and has been commercialised in the field of hydrogen fuel cell vehicles (Walter et al., 2010). In March 2019, Premier Li Keqiang mentioned 'promoting the construction of hydrogen refuelling and other facilities' in a government work report, and society's attention to hydrogen energy has further increased. Coastal provinces such as Guangdong and Jiangsu, which have large-scale offshore wind power construction, are also provinces with rapid development of hydrogen energy and fuel cells. The development of the hydrogen energy industry in cities such as Foshan in Guangdong Province, and Guangzhou, Yunfu, and Rugao in Jiangsu Province is leading the country and requires a large amount of high-purity hydrogen. The purity of hydrogen produced by electrolysed water from renewable energy reaches 99.999%, which can be directly applied to fuel cell vehicles, saving the cost of hydrogen production from fossil energy and the purification of by-product hydrogen. As a secondary energy source, hydrogen energy can be produced by reforming fossil energy sources such as coal, oil, and natural gas, biomass pyrolysis, or microbial fermentation. It can also come from industrial by-product gas such as coking, chlor-alkali, iron and steel, and metallurgy (Nagpal and Kakkar, 2018). The use of electrolysed water, especially in combination with renewable energy power generation, can not only achieve a green and clean life cycle, but also expand the use of renewable energy (Qi, Zhang, and Cao, 2018).

The consumption of hydrogen energy is currently mainly in the industrial sector. With the maturity of fuel cell technology, the transportation and energy fields are becoming a new breakthrough for development, realising the transition of hydrogen energy from auxiliary energy to main energy (Abe et al., 2019). At present, the United States, Japan, Republic of Korea, Europe, and China regard hydrogen energy as an important part of their future energy strategies. The application of hydrogen energy in the transportation sector is more advanced and technologically advanced in Japan. The consumption demand for hydrogen energy will grow rapidly in the future (Bartela, 2020; Goltsov and Goltsova, 2014). A large part of the consumption in the industrial sector comes from the production capacity of chemical by-products. To meet the new demand for hydrogen energy in the large-scale transportation sector, it is necessary to develop clean power electrolysis of water hydrogen production capacity.

According to the statistics of the China Hydrogen Energy Alliance, it is estimated that by 2030, China's hydrogen demand will reach 35 million tons, accounting for 5% of the final energy system, and hydrogen energy will account for at least 10% of the final energy system by 2050. The demand for hydrogen energy will reach 60 million tons of which 33.7 million tons will be used in the industrial sector and 24.58 million tons will be used in the transportation sector. Hydrogen in the transportation sector will account for about 19% of the energy consumption by 2050. It is the main driving force for the growth of hydrogen energy consumption in this sector. The increase in hydrogen energy consumption in the industrial sector will mainly come from the steel industry. By 2030, hydrogen energy consumption will exceed 50 million tons of standard coal and will further increase to 76 million tons. By 2050, hydrogen consumption in the transportation sector will reach 1 million tons of standard coal, the proportion of hydrogen produced from renewable energy will reach 70%. As far as Guangdong Province is concerned, primary energy sources such as coal and natural gas are scarce. Hydrogen produced from coal and hydrogen produced from natural gas cracking also violate the original intention of using hydrogen energy as a zero-carbon clean energy (Fouquet and Pearson, 2012). The amount of by-product hydrogen in Guangzhou is limited. Most of the by-product hydrogen has a low hydrogen concentration of 20–30%. The use of hydrogen in high-purity fuel cells requires complicated purification processes, and the purification costs are relatively high (Thomas et al., 2020). Guangdong Province has a good industrial foundation for hydrogen energy and fuel cells and requires a large amount of high-purity hydrogen. At the same time, Guangdong Province has the second Huizhou petrochemical base in the country and the third Maoming petrochemical base in the country, which has a 1 million-ton-level hydrogen supply demand every year. Hydrogen production from renewable energy could be the foundation to achieve green and sustainable development of the entire hydrogen energy industry chain (Jorge et al., 2019). Similar to the situation in Guangdong Province, hydrogen is urgently needed for its industrial development. However, hydrogen could not be self-sufficient in Guangdong due to the lack of primary energy sources such as coal and natural gas, and land-based renewable energy is limited (McDonagh et al., 2020). When 'green hydrogen' is an inevitable development trend, the development of hydrogen produced from offshore wind power is one of the key ways to solve the stable and reliable supply of hydrogen. The process of offshore wind power hydrogen production is outlined in Figure 5.2, reflecting the production process and basic uses of hydrogen. Combined offshore wind power and purified water from the sea, electrolysers can generate hydrogen and oxygen continually, which is used in offshore transportation and onshore utilities.

However, the rapid development will also be accompanied by the same dilemma faced by the wind power industry in other countries. Even Germany, which is known for its scientific planning and rigorous rigor, cannot escape. The lagging power grid construction speed cannot meet the rapidly expanding offshore wind power transmission needs. Direct hydrogen production by offshore wind power avoids the difficulties of power system construction and provides a feasible idea for the development of offshore wind power. Shell, Siemens, and TenneT jointly called on European governments to accelerate the use of offshore wind power hydrogen production technology research and proposed to consider launching offshore wind power hydrogen production project bidding, effectively alleviating the contradiction between the rapid growth of offshore wind power and the slower speed of power grid construction, thereby promoting European offshore wind power development. Shell, Siemens, and TenneT proposed the 'Power to Gas' programme, which is to balance the power supply and demand relationship in the power grid by producing hydrogen and oxygen through electricity. Besides, led by Ørsted, the largest developer of offshore wind power, with participation of the hydrogen energy company ITM Power and energy consulting company Element Energy, the project named 'Gigastack', a low-cost offshore wind power hydrogen production demonstration project, has received funding support of £500,000 from the British government.

**Figure 5.2: Offshore Wind Power Hydrogen Production**




Source: Dinh and McKeogh (2019).

Conventional ways of energy storage cannot provide long-term storage due to practical and economic limitations (Franco et al., 2021; Ghorbani, Zendehboudi, and Moradi, 2021; Delpierre et al., 2021). The development trend of hydrogen production from offshore wind power is inevitable. Therefore, this chapter first provides insight into the cost analysis of offshore wind power construction. Then, the chapter analyses and summarises the common ways of hydrogen production from offshore wind power, including alkaline water electrolysis, proton exchange membrane electrolysis of water, and solid oxide electrolysis of water. Electrolysed water hydrogen production equipment and economic analysis are introduced specifically. With the development and progress of water electrolysis hydrogen production technology, hydrogen production from offshore wind power will be more economical and widespread.

## 2. Cost Analysis of Offshore Wind Power Construction

Take an offshore wind farm in Guangdong Province as an example. The wind farm site has a water depth of about 31 to 37 metres (m), is 20 kilometres (km) offshore, with an installed capacity of 400 megawatts (MW), and a total of 73 wind turbines with a single capacity of 5.5 MW were built. The main equipment of the wind farm includes an offshore wind turbine generator (including foundations), a 35 kilovolt (kV) current collection submarine cable, a 220 kV sea booster station (two transformers), a 220 kV landing cable, and a land booster station (500 kV, share). The total static investment of the wind farm project is about CNY6.17 billion, and the static investment per kilowatt is about CNY15,500/kW.

Referring to the offshore shallow water area cost, the far-sea deep water area cost (assuming 60 km offshore, water depth 50 m), the procurement and installation cost of the landing submarine cable is three to four times that of the offshore shallow water area; the power generation equipment submarine cable procurement and installation cost is two to three times that of the offshore diving zone. The construction cost of the sea booster station in the deep water area is twice that of the shallow water area; the basic cost of the wind turbine is one and a half to two times that of the shallow water area; other costs are basically unchanged. The cost of the far-sea deep water sea ascending station, submarine cable, land ascending station (shared), and centralised control centre is approximately CNY1.70 million, accounting for about 22% of the total investment. The unit cost of offshore wind power in the deep water areas is CNY19,500/kW, which is 40% higher than that in the shallow water area of CNY15,500/kW, mainly due to the increase in the basic costs of submarine cables, sea booster stations, and wind turbines. For the wind turbine foundations, Europe has developed floating offshore wind power, which can reduce the basic cost of wind turbines in deep water areas. How to reduce the cost of submarine cables and sea booster stations is a topic worth studying.

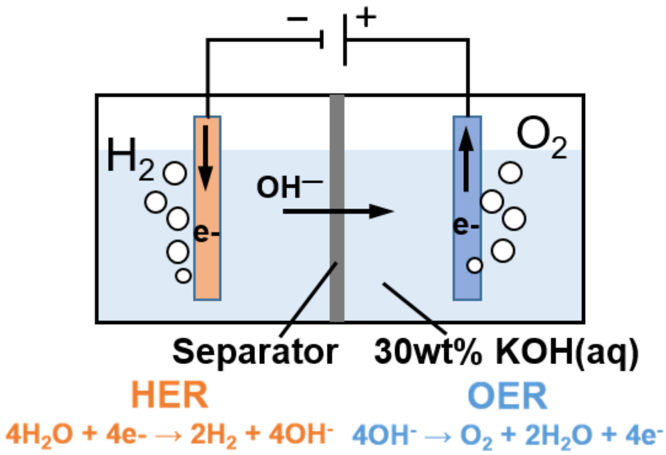
## 3. Electrolysed Water Hydrogen Production Equipment

Hydrogen production by electrolysis can be divided into alkaline water electrolysis (AEC), proton exchange membrane electrolysis of water (PEM), and solid oxide electrolysis of water (SOEC). SOEC has the highest electrolysis efficiency, followed by PEM, and AEC is the lowest. But SOEC is still in the laboratory stage.

### 3.1. Alkaline Water Electrolysis

An AEC device has mature technology, large capacity, and low cost, but a large volume. A schematic diagram of AEC is shown in Figure 5.3. In the past 10 years, China has planned to build many high-parameter, large-capacity generator sets. The generators need to be equipped with hydrogen cooling devices, which has driven the development of China’s alkaline electrolysis hydrogen production technology. At present, China’s alkaline electrolysed water hydrogen production technology and equipment manufacturing capabilities are in a leading position in the world, and manufacturers such as Suzhou Jingli, Tianjin Continental, and China Shipbuilding Industry Corporation 718 are in the leading position.

**Figure 5.3: Principles of Alkaline Water Electrolysis**

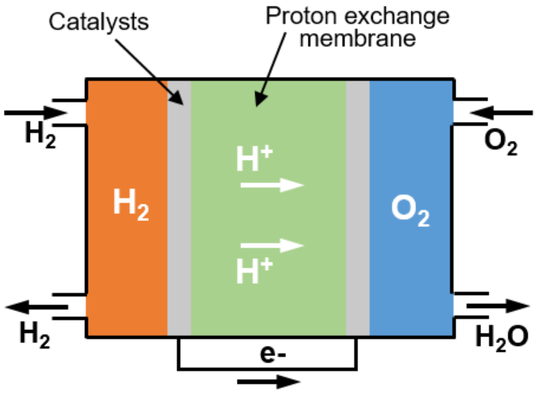



HER = hydrogen evolution reaction, KOH = potassium hydroxide, OER = oxygen evolution reaction.
Source: Prepared by authors.

### 3.2. Proton Exchange Membrane Electrolysis of Water to Hydrogen

PEM electrolysed water is a new technology from Canada (Zhao et al., 2021; Kilikovsky, 2017). It is the result of project research after 10 years. It is small in size and fast in dynamic response; but the price is relatively high in the initial stage of commercialisation. Hydrogen production by PEM electrolysis of water is the reverse process of proton exchange membrane fuel cell (PEMFC) power generation of hydrogen energy proton exchange membrane fuel cells for automobiles on the market. The main components include cathode and anode end plates, cathode and anode gas diffusion layers, cathode and anode catalyst layers, and proton exchange membranes (Figure 5.4) (Steinberger et al., 2018). Amongst them, the end plate plays the role of fixing the electrolytic cell components, guiding the transfer of electricity and the distribution of water and gas. The diffusion layer plays the role of collecting current and promoting the transfer of gas and liquid. The core of the catalytic layer is composed of a catalyst, electron conduction medium, and proton conduction. The three-phase interface formed by the medium is the core place where the electrochemical reaction occurs; the proton exchange membrane acts to isolate the gas generated from the anode, and the anode prevents the transfer of electrons, and transfer protons at the same time.

**Figure 5.4: Principles of Proton Exchange Membrane Electrolysis of Water to Hydrogen**




Source: Prepared by authors.

In PEM technology, hydrogen ions in water pass through a proton exchange membrane and combine with electrons to form hydrogen atoms, and hydrogen atoms combine with each other to form hydrogen molecules. This technology allows the electrolyser to work at high current density and high pressure, and is suitable for situations where space is limited, or when renewable energy is used to generate hydrogen when the electricity is unstable. The hydrogen produced by PEM electrolysed water has a high purity and can be directly used by vehicle fuel cells; the purity of by-product oxygen reaches 99.5%, which meets the standard for medical oxygen use. In 2014, Canada's hydrogen's MW-level PEM electrolyser was officially put into production, which performed very well. The PEM water electrolysis device has been produced in China. The capacity of a single PEM produced by Shandong Saikesaisi and other manufacturers has reached the MW level. Table 5.1 shows the main technical parameters of the 200 normal cubic metre per hour ($Nm^3/h$) PEM device. In China, PEM electrolysed water hydrogen production technology has been applied in the military with good performance. However, PEM is in the early stage of commercialisation, the scale of mass production is small, the core equipment components need to be imported, and the high cost of catalysts make the current price high.

**Table 5.1: Parameters of Unit Electrolysis Hydrogen Production Equipment**

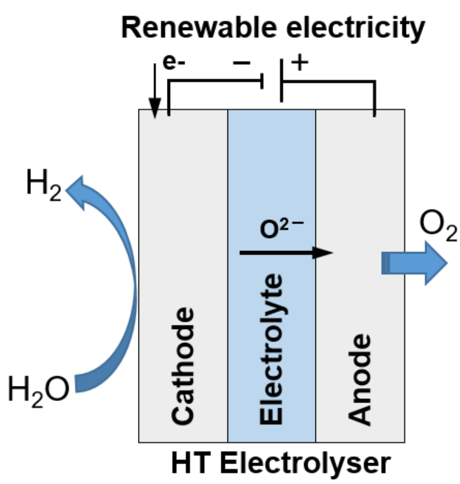
| System | **Power consumption per hour** (kWh) | **Hydrogen production per hour** ($Nm^3$) | **Water consumption per hour** (kg) | **Equipment cost** (CNY million) | **Civil engineering and installation cost** (CNY million) | **Area** ($m^2$) |
|---|---|---|---|---|---|---|
| AEC | 5000 | 1000 | 1000 | 8 | 2 | 800 |
| PEM | 1000 | 200 | 200 | 5 | 0.2 | 100 |

AEC = alkaline water electrolysis, PEM = proton exchange membrane electrolysis of water, kg = kilogram, kWh = kilowatt hour, $m^2$ = square metre, $Nm^3$ = normal cubic metre.
Source: Prepared by authors.

### 3.3. Hydrogen Production by Solid Oxide Electrolysis

SOEC uses solid oxide as the electrolyte material, works at a high temperature of 650°C–1,000°C, can use heat for electro-hydrogen conversion, has the advantages of high energy conversion efficiency, does not require the use of noble metal catalysts, and is highly efficient in three electrolytic water hydrogen production technologies (Figure 5.5) (Kim et al., 2018). SOEC is the only device that can directly electrolyse seawater to produce hydrogen (the alkaline electrolyser has completed the laboratory demonstration for direct electrolysis of seawater, 1,000 hours). The SOEC electrolysis process can simultaneously absorb $CO_2$ greenhouse gases, which is a 'negative carbon' emission process. SOEC technology is still in the laboratory stage. Research institutes such as the Huazhong University of Science and Technology have a technical basis for single electrolytic cells, but SOEC system integration has a certain gap with foreign technology. Its technological maturity requires catalytic verification of demonstration projects.

**Figure 5.5: Principles of SOEC Water Electrolysis**




HT = high temperature, SOEC = solid oxide electrolysis.
Source: Prepared by authors.

## 4. Offshore Wind Power Hydrogen Production

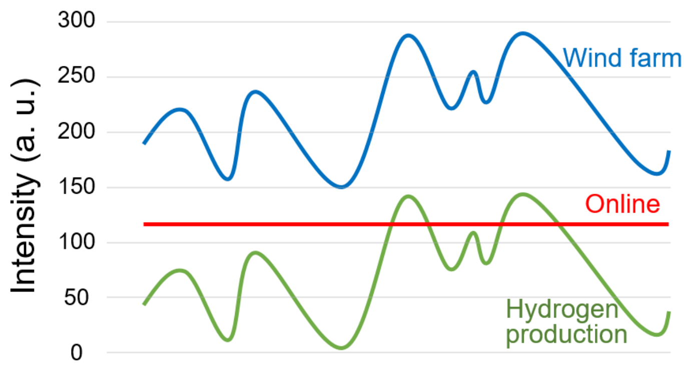
In view of the large impact of offshore wind power on the power grid and the high cost of construction in deep sea areas, research on offshore wind power hydrogen production technical solutions is conducted. Through the configuration of hydrogen production equipment, a flexible control system is constructed to efficiently, safely, and reasonably allocate on-grid electricity and hydrogen production and achieve optimal distribution of wind power and hydrogen production. By optimising the integration of hydrogen production equipment in the wind turbine tower, direct hydrogen production by offshore wind power on-site can eliminate the construction cost of submarine cables and sea booster stations and reduce the cost of offshore wind power. Through the study of offshore wind power storage schemes, zero wind power curtailment in offshore wind power is achieved, and the paid auxiliary service fees paid by wind power companies are reduced. The offshore wind power industry, the hydrogen energy industry, and the grid system promote each other, coordinate and orderly develop, and jointly build a 'clean, low-carbon, safe, and efficient' energy structure system (Apostolou and Enevoldsen, 2019).

In view of the impact of offshore wind power on the power grid and the high cost of offshore wind power construction in deep water areas, a hydrogen production plan for offshore wind power is proposed, combined with an analysis of the demand for high-purity hydrogen in the transportation and energy sectors. It is divided into four parts. Research on technical solutions for onshore hydrogen production by offshore wind power, research on offshore hydrogen production technical solutions with integrated hydrogen production devices in offshore wind turbine towers, research on off-grid direct hydrogen production technical solutions for offshore wind power, and off-grid offshore hydrogen production technology for offshore wind power. The program study has four steps, and it is studied step by step. First, for the large-scale construction of offshore wind power, the onshore hydrogen production station is configured to absorb fluctuating power, so that offshore wind power becomes a grid-friendly 'peak shaving power source'; then, it will study the integration of hydrogen production equipment in the wind turbine tower. From onshore hydrogen production to offshore hydrogen production, the integration of equipment is improved, the area is reduced, and the technical reserves for all hydrogen production of offshore wind power. For offshore wind power in deep water areas, a full hydrogen production plan for offshore wind power is proposed, and the energy storage system is configured to achieve off-grid hydrogen production by offshore wind power saves the cost of submarine cables and sea booster stations and reduces construction costs. Finally, for the medium and long-term deep water floating offshore wind power, SOEC hydrogen production devices that can directly electrolyse seawater are used to eliminate soft water supply pipelines and hydrogen and oxygen transmission pipelines to realise offshore wind power off-grid and offshore operation.

### 4.1. Onshore Hydrogen Production

In response to the problems caused by intermittent, volatile, and irregular offshore wind power grids, combined with shallow water offshore wind farms, a large-scale alkaline electrolysed water system is installed near the land riser station (a small amount of PEM electrolysed water equipment is equipped to achieve fast load tracking). The hydrogen production station uses electrolysed water to produce hydrogen to absorb part of the fluctuating power of offshore wind power, and the remaining stable power transmission network effectively solves the impact of offshore wind power fluctuations on the grid system (Figure 5.6). It is necessary to construct a flexible electrical energy control and distribution system to efficiently, safely, and reasonably distribute the grid power and hydrogen power. At the same time, the hydrogen production station can receive the control and dispatch of the grid system and control the hydrogen production consumption according to the grid load demand, indirectly achieving the goal of controlling the load of offshore wind power. The final goal is to achieve zero wind curtailment for offshore wind power and promote offshore wind power to become a grid-friendly peak shaving power source.

**Figure 5.6: Load Distribution of Offshore Wind Power Generation Hydrogen Production**




Source: Prepared by authors.

### 4.2. Offshore Partial Hydrogen Production

The power of offshore wind power fluctuates greatly. The selection of equipment, the calculation of the submarine cable section, and the capacity and foundation of the sea booster station are designed according to the maximum power generation capacity of the wind turbine. The probability of high load operation of the equipment is low, and the construction cost allocation is high. The PEM hydrogen production equipment is directly integrated in the fan tower barrel, shown in Figure 5.7, directly from the direct current (DC) bus bar of the fan to the electrolytic water hydrogen production device. The bottom of the fan tower barrel has a diameter of about 6.5 m, which is enough to accommodate 2400*1700*2000 size PEM electrolysis equipment (Figure 5.8). This solution has the following advantages while realising the function of hydrogen production peak shaving:

- The wind turbine generates hydrogen directly, eliminating the loss of power transmission and voltage conversion, and improving the power utilisation efficiency.
- It saves land and integrates the system in the wind turbine tower. The hydrogen production device could be highly integrated in the bottom of the wind turbine tower instead of building large-scale hydrogen production station onshore.
- The capacity of submarine cables and ocean booster stations can be selected and designed according to the conventional power generation of wind turbines, and the equipment utilisation is high and reduces construction cost.

**Figure 5.7: Integrated Hydrogen Production at the Bottom of the Fan Tower**

Source: The General Electric Company.

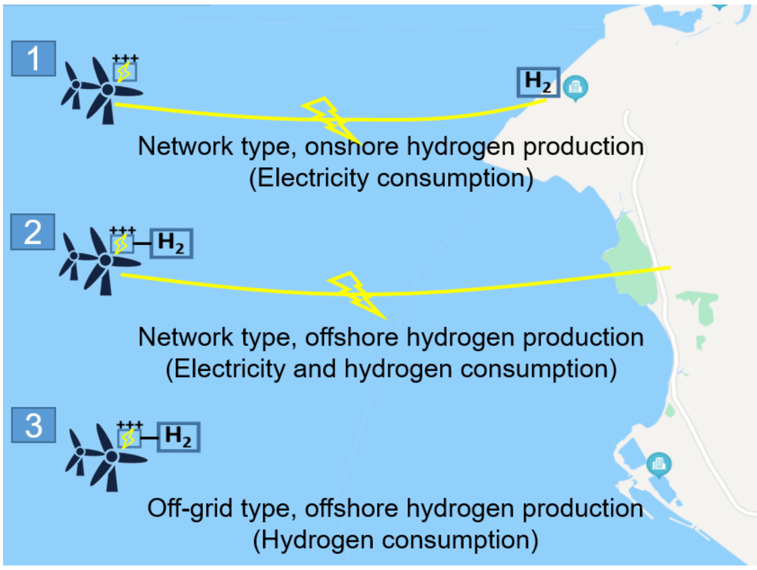
**Figure 5.8. Equipment of 200 $Nm^3/h$ (1 MW) PEM (size: 2400*1700*2000)**

MW = megawatt, $Nm^3/h$ = normal cubic metre per hour, PEM = proton exchange membrane.
Source: Shandong Saikesaisi Hydrogen Energy Co., Ltd.

### 4.3. Off-grid Direct Hydrogen Production

The PEM hydrogen production equipment with the same rated power generation capacity of the fan is integrated in the wind turbine tower. The power generation is onsite, and the hydrogen and pure oxygen are transported ashore to realise off-grid operation. It eliminates submarine cables, sea booster stations, and transformers in wind turbines, alternate current/direct current (AC/DC) inverters, and other equipment. It adds hydrogen production equipment, onshore pure water pipelines, and hydrogen and oxygen return pipelines. The AC power generated by the wind turbine is directly converted into hydrogen production equipment through the AC/DC inverter, eliminating the need for AC/DC inverters, wind turbine transformers, sea booster stations, submarine cables, land-based voltage reduction equipment, hydrogen production rectifier equipment, and other intermediate power transmission and transformation links to improve power utilisation. The produced high-purity hydrogen can be directly used in fuel cell vehicles to provide a green hydrogen source for the development of the hydrogen energy industry in Guangdong Province; the purity of oxygen can reach medical standards and has good commercial value. PEM electrolysed water hydrogen production equipment QLS-M200 (output 200 $Nm^3/h$) weighs about 8 tons, the 5.5 MW fan is equipped with six sets of configurations, the total weight is less than 50 tons, and the equipment is installed at the bottom of the tower. At the same time, the weight of the AC/DC inverter and 690 V-35 kV AC transformer can be omitted. Compared with the wind turbine with a weight of nearly 1,000 tons, the influence on the selection and design of the wind turbine foundation and the cost is almost negligible. The comparison of the different methods of electrolysis production and the according consumption is illustrated in Figure 5.9.

**Figure 5.9: Different Methods of Electrolysis Production and the According Consumption**

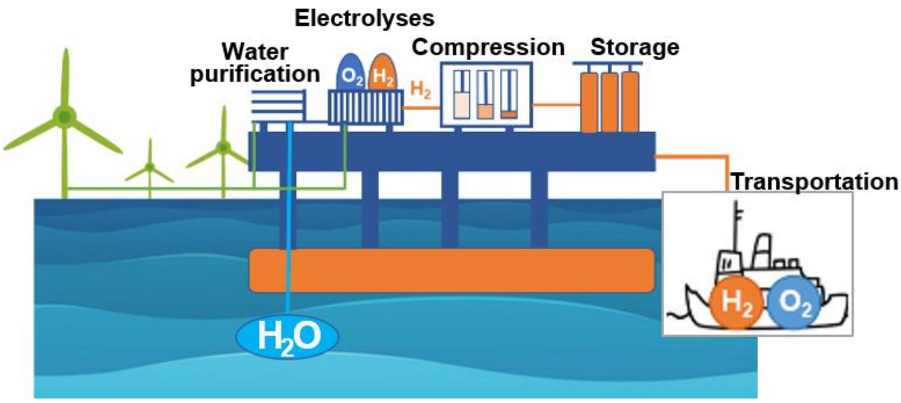



Source: Prepared by authors.

### 4.4. Off-grid Offshore Hydrogen Production

With the planning of offshore wind power to deep sea areas, large-capacity floating offshore wind power has become a trend and the diagram is shown in Figure 5.10. The world's largest single fan capacity GE Hailde-X reaches 12 MW, and the 8 MW fan produced by Shanghai Electric is the largest single fan capacity in China. SOEC is the only device that can directly electrolyse seawater to produce hydrogen. In the future, if the SOEC technology is mature, direct electrolysis of seawater to produce hydrogen, hydrogen and oxygen are compressed and liquefied on the offshore platform and then shipped, eliminating the need for water, hydrogen, and oxygen submarine pipelines to realise offshore wind power hydrogen production completely off-grid and offshore operation.

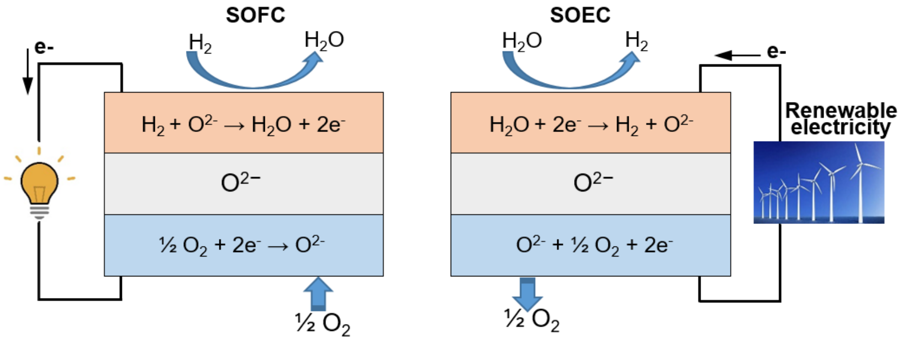
**Figure 5.10: Schematic Diagram of the Isolated Island Operation Plan for Direct Hydrogen Production by Floating Offshore Wind Power**




Source: Det Norske Veritas.

SOEC is the reverse process of solid oxide fuel cell (SOFC). SOEC electrolyses seawater to produce hydrogen, generates water through SOFC power generation, and produces hydrogen and stores energy while achieving desalination. It is suitable for islands and offshore oil and gas development platforms. The principle of SOEC and SOFC is demonstrated in Figure 5.11. Another working mode of SOEC is to convert $CO_2$ and $H_2O$ into CO, $H_2$ synthesis gas and oxygen through the electrolysis reaction to efficiently use heat and electric energy to produce hydrogen while absorbing $CO_2$ greenhouse gases, which is a ‘negative carbon’ reaction process.

**Figure 5.11: Principles of SOEC and SOFC**




SOEC = solid oxide electrolysis, SOFC = solid oxide fuel cell.
Source: Prepared by authors.

## 5. Economic Analysis

The above four offshore wind power hydrogen production plans, combined with the feasibility, economy, market potential, and technical maturity of hydrogen production equipment, recommend all hydrogen production plans for offshore wind power off-grid. The following economic analysis is an analysis of all hydrogen production schemes for offshore wind ionisation grids.

### 5.1. PEM Hydrogen Production Equipment Price Forecast

There are three main reasons for the high cost of PEM electrolysis hydrogen production equipment: the low output and small scale of the equipment in the initial stage of commercialisation; the need to import core equipment components; and the high cost of catalysts. PEM electrolysis is the reverse process of PEMFC for proton exchange membrane fuel cells. Referring to the curve of PEMFC fuel cell's 10-year cost drop by 60% and the curve of lithium batteries 10-year cost drop by 70%, it can be inferred that with the large-scale production of PEM water electrolysis equipment, and the promotion of localisation of components and technological progress, the cost of PEM can be reduced to CNY10,000/$Nm^3$ in the next 5 years.

### 5.2. Cost Analysis of Offshore Wind Power Construction

This part analyses the cost of offshore wind farms in deep water with a scale of 400 MW, 73 sets of 5.5 MW wind turbines, 60 km offshore, and 50 m water depth. The cost of sea risers, submarine cables, and land risers (shared) is CNY1.7 billion. Direct hydrogen production from offshore wind power eliminates the need for AC/DC inverters and transformers in the wind turbines. The cost per unit is about CNY1.6 million, and the cost for 73 units is about CNY117 million.

According to the off-grid hydrogen production plan, offshore wind power costs CNY11 million PEM hydrogen production for a single 5.5 MW wind turbine, CNY803 million for 73 sets of wind turbines, and approximately CNY200 million for the procurement and installation of submarine water, hydrogen and oxygen pipelines, with a total cost of approximately CNY1 billion. The total cost of offshore wind power hydrogen production construction has been reduced by CNY800 million, and the cost is reduced by about 10%.

### 5.3. Economic Analysis of Electricity Sales versus Gas Sales

The current on-grid electricity price for offshore wind power is CNY0.85/kWh, and the electricity price consists of CNY0.4 on-grid fee and CNY0.45 government subsidy. According to the 'Notice of the National Development and Reform Commission on Improving the Policy of Wind Power Feed-in Tariff (Development and Reform Price [2019] No. 882)' issued by the National Development and Reform Commission, onshore wind power will achieve parity on the grid in 2021.

Offshore wind power PEM electrolysis hydrogen production, 4.5 kWh corresponds to 1 $Nm^3$ hydrogen. The 400 MW wind farm generates 3,000 hours of electricity annually and produces 23,800 tons of hydrogen annually.

Based on the hydrogen consumption of a hydrogen fuel cell bus of 8 kilograms (kg) per 100 kilometres (km), a bus generally runs about 250 km per day and consumes about 20 kg a day. Therefore, the electricity generated from a 400 MW wind farm can be used for annual operation of 3,300 buses. A taxi consumes 1 kg of hydrogen per 100 km, and a taxi generally consumes 6 kg per day for 600 kms. Thus, the electricity generated from a 400 MW wind farm can be used for annual operation of 11,000 buses or 100,000 family cars. Household hydrogen fuel cell passenger cars consume 1 kg of hydrogen per 100 km, and fossil fuel vehicles cost CNY50 per 100 km. The price of hydrogen at hydrogen refuelling stations is CNY40/kg (CNY3.6/$Nm^3$), and thus hydrogen fuel cell cars take advantage over fossil fuel vehicles without considering the storage and transportation costs of hydrogen. The price of hydrogen is calculated based on CNY2.5 or CNY2.0/$Nm^3$. The oxygen purity of the by-product of PEM water electrolysis hydrogen production reaches 99.5%, which meets the medical oxygen standard. It has good commercial value as medical oxygen and industrial oxygen. The oxygen price is calculated at CNY2.0 or CNY1.5/$Nm^3$. Table 5.2 shows the price of electricity and gas with and without offshore wind power subsidies. Due to the uncertainty of the subsidy policy in various period, we assume a different range of subsidies (CNY0.45, CNY0.35, CNY0.25 and CNY0.15) for calculation. The ratio of hydrogen and oxygen products is 2:1, and every 1 $Nm^3$ of hydrogen produced is accompanied with 0.5 $Nm^3$ of oxygen. Therefore, there are four combinations for every normal cubic hydrogen price, from CNY3.5 to CNY2.75. It is safe to conclude that selling hydrogen has more economic advantages than selling electricity without subsidies.

**Table 5.2: Comparison of Electricity and Gas Prices with and without Offshore Wind Power Subsidies**

| Type | Amount | Price (CNY) | | Total Price (CNY) | Note |
|---|---|---|---|---|---|
| | | Parity | Subsidy | | |
| Selling electricity | 4.5 kWh | 0.4 | 0.45 | 3.825 | Need to pay ancillary service fees |
| | 4.5 kWh | 0.4 | 0.35 | 3.375 | |
| | 4.5 kWh | 0.4 | 0.25 | 2.925 | |
| | 4.5 kWh | 0.4 | 0.15 | 2.475 | |
| | 4.5 kWh | 0.4 | 0 | 1.8 | |
| Selling gas (take 4.5 kWh as reference) | 1 $Nm^3$ $H_2$ | 2.5 | \ | 3.5 | The prices for $H_2$ and $O_2$ are estimated based on the current market without considering the cost of storage, transportation, and refilling. |
| | 0.5 $Nm^3$ $O_2$ | 2 | \ | | |
| | 1 $Nm^3$ $H_2$ | 2.5 | \ | 3.25 | |
| | 0.5 $Nm^3$ $O_2$ | 1.5 | \ | | |
| | 1 $Nm^3$ $H_2$ | 2 | \ | 3 | |
| | 0.5 $Nm^3$ $O_2$ | 2 | \ | | |
| | 1 $Nm^3$ $H_2$ | 2 | \ | 2.75 | |
| | 0.5 $Nm^3$ $O_2$ | 1.5 | \ | | |

CNY = yuan, kWh = kilowatt hour, $Nm^3$ = normal cubic metre.

Note: The cost of submarine integrated pipelines (hydrogen transmission) is much cheaper than that of submarine cables and sea booster stations (electricity transmission).

Source: Prepared by authors.

## 6. Conclusion

In summary, this chapter introduced the different ways of producing hydrogen and elicited offshore wind power technology. In addition, the important methods of offshore wind power hydrogen production were analysed, and cost and economic analyses were further carried out systematically. It can be concluded that combining the technical advantages of offshore wind power turbines, integrating PEM hydrogen production equipment in the wind turbine tower, and all off-grid hydrogen production solutions, is a promising route to produce hydrogen through offshore wind power technology. Moreover, this chapter suggests that by deploying offshore wind power hydrogen production models in deep sea areas in advance to solve the cost problem of offshore wind power construction, is an important path for the future development of offshore wind power hydrogen production.

This chapter also revealed that the transportation method of hydrogen is closely related to the offshore distance for the hydrogen production station. Submarine pipeline and liquid hydrogen ships are two promising hydrogen transportation methods for hydrogen production from offshore wind power. According to a preliminary estimation, selling hydrogen has more economic advantages than selling electricity without subsidies.

Further technical research is essential to push forward the development of the offshore wind power hydrogen production industry. Relevant policy support and more flexible financing methods are also necessary to compensate for the economic disadvantages in its early stage. In addition, the relevant standards for hydrogen energy, offshore wind power, and hydrogen production from offshore wind power also need to be improved as soon as possible to ensure the sustainable development of the offshore wind power hydrogen production industry.

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# Chapter 6

# Financing Solutions for the Economic Feasibility of Hydrogen Projects: Case Study in China

Farhad Taghizadeh-Hesary, Yanfei Li, Ehsan Rasoulinezhad, Aline Mortha, Yan Long, Yu Lan, Zhehao Zhang, Nan Li, Xunwen Zhao, and Yao Wang

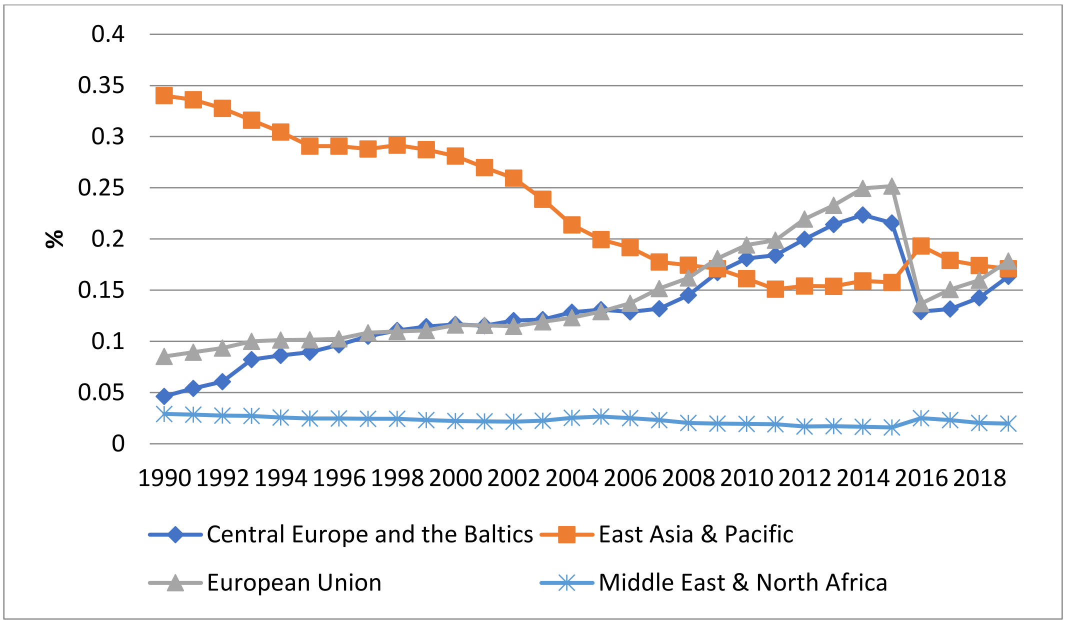
This chapter emphasises the economic and financial feasibility analysis of hydrogen energy projects in China to identify appropriate financing solutions for them. Cost–benefit and sensitivity analysis approaches were carried out for the three hydrogen projects in Guangdong province (two cases) and Jiang Xi province (one case). The profitability analysis revealed that the examined hydrogen projects in China at the real discount rate of 8% are profitable. Moreover, the sensitivity analysis results depicted different reactions of hydrogen projects to the financing cost variables. Besides, hydrogen projects are more sensitive to the discount and income tax rates, amongst other financing costs. The main reasons are the capital-intensive nature of green energy projects and the role of tax in the return on investment of green projects in the long term. Moreover, the results revealed that a lower financing risk could make the net present value (NPV) of a project more profitable, and the NPV becomes positive on a shorter horizon. The optimal weight of bank loans for the studied hydrogen projects in China was calculated at nearly 56%, meaning the weight of green bonds is approximately 44%. In other words, diversifying channels of financing instead of just relying on bank loans is recommended. As a major policy implication, we recommended various de-risking tools, such as the green credit guarantee corporation, to attract private investments in hydrogen projects.

Keywords: Hydrogen project, economic feasibility, sensitivity analysis, de-risking tools

## 1. Introduction

The oil price crisis beginning in the 1970s is the primary origin of the alarming fossil fuel participation in the global economy (e.g. see Ringel, 2006; Aquila et al., 2016; and Junior et al., 2019). Consequently, this alarming situation became central in the scholars' approach to study appropriate alternatives to fossil fuels that are environment-friendly. The consumption of renewable energy resources has increased over the last decades; however, their movements in different regions are not a stable, increasing slope. Figure 6.1 shows the ratio of renewable energy consumption to fossil fuel energy consumption in various world regions. It shows that this ratio's movement did not increase, particularly after the oil price drop in 2014.

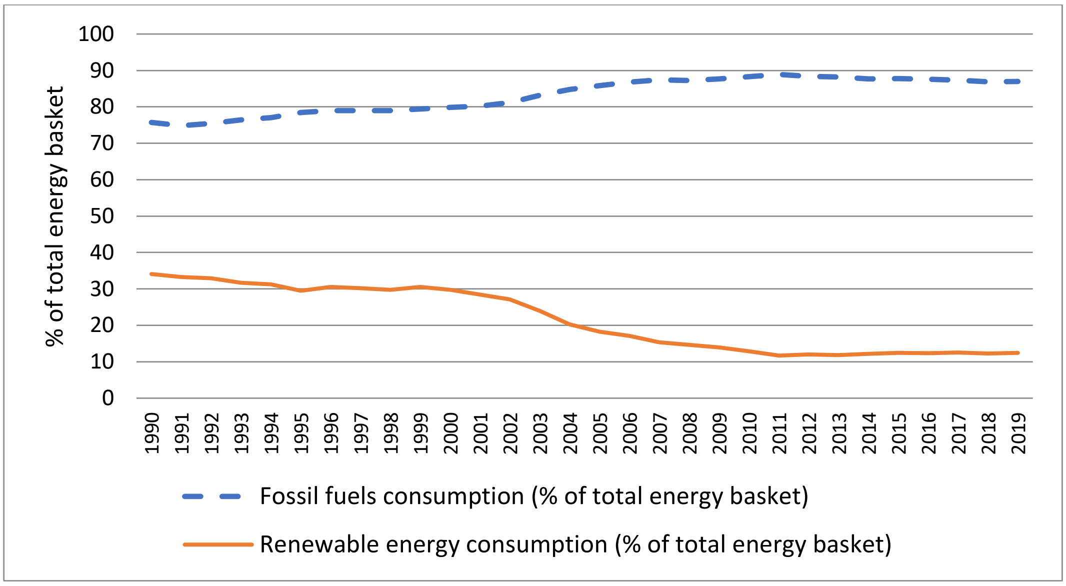
**Figure 6.1: Ratio of Renewable Energy Consumption to Fossil Fuel Energy Consumption (%)**




Source: Authors' compilation based on World Bank database and BP 2020 report.

The lack of increased movement to renewable energy resources is more highlighted for the major carbon emitters globally due to their contributions to the global threats of climate change and air pollution. China is the biggest carbon emitter globally (Zheng et al. 2019), spreading over 9,825 million tonnes of carbon dioxide ($CO_2$) in 2019. This is more than the total $CO_2$ emissions of North America (5,975 million tonnes); Europe (4,110 million tonnes); the Commonwealth of Independent States (2,085 million tonnes); and Africa (1,308 million tonnes) in 2019 (BP, 2020). Therefore, China is the first country that needs more efficient and diversified policies and attention to promote renewable energy resources in its total energy basket. Due to its impressive economic growth, its primary energy consumption has significantly jumped over the last decades. Based on the *Statistical Review of World Energy* (BP, 2020), China's primary energy consumption per capita increased from about 7.6 gigajoules per capita in 1965 to 32.9 gigajoules per capita in 2000. Since then, due to its remarkable domestic production growth, the consumption of energy as a primary production input had risen rapidly and reached approximately 98.8 gigajoules per capita in 2019. This high level of increased energy consumption has made China consume more common and economical fossil fuels than green energy resources. Figure 6.2 shows the rate of fossil fuels and renewable energy consumption in China from 1991 to 2019.

**Figure 6.2: Renewable Energy and Fossil Fuels Energy Consumption in China (% of total energy basket)**




Source: Authors' compilation based on World Bank database and BP 2020 report.

As represented in Figure 6.2, since 2000, the fossil fuels share in China's total energy basket has been increasing. Vice versa, the share of clean energy in the total energy consumption basket has gradually decreased. Murata et al. (2016) expressed that the country's clean development mechanism would be vital for our globe by reducing air pollution and controlling climate changes.

Recently, China has been ambitious in supporting green projects and developing green energy technologies to improve its energy security, lower its carbon emissions, and boost renewable energy contribution in its local economic sectors. The appropriate renewable energy potential in China can be a reliable factor in this way. Table 6.1 reports China's capacity in selected renewable energy resources.

**Table 6.1: Renewable Energy Capacity in China, 2000–2019 (MW)**

| Renewable Energy Source | 2000 | 2005 | 2010 | 2015 | 2019 |
|---|---|---|---|---|---|
| Wind capacity | 341 | 1,060 | 29,633 | 131,048 | 210,478 |
| Solar capacity | 34 | 141 | 1,022 | 43,549 | 205,493 |
| Geothermal capacity | 22 | 22 | 24 | 26 | 26 |

Source: Authors' compilation based on BP 2020 report.

Amongst different green energy sources, hydrogen is a secondary energy source that Chinese scientists and scholars have considered clean and environment-friendly to substitute for fossil fuels. Deyou (1994) declared that, in the mid-1990s, the government approved the hydrogen energy research programme to help boost the share of hydrogen in China's total energy basket. Since then, the government has approved and issued different plans and policies to support the hydrogen projects. Hong and Jin (2021) argued that various policies and plans, such as China's 5-year plans, make the target of green project investment clearer and more accessible. However, according to the arguments of several scholars, such as Yuan and Lin (2010), Pudukudy et al. (2014), and Ren et al. (2020), hydrogen project enhancement in China faces various challenges and obstacles.

Hydrogen projects generally need the participation of private investors who make decisions based on costs and benefits. Voica et al. (2015) expressed that fiscal constraints are the major challenge towards green investments for which increasing motivations for the participation of private investors is a suitable solution. In another study, Engelen et al. (2016) revealed that the main reason behind the low level of private investment in hydrogen projects is their limited return. Tian et al. (2020) mentioned that the financial feasibility environment investment plays a chief role in exploring whether a green project is profitable for private investors to consider in decision-making.

Few academic studies focused on the financial and economic feasibility of hydrogen projects. Examples are those conducted by Shah (2020) for Pakistan, Southall et al. (2016) for the United Kingdom, Derbal-Mokrane et al. (2011) for Algeria, and Wietschel and Hasenauer (2007) for the European Union. Moore (1983) also studied the feasibility of advanced technology for hydrogen production, particularly for the case of China (e.g. see Qiu et al. [2020]; Liu et al. [2020] for underground hydrogen storage; and Lv et al. [2008] for hydrogen production). The authors did not find any studies related to the economic and financial feasibility of ongoing hydrogen projects in China. Therefore, this chapter will fill in this literature gap using project data from the interviews and analysing data through the cost–benefit approach and sensitivity analysis.

Section 2 of this chapter reviews the literature to debate earlier studies and clarify the literature gap. Section 3 discusses the policies and initiatives for the hydrogen economy in China, and Section 4 discusses the research methodology. Section 5 presents the findings, followed by the last section, which concludes and explores major policy implications.

## 2. Literature Review

### 2.1. Economic feasibility of hydrogen projects

The economic feasibility of hydrogen production is being debated amongst scholars, as hydrogen is still expensive (IEA, 2019). First, its economic feasibility depends on the technology used for production and the price of primary resources used as inputs. IEA (2019) and Zhang et al. (2020a) highlighted that hydrogen produced from hydrocarbons remains the cheapest option for hydrogen production in industries. This is reflected by the fact that more than 96% of hydrogen supplied globally is produced from fossil fuels (IEA, 2019; Zhang et al., 2020b). Even in recent years, Keipi et al. (2018) highlighted that the thermal decomposition of methane, which represents nearly half of the global hydrogen production, remains more competitive than any other method, including water electrolysis powered by electricity from renewable sources.

Even if fossil fuels remain the favoured option due to low costs, increasing concerns over climate change have prompted several studies to examine the economic feasibility of low-carbon hydrogen production. Hence, some research focused on alternative, low-emissions hydrogen production strategies based on fossil fuels. Through a comprehensive review of the literature on the topic, Muradov (2017) compared different hydrogen production strategies, namely, coupling fossil fuel production with carbon capture and storage (CCS), decomposition of light hydrocarbons, and using renewable and nuclear electricity for powering hydrogen production from fossil fuels. Despite the technological maturity of the CCS, the author highlighted that it remains economically unfeasible without regulatory or economic incentives and due to long-term uncertainties of the CCS's storage capacity. Hydrogen produced from a light hydrocarbon can be a low-carbon option but is technologically not mature enough to represent a viable method (Muradov, 2017).

Similarly, Khojasteh Salkuyeh, Saville, and MacLean (2017) analysed emerging methods for producing hydrogens such as syngas chemical looping (SCL) and chemical looping reforming (CLR) and compared them with steam methane reforming and auto-methane reforming in terms of economic feasibility. The study concluded that, even though the CLR is the most economically profitable method, scaling up and commercialisation remain challenges that impede CLR deployment (Khojasteh Salkuyeh et al., 2017). Most industrial-scale hydrogen plants use the steam methane reforming (SMR) process to convert hydrocarbons to $H_2$, CO, and $CO_2$ (Welaya et al., 2012). However, the SMR technology has higher $CO_2$ emissions than other natural gas–reforming technologies (Wilhelm et al., 2001). Khojasteh Salkuyeh et al. (2017) showed that the SCL with carbon capture is more financially attractive than the autothermal reforming and SMR processes only when the carbon price is above \$47/tonne $CO_2$. Their financial analysis shows that the minimum hydrogen selling price of the CLR system is 50%–90% of the price for the other technologies. Finally, a carbon price of only \$5/tonne $CO_2$ is required to make the CLR option (with zero direct carbon emissions) more financially attractive than the SMR.

A second option for low-carbon hydrogen production is water electrolysis, using electricity produced from renewable energy and water. However, some studies tended to dismiss this option due to high costs (Nagashima, 2018). Muradov (2017) confirmed the relative lack of competitiveness of renewable energy as input for hydrogen production since water electrolysis would necessitate a spectacular increase of renewables' share in the energy mix to become a viable option. However, a recent article by Proost (2020) examined the economically viable minimum production scale needed for hydrogen produced from renewable energy sources (RES)) to compete with hydrogen produced from fossil fuels. Using recent data on hydrogen production costs and life-cycle analysis (including capital expenditure), the author finds that parity could be achieved at a small production scale. However, this would require further intensification of the water electrolysis process (Proost, 2020). Using a similar approach, Dinh et al. (2020) posited that offshore wind farms would become profitable soon. Generally speaking, if most research acknowledges that hydrogen production from RES is costly, many studies on wind and solar farms still advocate for the economic feasibility of hydrogen production from RES. For instance, Yan et al. (2017), Fereidooni et al. (2018), Li and Kimura (2018), Kimura and Li (2019), and Nadaleti et al. (2020) found that hydrogen production from renewable surplus is a viable option to solve curtailment issues. Finally, Hou et al. (2017) explored different configurations of offshore wind farms that demonstrated benefits and profitability of some cases provided demand was sufficient.

Nevertheless, even if hydrogen production from water electrolysis is deemed economically feasible, it relies heavily on freshwater as an input. Hence, it might be limited in regions of scarce water (Shi et al., 2020). In particular, the People's Republic of China (PRC) is especially at risk due to its high water scarcity index.

### 2.2. Hydrogen produced from renewable sources to supply fuel cell vehicles (FCVs)

This study aims to determine the economic feasibility of hydrogen projects. Thus, this subsection discusses recent studies that examined the feasibility of using hydrogen produced from RES to supply the FCVs. The transport sector is often amongst the main emitters of greenhouse gases (GHGs). Using renewable hydrogen to fuel vehicles has offered certain benefits, including a greater degree of energy security, a reduction in pollution level, and a drop in GHG emissions (Southall and Khare, 2016; Li and Taghizadeh-Hesary, 2020a and 2020b). Nevertheless, the development of renewable–produced hydrogen has been relatively slow.

The first obstacle to its development is the 'chicken and egg dilemma' (Southall and Khare, 2016; Campiñez-Romero et al., 2018). Campíñez-Romero et al. (2018) argued that the main reason behind the lack of FCVs is the lack of H2 refuelling network, contributing to low demand for FCVs. Similarly, Reddi et al. (2017) highlighted that the costs of refuelling stations dominate the hydrogen costs for FCVs. The high cost of equipment, relatively small infrastructure, lack of economies of scale, and low level of utilisation of existing stations explain this phenomenon. However, the study also showed that the levelized hydrogen costs can be drastically reduced from improved capacity utilisation and developed economies of scale (Reddi et al., 2017). Generally, to create hydrogen-refuelling stations, a fundable and economically viable infrastructure is necessary, which is not the case because of the low demand. Southall and Khare (2016) addressed the issue arguing that, despite commercial-scale hydrogen production, the distribution network depends on hydrogen vehicles' sales. They proposed the example of collaboration between the United Kingdom's industry and government to end the vicious circle.

The lack of infrastructure for hydrogen-refuelling stations is the high upfront investment needed to build them. Nagashima (2018) argued that the biggest hurdle for hydrogen vehicles is the lack of fuelling infrastructure. Despite heavy subsidies for FCV development in Japan, the tight regulations and technical constraints contribute to increased costs for infrastructure building: a hydrogen station costs two to three times more than in Europe. However, some authors argued that the lack of infrastructure and financial resources used to be an issue at the beginning of fossil fuel commercialisation (Singh et al., 2015). Therefore, such issue can be overcome with government authorities' support and state subsidies (Campiñez-Romero et al., 2018). Indeed, subsidies could be crucial for reducing hydrogen technologies' costs (Nistor et al., 2016) and would help increase the share of hydrogen produced from renewable energy sources (Southall and Khare, 2016). While wind technology can meet all demand for FCVs in the short run, once the FCV fleet is established, RES alone cannot produce enough hydrogen to satisfy demand (Southall and Khare, 2016). Through a case study of a Swiss district, Prasanna and Dorer (2017) shared similar views. While results proved that hydrogen produced for *photovoltaic thermal collectors* is technically viable if combined with short- and long-term storage, their model does not include hydrogen use for mobility. In particular, stored hydrogen is fully used to meet peak demand in winter. Hence, the authors argued that a greater storage capacity would be required for hydrogen to meet both power and transportation demand.

Most studies that assessed the economic feasibility of hydrogen use for FCVs concluded that subsidy schemes and economies of scale of installed electrical equipment and the electrolyser capacity and hydrogen storage equipment could bring down costs (Southall and Khare, 2016). In particular, Nistor et al. (2016) argued that the hydrogen unit cost could be below that of petrol if the expected return on investment period is over 10 years for the proton exchange membrane and electrolysers, and 5 years for alkaline electrolysers. While hydrogen technologies seem to be profitable in the long term, short-term hydrogen production infrastructure, coupled with renewable energy tariffs, is still financially viable under certain configurations (Southall and Kharem, 2016).6

## 2.3. Policies and initiatives helping renewable energy development in the PRC

In recent years, published literature on the development of renewable energy has grown tremendously. Since the study aims to look at the economic feasibility of hydrogen produced from renewable sources, it is crucial to understand what can help increase renewable energy production. Because of the size of the literature on the topic, we narrowed down this literature review to examine previous studies analysing the PRC's case. As mentioned in the introduction, the PRC has experienced spectacular growth in renewable energy, led by generation from wind and solar photovoltaic. Simultaneously, the country has a high curtailment rate for these two technologies, partly explained by regional disparity (Du and Takeuchi, 2020), which extensive hydrogen storage could solve.

First, the PRC introduced public schemes to encourage the growth of renewable energy. The country has extensive subsidies to support renewable energy development nationally and regionally since the Renewable Energy Law of 2005. These subsidies are of various forms, from research and development incentives for vehicles and solar power since 2009 to tax preference systems and direct subsidies (Shen and Luo, 2015). Evaluating the effect of these subsidies, Shen and Luo (2015) concluded that, while the multiplication of subsidies has undoubtedly contributed to the acceleration of renewable energy

[6] The authors used average wind speeds in the United Kingdom for their calculations. Varying wind speed might affect the results of the study.

development, it also created overcapacity issues, fierce competition, and lack of funds. In 2009, the country introduced a regionally differentiated feed-in-tariff. Du and Takeuchi (2020) evaluated the policy's success in fostering solar and wind power growth. They concluded that the policy had mixed effects for solar power in 2011 and 2013 but had a positive and significant impact on wind for regions with a lower endowment, especially after the tariff gap widened between regions (Du and Takeuchi, 2020). This was not the first study to show that the feed-in-tariff results are highly dependent on tariff and subsidy rates (Böhringer et al., 2013). After controlling tariff size, contract duration, digression rate, electricity price for each country, and production costs, Jenner, Groba, and Indvick (2013) found that feed-in-tariff had little effect on renewable generation. Finally, the PRC has been considering implementing an emission trading scheme (ETS) since 2017. Because the ETS charges more for fossil fuel, this policy could indirectly foster renewable growth through increased demand. Using a Computable General Equilibrium framework, Lin and Jia (2020) explored the ETS's impact on renewable development and different revenue-sharing scenarios. They concluded that the ETS could help renewable development if the revenue generated from the policy is used as a renewable energy subsidy.

A second option to increase the economic feasibility of renewable projects is the use of private green finance. Financial instruments to fight climate change have been steadily rising. In particular, the use of green bonds, a form of fixed-type security solely defined by its aim to finance 'green' projects, has been rising in the PRC. As of 2019, the country is the second issuer of these bonds, both in number and amount (CBI, 2020). Flaherty et al. (2017) proved that green bonds could finance climate change mitigation practices and improve intergenerational welfare in an empirical analysis of overlapping generation models. Similarly, Lee and Zhong (2015) presented a hybrid form of bonds to bridge the investment gap for renewable projects. The bond consists of a portfolio of renewable projects, which can manage risks associated with initial project development while providing enough capital funds to support projects. Finally, Taghizadeh-Hesary and Yoshino (2019) proposed another framework, mixing public and private entities, to reduce risks associated with renewable projects. The Green Credit Guarantee Scheme presented in the study aims to decrease risks and uncertainties of renewable projects through credit guarantee, in turn, financed by tax spillovers generated by the installation of renewable energy (Taghizadeh-Hesary and Yoshino, 2019). The PRC had implemented a credit guarantee for green projects in some selected pilot cities (Li et al., 2018).

## 3. Policies and initiatives for hydrogen energy in the PRC

Since John Bockris introduced the concept of hydrogen economy in the early 1970s, many scholars and policymakers in different countries have considered using this energy resource instead of fossil fuels. However, hydrogen has not considerably contributed to the total energy basket in the world. As a major energy consumer and the biggest air polluter globally, China has tried to boost hydrogen production to reach a higher level of green energy than fossil fuels. It produced over 12.4 million tonnes of hydrogen in 2007 for ammonia, methanol, and oil refining processes (Deng et al., 2010). The hydrogen produced in China has increased dramatically and generates over 20 million tonnes annually in recent years. Compared with other pioneers in the green economy, in January 2020, the number of hydrogen-refining stations were about 61, 81, and 116 in China, Germany, and Japan, respectively (Yue and Wang, 2020).

China is motivated to use appropriate production technologies to increase its hydrogen production capacity (Gao et al., 2020). Because the currently produced hydrogen in China is from coal via 1,000 gasifiers (about 5% of China's total coal consumption [De Blasio and Pflugmann, 2020]), the country needs to ensure green hydrogen.

Notably, China has invited pioneer foreign companies to produce green hydrogen. For example, Siemens Energy Company, with Beijing Green Hydrogen Technology Development Co. Ltd., will provide the first-megawatt green hydrogen production project in the Yanquing District of Beijing (Larson, 2020).

Without government support, cooperation with foreign companies and hydrogen energy production's capacity could not expand. In the 1990s, China's major approach to renewable energy development was ensuring agricultural fuels (Liu, 2019). Since the early 2000s, the regulations related to green energy resources had been gradually improved to help electricity production (Huang and Huang, 2017). Due to China's severe air pollution, the government passed the Renewable Energy Law (REL) in 2005, reflecting the country's acceptance of renewable energy development. However, due to a few barriers, such as the rapid growth of fossil fuel capacity, lack of connection between renewable generation capacity with the electricity grid, and low efficiency of renewable electricity plants in China, REL could not lead China to an optimal level of the green economy (Wang et al., 2010). In 2016, the 13th Five-Year National Development Plan of China included enhancing on-board hydrogen storage systems and constructing hydrogen refuelling stations (Gosens et al., 2017). In the same year, the government issued a road map on the hydrogen fuel industry, which estimated that total hydrogen fuelling stations would be 100 and 1,000 units in 2020 and 2030, respectively (Yuanyuan, 2020).

In February 2018, a government-supported alliance, the China Hydrogen Alliance, was launched to improve the hydrogen sector. In March 2019, to upgrade the green regulations, China added policies to construct renewable hydrogen facilities for new energy vehicles, motivating the car industry to produce vehicles fuelled by renewable hydrogen (De Blasio and Pflugmann, 2020). In 2020, for the first time, hydrogen was listed as an energy source in the PRC's Energy Law as an essential solution to decarbonising transportation in the country. Bruno Forget, Air Liquide's head of hydrogen in China, mentioned that the government's energy strategy for 2020 provides different policies to support China's hydrogen energy sector (S&P Global Platts, 2020). This government support is also motivated by the 2022 Winter Olympics, making China develop green energy consumption, especially for transportation purposes. Zhang et al. (2020a) proved that a fuel cell transit bus with renewable hydrogen is economically feasible for China, highlighting this motivation.

Through existing government support for the hydrogen economy, the investment flow in this sector increased considerably from approximately US$11 billion in the first 6 months of 2018 to about US$14 billion in the same period of 2019, emphasising China's efforts to increase the contribution of hydrogen in its total energy consumption.

## 4. Theoretical Approach and Sample Data Description

There are various methods for evaluating and calculating the economic and financial feasibility of investment projects. However, in energy-related projects, many scholars, such as Ertürk (2012), Li et al. (2013), Holdermann et al. (2014), and Arnold and Yildiz (2015), suggested that the net present value (NPV) method is the key indicator of economic and financial feasibility. Its features make it possible to consider the risks and calculate the value created by investing in an energy project. So, when the NPV of an energy project is more than zero, it means that the project creates value. Thus, the energy project is economically justifiable. Through a comparative analysis, Taylor (1988) found out that the NPV leads to a better result than other criteria, such as NPV/K. Yang et al. (2012) declared that the NPV's acceptance happens when its measure is greater than zero; otherwise, the project should be rejected. The NPV criterion can be expressed by Eq. 1 as follows:

$$NPV = -I + \sum_{j=1}^{n} \frac{CF_j}{(1+k)^{j'}} \qquad (1)$$

$CF_j$ denotes the cash flow in period $j$, while k represents the minimum attractiveness rate (the minimum return that the investor wants to obtain in the energy project investment). $I$ stands for investment. In the NPV equation, cash flow (CF) shows money value in the energy project, whereas a discount rate is employed to explore the value at present. Therefore, the flow volume is determined by the project developer's view, including both client and investor.

Furthermore, we determined the internal rate of return (IRR) to check the profitability of the hydrogen project investment. The related equation is as follows:

$$0 = \sum_{t-1}^{n} (C_t - C_0)(1 + IRR)^{-t} \qquad (2)$$

In Eq. 2, $C_t - C_0$ depicts net cash flow at $t_{th}$ year.

To explore results in more detail, we employed a sensitivity analysis method to prioritise the major parameters that significantly impact the target cost. In this study, we used the gradient sensitivity analysis through the Expert Choice 11 software to prioritise the financing cost impacts on the NPV of the examined hydrogen projects in China.

This research was undertaken in three hydrogen projects located in China's southern provinces Guangdong and Jianxi. The first one has a hydrogen production purpose and located in the Jiangxi province of China. Its electrolyser capacity is about 30 MW and produces 12 tonnes of hydrogen (gas) per day. Moreover, 12 liquid hydrogen refuelling stations have a specification of 1,000 kg/d.

The second sample is a liquefaction plant of liquefied hydrogen located in Taihe county in Jiangxi province. It includes transporting liquid hydrogen via tube trailers from Jiangxi to Foshan city in Guangdong province for 500 kilometres.

The third project is a hydrogen refuelling station in Foshan city of Guangdong province, tasked to fill buses with hydrogen fuel. It costs over US$16 million,[7] including various expenditures such as equipment (US$714,000); land and construction cost (US$57,400); capital (US$5,886,000); total debt amount (US$2,522,800); a loan interest rate of 5%; and revenue volume of US$1,126,200.

We gathered all the required data to calculate the hydrogen projects' economic and financial feasibility by interviewing the experts working on those projects. The average cost of equipment for the three hydrogen projects in China is nearly US$65,000, while the estimated operation and maintenance cost is US$2 million. The estimated land and construction cost is US$50,000, and financing cost of US$10 million.

Table 6.2 reports the financing costs indicators.

**Table 6.2: Financing Costs of Hydrogen Projects (%)**

| Parameter of Costs | Value |
|---|---|
| Discount rate | 8% |
| Equity/Debt ratio | 30%/70% |
| Loan interest | 5% |
| Operation period (project life) | 20 years |
| Repayment period | 10 years |
| Income tax rate | 20% |

Source: Authors' compilation from interviews with the project managers.

The discount rate of green energy projects, such as hydrogen one, is almost between 6%–10%; in our sample, the average is 8%. Moreover, loan interest and income tax rates are 5% and 20%, respectively. The repayment period is 10 years, and the operation period 20 years. The loan interest of these three projects averages 5%. In contrast, the equity/debt ratio is 30%/70%, meaning that about 70% of the initial capital investment in China's hydrogen projects is from bank loans.

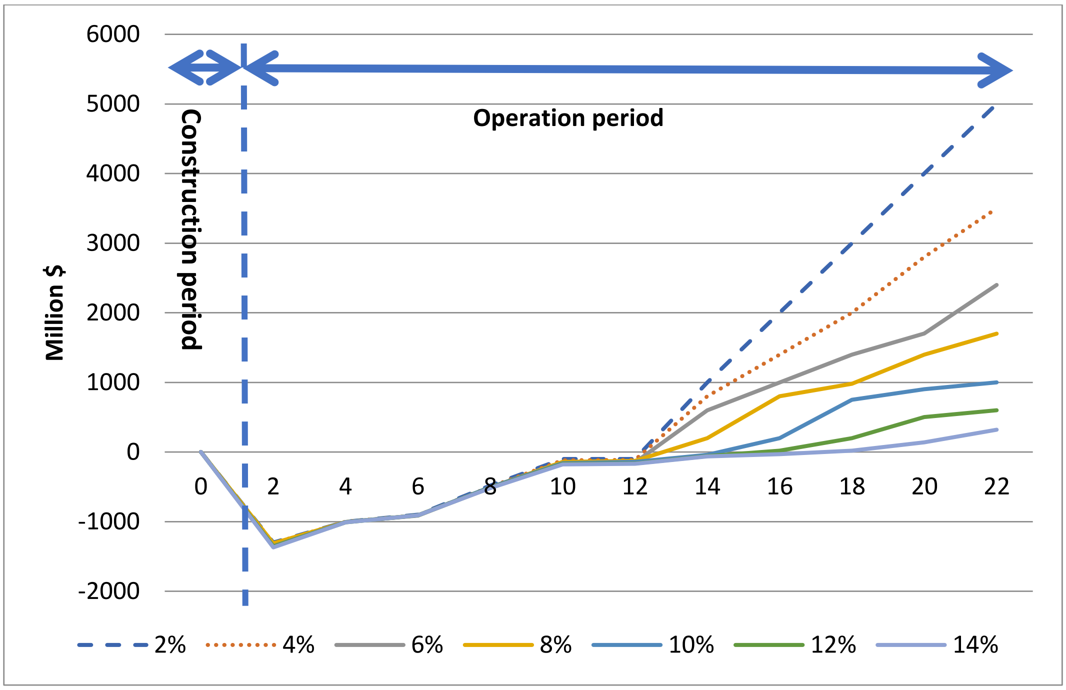
[7] US$1.00 = CNY6.48.

## 5. Empirical Results

### 5.1. Analysis of profitability

To analyse the hydrogen project's economic feasibility, we used NPV and IRR to explore profitability. Figure 6.3 shows the NPV findings of China's hydrogen projects with different discount rates. The NPV curves in different discount rates (2%–14%) have two breakpoints: (i) at 2% at the end of the construction period of large-scale liquefaction project (the construction period for CCHP (combined cooling heating and power systems) wind project is 2 months and for the bus project, it depends on buying buses and running the project; and (ii) at 12% (at the middle of the project life) when the equipment needs major repair or replacing. Vogel (2014) and Okoro et al. (2019) named it as a depreciation line that happens over 10 years over the operation period.

**Figure 6.3: NPV of Hydrogen Project in China with Different Discount Rates**



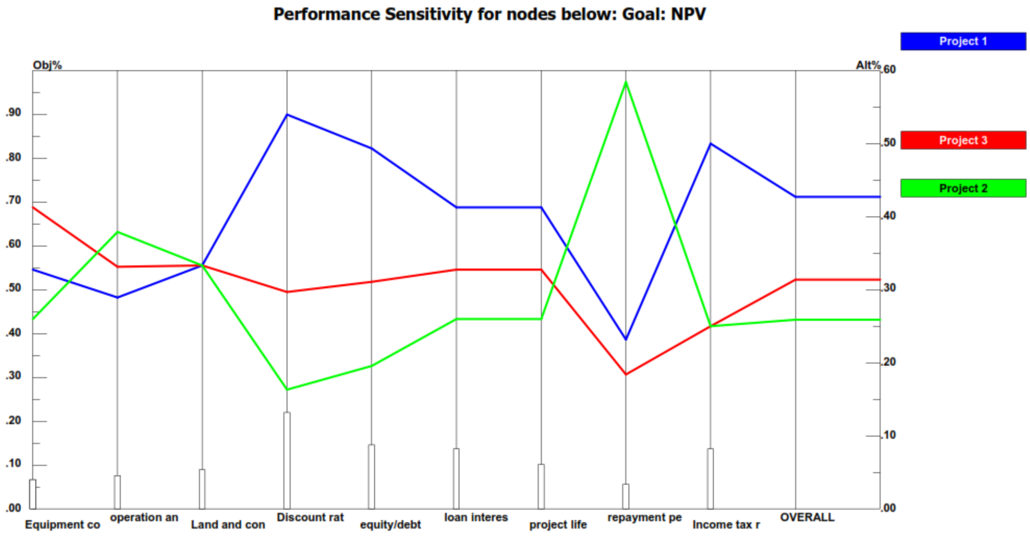

Source: Authors' calculation.

The average IRR for the three hydrogen projects is calculated at 15.38%, which is more than the real discount rate (8%) of a hydrogen project in China. A project is economically feasible if its IRR exceeds the real discount rate (Liu et al., 2020). Thus, we can conclude that China's hydrogen projects are economically feasible based on the profitability analysis.

## 5.2. Sensitivity analysis

We carried out a sensitivity analysis to explore the effects on the NPV of hydrogen projects due to different costs. To this end, we conducted a gradient sensitivity analysis via the Expert Choice software.

**Figure 6.4: The Sensitivity of Costs of Hydrogen Projects**




Source: Authors' calculation from Expert Choice 11.

Figure 6.4 illustrates the sensitivity analysis results and reveals that the NPV of hydrogen projects in China is more sensitive to financing costs, such as discount rate, income tax rate, and loan interests. The main reason for the high sensitivity of these projects to the discount rate is due to the capital-intensive nature of green energy projects, as expressed by earlier studies (Walker, 1996; Shakya et al., 2005). Regarding the income tax rate, following Assidi et al. (2016), tax policy is a significant factor in increasing/decreasing investment returns and attracting/not attracting investments. Moreover, the sensitivity of each project to the cost variables is not similar. For instance, as shown in Figure 4, Project 1 is more sensitive to financing costs than the second and third hydrogen projects in China. Project 1, which is in Jiangxi province, produces hydrogen, its electrolyser's capacity is about 30 MW, and produces 12 tonnes of hydrogen (gas) per day.

## 6. Financing Risk of Hydrogen Projects

The empirical findings, represented in Section 5, emphasise the role of financing solutions to lower the project's financial risk. If we use scenario analysis to find the expected NPV of a hydrogen project based on different financing schemes, we can define the share of bank loans and green bonds (Table 6.3).

**Table 6.3: Input–Output Table for the NPVs Based on Different Funding Scenarios, %**

| NPV | Share of Bank Loans | Share of Green Bonds |
|---|---|---|
| NPV0 | 100 | 0 |
| NPV1 | 90 | 10 |
| NPV2 | 80 | 20 |
| NPV3 | 70 | 30 |
| NPV4 | 50 | 50 |

Source: Authors' compilation.

If the equation for calculation of NPV is considered as Eq. (4):

$$NPV = \sum_{t=1}^{n} \frac{(C_1 - C_0)}{(1+i)^t} \quad (4)$$

The financing risk ($\sigma^2$) can be included in Eq. (4) as follows:

$$E(NPV) = \sum_{t=1}^{n} \frac{(C_1 - C_0)}{(1+i)^t + \sigma^2} \quad (5)$$

Calculating the E(NPV), considering the financing risks at different interest rates, represents a new version of Figure 6.3. We gathered data from the Green Bond Bloomberg terminal database, which includes data of 339 green bonds issuers in China with different Moody's risk ratios. Examples of these issuers are the Sihui Rural Commercial Bank, Bank of Guizhou, Industrial Bank Co Ltd, Fudian Bank, China Everbright Water, China Three Gorges Corporation, Huishang Bank, and Kaifeng Development Investment. We addressed different long-term ratings in nine groups (Table 6.4).

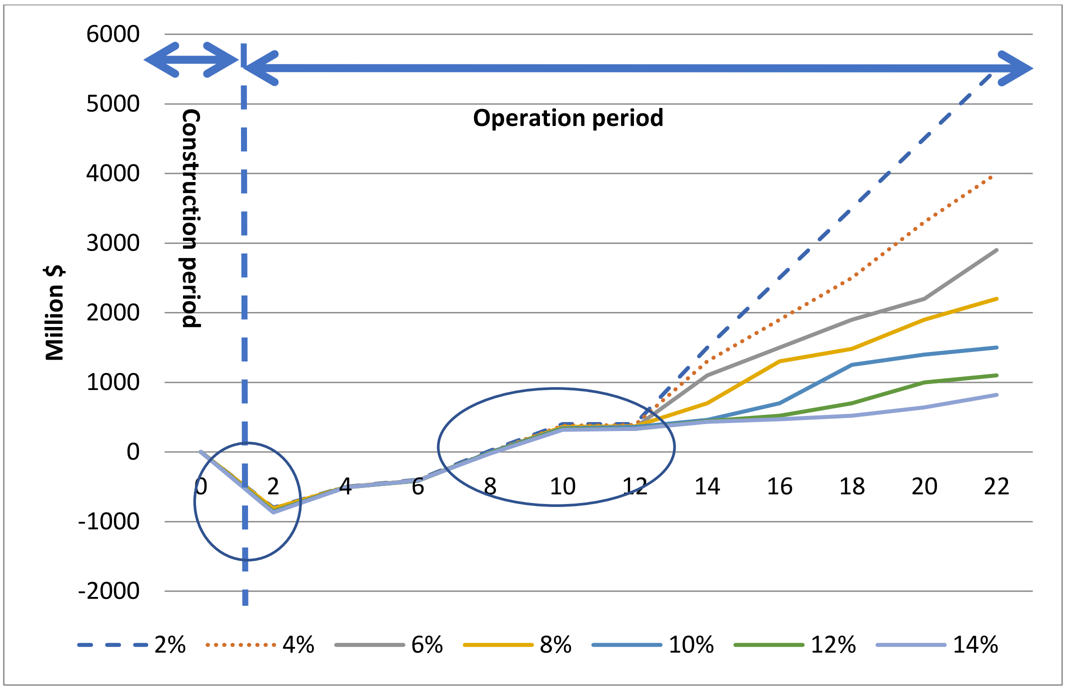
**Table 6.4: Classification of Different Long-Run Investment Rating by Moody's**

| Rank | Rating | Description |
|---|---|---|
| 1 | Aaa | The highest quality and lowest credit risk |
| 2 | Aa1, Aa2, Aa3 | High quality and very low credit risk |
| 3 | A1, A2, A3 | Upper-medium quality and low credit risk |
| 4 | Baa1, Baa2, Baa3 | Medium quality and moderate credit risk |
| 5 | Ba1, Ba2, Ba3 | Significant credit risk |
| 6 | B1, B2, B3 | Speculative and high credit risk |
| 7 | Caa1, Caa2, Caa3 | Poor quality and very high credit risk |
| 8 | Ca | Highly speculative |
| 9 | C | The lowest quality and low ability to recover interest or principal |

Source: Authors' compilation from Moody's (www.moodys.com).

Amongst 339 green bond issuers in China, the highest risk is for the Panda Green Energy Group, with a rating of Caa2. There are 28 issuers with a rating of A1 (the lowest risk amongst other issues in China). We classified nine various ratings into three ones as upper-middle quality (As with number 1), middle quality (Bs with number 2), and poor quality (Cs with number 3). We calculated the average ratio of the 339 Chinese issuers with 0.8 (meaning, the average green issuers in China have upper-middle quality and ability to recover principal and interest) and then used Equation (5). Figure 6.5 shows the E(NPV) at different discount rates.

**Figure 6.5: E(NPV) of Hydrogen Projects in China with Different Discount Rates**




Source: Authors' calculation.

Compared with Figure 6.3, a lower financing risk can make the NPV of the project more profitable, and the NPV became positive earlier. Green bond issuers in China should have a good risk ratio to reduce the financing risks of green projects.

Investors always try to optimise the financing portfolio. For a hydrogen project, the utility of the investors (U) can be written as Eq. (6):

$$U = r - \beta\sigma^2 \qquad (6)$$

Where r denotes IRR of the project depending on different financing schemes, whereas $\sigma^2$shows the project's financing risk depending on different financing schemes. Defining $r_L$ and $r_B$ as IRR in case of 100% bank loan financing and 100% financing by green bonds, respectively, we can write Equations 7–9 as:

$$r = \alpha r_L + (1-\alpha).r_B \quad (7)$$

$$\sigma^2 = \alpha^2.\sigma_L^2 + (1-\alpha)^2.\sigma_B^2 + 2\alpha.(1-\alpha).\sigma_{L.B} \quad (8)$$

$$U = \alpha r_L + (1-\alpha).r_B - \beta\{\alpha^2.\sigma_L^2 + (1-\alpha)^2.\sigma_B^2 + 2\alpha.(1-\alpha).\sigma_{L.B}\} \quad (9)$$

Solving the agent's utility maximisation problem, we applied the first-order condition to $\alpha$ (share of financing from bank loans). Then, we derived the optimal weight as Eq. (10):

$$\frac{\delta U}{\delta \alpha} = r_L - r_B - 2\beta.\alpha.\sigma_L^2 - 2\beta.(1-\alpha).\sigma_B^2 + \beta(2-4\alpha).\sigma_{L.B} = 0 \quad (10)$$

Consequently, the optimal weight of bank loans can be calculated as Eq. (11):

$$\alpha^* = \frac{\frac{1}{\beta}(r_L - r_B) + 2\sigma_{L.B} - 2\sigma_B^2}{2\sigma_L^2 - 2\sigma_B^2 + 4\sigma_{L.B}} \quad (11)$$

The optimal weight of bank loans for the studied hydrogen projects in China, based on the data gathered from the projects and financing risks of 0.8 (as mentioned before), is nearly 56%. This means the weight of green bonds is approximately 44% (1–0.56). In other words, the share of green projects financing by bank loan should be more than green bonds. However, instead of relying on bank loans, the financing channels' diversification can reduce the financing risk and increase the expected NPC. The role of green bond financing is so important in these projects (as also argued by Zhang et al., 2020b). In line with Cao et al. (2021), China tries to improve green investments based on the Green Bond Issuance Guideline, which loosened barriers to green energy investments. Based on the optimal weight of bank loans, an appropriate mix of bank loans and green bonds is highly recommended to lower the financing risk of China's hydrogen projects. Not only can reducing risks associated with hydrogen projects spark further interest from investors, but it can also help reduce costs in the long term. Furthermore, establishing a green credit guarantee corporation (GCGC) as a new de-risking tool can be used to reduce the risk of green bonds in hydrogen projects. Taghizadeh-Hesary and Yoshino (2020) proved that a GCGC could lower the investment risk in green projects through credit enhancement and create a balance in private borrowers' and financial institutions' creditworthiness.

## 7. Concluding Remarks

Given the need for countries worldwide to develop green projects to reduce environmental pollution and combat the threat of climate change, exploring the worthiness of green projects needs to be answered. Amongst the countries, China has focused on developing and implementing renewable energy projects, primarily hydrogen, due to the country's high consumption of fossil fuels and being the largest carbon dioxide emitter. This paper studied the profitability and sensitivity analysis of the three ongoing hydrogen projects in Jiang Xi and two projects in Guangdong, China. The major concluding remarks based on the empirical findings are as follows:

1) Using data on capital expenditure and operating costs of hydrogen projects in areas with high hydrogen demand, decreasing the financing risks of hydrogen projects is needed.
2) The examined hydrogen projects in China, at a real discount rate of 8%, are profitable.
3) The sensitivity analysis revealed different reactions of hydrogen projects to financing cost variables. Therefore, each project needs different and adopted policies to lower financing risks and increase return on investment.
4) Various de-risking tools to absorb investment in hydrogen projects can be used. One of the latest is establishing the GCGC, which can lead to credit enhancement in green projects.
5) Hydrogen projects are more sensitive to discount and income tax rates amongst other financing costs. The main reasons are the capital-intensive nature of green energy projects and the role of taxes in the return on investment of green projects in the long term.
6) A lower financing risk can make the NPV of a project more profitable, and the NPV becomes positive on a shorter horizon. That most green bond issuers in China have a good risk ratio reduces the financing risks of these kinds of projects.
7) The optimal weight of bank loans for hydrogen projects in China was calculated at nearly 56%, meaning the weight of green bonds is approximately 44% (1–0.56). In other words, the share of green projects financing by bank loan should be more than green bonds. However, the role of green bond financing is so important in these projects.

As for recommendations for future studies, we can highlight the role of the study on challenges in developing clean technology, the infrastructure of hydrogen vehicles, and cooperation in green projects amongst emerging markets. Applying advanced techniques, such as the Artificial Neural Networks for a larger sample, is highly recommended to determine the impacts of various costs of hydrogen projects.

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# Chapter 7

# China's Hydrogen Energy Perspectives: A Survey of Policy and Strategy from the Hydrogen Technology Leading Economies

Xiansheng Sun and Yufeng Yang

## 1. Background

Hydrogen is the most common element in the universe. Hydrogen energy is rich in sources and widely used. It can achieve zero carbon emissions in providing energy services and is expected to be an 'integrator' of the energy transition. However, hydrogen is a scarce resource. According to its sources, there are 'green hydrogen', 'blue hydrogen', and 'grey hydrogen'. The production, transportation, storage, and utilisation of hydrogen have many challenges. The core technology in the industry chain is becoming the commanding heights of global energy technology research and development (R&D) and innovation.

Following Japan's identification of hydrogen energy development as a national strategy in 2017, Germany also adopted the 'National Hydrogen Strategy' on 10 June 2020 and established a 25-member National Hydrogen Energy Committee. The Republic of Korea (henceforth Korea) introduced a hydrogen energy development roadmap in early 2019 and set ambitious development goals. Based on the original hydrogen energy roadmap, the European Union issued a hydrogen energy strategy on 8 July 2020. The goal is to increase the proportion of hydrogen energy in energy consumption from less than 2% to 24% by 2050 and create at least 5.4 million jobs. The United States (US) is the first country to advocate a hydrogen energy economy and is the world's largest hydrogen fuel-cell vehicle market. In March 2020, 19 companies and organisations jointly issued the 'New Roadmap for the US Hydrogen Energy Economy', aimed at allowing hydrogen energy to meet 14% of the US final energy demand by 2050.[8] In China, the positioning of hydrogen energy in the energy system is not yet clear. Related technology R&D and industrial arrangement and deployment are calling for a clear national policy and strategy.

### 1.1. Understanding Hydrogen: Green and Grey

According to BloombergNEF[9], green hydrogen produced through electrolysis using renewable energy will be cost-competitive in around a decade with blue hydrogen, zero-carbon hydrogen produced via fossil fuels with carbon capture. In addition, it is competitive with grey hydrogen produced from fossil fuels without carbon capture, at around US$1/kg by 2050.

[8] Federal Ministry for Economic Affairs and Energy Public Relations Division, The National Hydrogen Strategy, www.bmwi.de, June 2020, Berlin.
[9] BloombergNEF refers to Bloomberg New Energy Finance.

### 1.2. Hydrogen in the Fourth Industry Revolution

Hydrogen gas was first produced artificially back in the 16th century, while the first fuel cells and electrolysers were made in the 19th century. Until recently, however, the price of electrolysers, which produce hydrogen by splitting water into hydrogen and oxygen with electricity, and fuel cells, which recombine them to produce electricity and heat, was too high. These have all changed. The price of electrolysers went from €2–€4 million/MW a few years ago to around €0.5 million now. This means the main driver for the cost of hydrogen produced by electricity is electricity itself, representing three-quarters of the production cost. As green electricity gets cheaper every day, low-cost green hydrogen is coming. In parallel, as with solar and wind, the cost of hydrogen production is falling exponentially as system sizes and production volumes grow while performance improves. This is a notable feature in the new round of industry revolution along with energy transition and technology.[10]

Hydrogen technology allows storing hydrogen seasonally. An ordinary battery has its properties before being discharged; it needs constant conditions to keep its charge. For hydrogen, everything is much simpler; it is stored in any form – liquefied or under pressure. And if pumped into a container, nothing more is needed – just the right capacity. Even underground gas storage, where we now store natural gas, can be used. We used to be told, 'Our gas storages are full! We will safely pass the winter!' This is how we can deal with hydrogen.

### 1.3. Hydrogen and CO2 Emission Reduction

Most importantly, hydrogen can deal with climate change. The Hydrogen for Climate Action programme was launched in Europe to preserve our planet's climate and prevent an environmental catastrophe. The projects in this programme aimed at transporting hydrogen, its use in a centralised heating system, the construction of large vessels operating on hydrogen, and infrastructure development. Hydrogen is the only energy that does not contain any carbon, and so using it for heating and transport does not generate any CO2, only water. Developing it from green power helps store it and balances the grid. On the heating side, green hydrogen can be mixed up to 20% with natural gas in pipelines, or dedicated pure hydrogen pipelines can be laid (there are several thousands of kilometres of them around the world already). It can then be used in existing gas appliances or dedicated fuel cells to generate heat and power. On the transport side, hydrogen can power fuel cell–based vehicles, such as electric vehicles carrying a hydrogen tank and a fuel cell that transforms on-demand hydrogen into electrons to power the car (IRENA, 2019a).

[10] Ministerial Council on Renewable Energy, Hydrogen and Related Issues Basic Hydrogen Strategy, 26 December 2017.

## 2. Survey on Hydrogen Policy and Strategy in Major Economics

### 2.1. Europe

The publication *Powering a Climate-Neutral Economy: An EU Strategy for Energy System Integration* and the accompanying communication, 'A Hydrogen Strategy for a Climate-Neutral Europe,' are a testament to the European Commission's commitment to a systemic change out of fossil into electricity and hydrogen to achieve the European Union's (EU) 2030 and 2050 climate targets (IRENA, 2019b).

Meeting the EU's long-term climate and energy goals and realising the promise of the EU Green Deal mean carbon-free power, increased energy efficiency, and deep decarbonisation of industry, transport, and buildings. Achieving all these will require both electrons and molecules, specifically renewable hydrogen and low-carbon hydrogen, at a large scale. Without hydrogen, the EU will not achieve its decarbonisation goals on time. As such, the hydrogen sector is primed to play a key role as an enabler of sector integration and a systemic role in the transition to renewable sources by providing a mechanism to transfer energy across sectors, time, and place flexibly. Hydrogen Europe is committed to working hand in hand with the renewables sector to pave the way together towards a climate-neutral economy based on 'HydroGenewables'.

Europe's targets are the following:

- To achieve a variety of clean hydrogen production technology pathways, especially the zero-carbon pathway, namely, blue hydrogen (hydrogen produced by fossil energy through the carbon capture process) and green hydrogen (hydrogen produced by renewable energy), and the production cost must reach €1.5–€3/kg
- To develop green hydrogen to drive 20–40 GW of renewable energy–installed capacity increment, that is, wind power and photovoltaic can be further developed in Europe
- The cost of large-scale hydrogen energy transportation to be less than €1/kg
- The total cost of hydrogen energy in the transport sector is lower than gasoline and diesel under tax-free conditions
- The cost of fuel-cell power systems is equivalent to the cost of gasoline and diesel power systems currently used
- Hydrogen energy can be used for power generation and large-scale heating, the establishment of 500,000 fuel-cell devices for households and buildings
- To realise the wide application and substitution of hydrogen energy in energy-consuming industries, such as steelmaking, petrochemical, and other industry (Rissmana et al., 2020).

The steel industry, along with cement, is the largest industrial emitter of CO2 in Europe. It is responsible for 20% of industrial and 8% of total emissions. Setting aside the 28% output from recycled steel, the most common way of processing raw iron ore is via the humble blast furnace, using coke produced from metallurgical coal. For net-zero steel, one has to either eliminate coking coal or capture the resulting CO2 emissions. Hydrogen-based steel would become competitive with the most expensive current steel production as soon as it could be made for €2.5/kg, which is any time now.

According to BloombergNEF's August 2019 Economics of Hydrogen Production from Renewables, by 2050, green hydrogen may achieve a price of US$0.8/kg, depending on directly connected renewable power being available at US$14 to US$17/MWh. To compete with US$2/MMBtu gas in the heat market, green electricity at those prices will need a US$56/tonne CO2 price. However, the green hydrogen it can produce for US$0.8/kg will require a price of US$94/tonne to be competitive. In Europe, where natural gas currently sells for US$4 per MMBtu, renewable electricity at US$17 per MWh will not need a carbon price at all. However, the green hydrogen it can produce will still need a CO2 price of US$57/tonne.

Will the resulting energy system be prohibitively expensive? Assume that 80%–90% of power is super cheap wind and solar at US$20/MWh or less, perhaps it will be US$30/MWh once some storage and interconnections are added. If the remaining 10%–20% of flexible power delivered from net-zero hydrogen provides 100% network uptime costs of US$150/MWh, that gives a blended wholesale power price of around US$50/MWh. That is not so far from where most industrialised countries are today – and it seems a small price to pay for a high-performing, resilient, net-zero economy.

### 2.2. Germany

Germany issued the 'National Hydrogen Energy Strategy' in 2020, and planned to invest €9 billion to develop hydrogen energy by 2030. The strategy stipulates that green hydrogen will account for 20% of the hydrogen energy market, and hydrogen energy is vital to ensuring Germany's future energy security. At the same time, it is necessary to enhance its industrial competitiveness through hydrogen energy innovation technology R&D and technology export. Germany regards hydrogen energy equipment as a major direction for the reindustrialisation of its emerging industries after automobiles (Albrecht et al., 2020).

### 2.3. Japan

Japan was the first country to formulate a hydrogen energy strategy. In the 'Energy Basic Plan' adopted in 2014, hydrogen energy was designated as the core of secondary energy. In December 2017, hydrogen energy was listed separately in this basic plan, and the 'Basic Hydrogen Energy Strategy' was formulated and proposed to build a hydrogen energy society. In 2019, the hydrogen energy development roadmap was further proposed, and the three major technical fields of hydrogen energy development – fuel cell technology, water electrolysis technology, and hydrogen energy supply chain technology – were very clearly presented (De Blasio and Pflugmann, 2020).

### 2.4. The Republic of Korea

Although the Hyundai Group is a world pioneer in hydrogen vehicles, Korea is late in deploying the hydrogen energy industry nationwide. Korea's real emphasis on hydrogen energy began in 2018. It moved quickly after formulating the 'Roadmap for Hydrogen Energy Economic Development' in January 2019. In October 2019, its Ministry of Land, Infrastructure, Transport, and Tourism announced the 'Hydrogen Pilot City Promotion Strategy'. The strategy's goal is for 40% of cities across the country to use hydrogen energy by 2040 (De Blasio and Pflugmann, 2020).

### 2.5. United States

US hydrogen energy is concentrated in California. The US Department of Energy publishes technical and economic evaluation indicators once a year, which guide the development of hydrogen energy. Currently, California's hydrogen energy application scenarios are the largest and most comprehensive in the world.

Developed economies and countries, such as the EU, Germany, Japan, Korea, and the US have issued national hydrogen energy industry development plans (or roadmaps), clarifying hydrogen energy's positioning in the future energy system. However, China's hydrogen energy industry development strategy, goals, and key directions are not clearly positioned. Hydrogen energy is more a part of developing new energy vehicles and lacks overall top-level design and strategic planning (De Blasio and Pflugmann, 2020).

## 3. Research Questions: Opportunities and Challenges in Developing Green Hydrogen Energy for China

China has the world's cheapest hydrogen resources, especially industrial by-product hydrogen, such as high-purity chlor-alkali hydrogen, and hydrogen from petrochemical plants and coking plants. It is very easy to build point application scenarios centred on middle-level cities. This industrial by-product hydrogen in China is large in quantity and very cheap. In addition, China's current curtailment of wind, solar, and water from renewable energy has reached 100 billion kWh. If the discarded renewable energy is used to produce hydrogen, the cost will be significantly low. China is rich in application scenarios. Commercial vehicles, ships, and buses have a huge market. This market has single-point and double-point hydrogen refuelling stations that can meet the requirements. It overcomes the difficulty that hydrogen refuelling stations must be connected into the network. Once a hydrogen refuelling station is deployed, 200 logistics vehicles can be profitable synchronously. It is difficult to find such application scenarios abroad.

On the other hand, developing China's hydrogen energy poses many challenges. The industry chain is not matched and incomplete, resulting in high costs. The market is led mainly by venture companies. Large enterprises are not more involved. The autonomous capabilities of crucial component technologies and products are far behind other developed countries. Subsidy policies need to be improved. Presently, China's subsidy policy is mainly in the automobile field, and no supporting policies and measures promote the development of hydrogen energy in the energy field. It is still 'energy revolves around cars'. Hydrogen energy production, storage, transportation, infrastructure construction as well as hydrogen energy safety and technical standards and specifications are lagging. No national hydrogen energy safety testing centre has been established.

### 3.1. Opportunities

#### 3.1.1. Support from the traditional industry

In 1970, Lawrence W. Jones, a nuclear physicist at the University of Michigan, presented a paper entitled 'Toward a Liquid Hydrogen Fuel Economy'. He stated: 'The use of liquid hydrogen as a long-term replacement for hydrocarbon fuel for land and air transportation must be seriously considered as the logical replacement for hydrocarbons in the 21st century'. In the mid-1970s, Japan listed hydrogen as one of five focus areas for its Sunshine Project, with a combined budget equivalent to US$2.4 billion today, designed to identify ways of supplying the resource-poor country with energy in the aftermath of the first oil shock (the other four being solar power, geothermal, coal gasification/liquefaction, and general supporting research). Vestiges of the status afforded to hydrogen in Japan as a saviour technology can be seen in the continuing support for its fuel-cell car programme. As with Japan, there are huge demand and potentials in China for the five kinds of hydrogen from industry, especially from the traditional industry (Kramarchuk et al., 2021).

#### 3.1.2. Huge blue and green market in the energy industry

Blue hydrogen is produced from reforming natural gas or gasifying coal, but with the CO2 emissions captured. According to the EU Hydrogen Strategy estimates, the current cost of producing blue hydrogen is €2/kg. But by 2030, there is no reason it cannot be produced at least as cheaply as the EU's 2030 target for green hydrogen, at €1.50/kg, given the extraordinary strengths in energy, carbon capture, and the chemicals industry. In the longer term, blue hydrogen is expected to fall behind the green in the cost stakes over a multi-decade period because it benefits from a slower learning rate. In China, coal is abundant, and more and more oil and gas will be replaced by clean energy. Hydrogen will be an essential option with a huge market. However, two legitimate reasons are often cited for reservations about blue hydrogen, and one poor one. The first real concern is that, generally, only 90% of CO2 is captured. This can be increased but only at an additional cost – though one might think it sensible to devote some of the vast funds earmarked for electrolysis research to improving the process. The second genuine concern is fugitive emissions: wherever natural gas is extracted, there is some loss to the atmosphere, and methane (the main constituent of natural gas) is a potent greenhouse gas. Now that miscreants can be so easily caught, the oil and gas industry is rallying around efforts to choke off fugitive emissions (Hydrogen Council, 2020).

On the other hand, only hydrogen produced from renewable energy (green hydrogen) is sustainable in the long term. Using surplus renewable energy to generate hydrogen will turn out to be, on the whole, a mirage. It might make sense from a small island grid to a highly connected large grid, continent-scale energy system. The only thing that matters is to produce the cheapest green hydrogen possible in the future, or one will be outcompeted by producers using the lowest-cost renewable electricity at high-capacity factors delivered via pipeline. Now, in China, renewables are becoming a leading large, full-chain industry.

Four main factors drive the cost of green hydrogen: (i) the cost of renewable electricity, (ii) the capacity factor at which plants run, (iii) the cost of electrolysers, and (iv) the cost of capital. The cost of renewable electricity continues to plummet around the world. The best wind and solar plants in the best locations now generate power at around US$15/MWh, and by 2030 this will drop to US$10/MWh. By 2030, large parts of the world would benefit from US$20/MWh wind or solar, around one-third the cost of power from any other source. Electrolyser costs have been plummeting, too – with learning rates of just under 20% per doubling of capacity, similar to wind energy. There are still plenty of remaining pathways to reduce costs. As the industry scales, we will most certainly see electrolyser costs come down. But there is a wrinkle. Leading Chinese manufacturers are already supplying equipment at US$200/kW – as revealed in BloombergNEF's 2019 Economics of Hydrogen Production from Renewable Power.

**3.1.3. Large potential in other non-energy industry (transportation, etc.)**

The steel industry, along with cement, is the largest industrial emitter of CO2. In Europe, it is responsible for 20% of industrial and 8% of total emissions. Setting aside 28% of the output from recycled steel, the most common way of processing raw iron ore is via the humble blast furnace, using coke produced from metallurgical coal. For net-zero steel, one has to either eliminate coking coal or capture the resulting CO2 emissions. In its 2019 analysis of the cost of making fossil-free steel , BloombergNEF concluded that hydrogen-based steel would become competitive with the most expensive current steel production as soon as it can be made for €2.5/kg, which is any time now. Outcompeting the cheapest steel production in the world would require a hydrogen price of €0.6/kg, which is unlikely even in 2050. A green hydrogen price of US$2/kg by 2030 would require a CO2 price of US$125/Mt, dropping to US$50/tonne by 2050 as hydrogen prices continue to fall. In China, steel and iron, and the other non-energy industry, have a significant market.

**3.1.4. Giant corporations as implementing entities**

Many companies set up organisations and business alliances, developed commercial projects, and lined up major investments in hydrogen. In 2017, a dozen Fortune 100 companies created the Hydrogen Council in Davos – comprising over 40 members, including major energy and transport companies – and stated for the first time that hydrogen would be part of the future for energy systems. In 2018, Chinese companies created a similar council, gathering major Chinese energy and transport companies, chaired by the chief executive of China Energy. Shell signed off on its first commercial hydrogen project in China in 2020 as it continues to build out its hydrogen business on several fronts. The first China project will see hydrogen refuelling stations established in Zhangjiakou City, which will host part of the 2022 Beijing Winter Olympics. The city is rolling out 1,000 hydrogen trucks and buses to support the games' logistical requirements. The new joint venture between Shell China and the authorities in Zhangjiakou City will build a 20 MW electrolyser and refuelling station.

#### 3.1.5. Powerful policy support

As a clean energy carrier, renewable hydrogen can contribute to China's political imperative of reducing air pollution levels, especially in the eastern economic heartland. At the same time, developing China's renewable hydrogen value chain will complement the climate mitigation measures taken to meet its Paris Agreement target of reaching a CO2 emission peak before 2030 and carbon neutrality before 2060. 'China government has announced growth targets of 100,000 fuel-cell vehicles by 2025 and 1 million vehicles by 2030'.[11]

The Chinese government had introduced subsidies in 2010 to promote electric vehicle (EV) sales, driven mainly by its desire to cut pollution levels. China's EV industry has also benefited from other government regulations to shift consumers away from internal combustion (fossil fuel–driven) vehicles. Beginning in 2016, the Chinese government has been steadily reducing its subsidies for EVs to progressively shift costs to its EV makers.

In 2019, the working report of the Chinese government included hydrogen energy for the first time. The State Council, the National Development and Reform Commission, the Ministry of Industry and Information Technology, and the National Energy Administration are the major departments involved. The main policy direction focused on supporting hydrogen fuel-cell vehicles, covering R&D support, incentive policies, investment management, technological innovation, and access management.

In 2019, China's hydrogen production exceeded 22 million tonnes, ranking first globally, and the industrial output value of the hydrogen application was close to 400 billion yuan. As of August 2020, the number of companies related to China's hydrogen industry chain reached 2,196. New registrations of hydrogen energy–related companies increased by 457% in the past 5 years.

### 3.2. Challenges

#### 3.2.1. Some high technologies in the hydrogen industry chain

Increasing renewable hydrogen production requires the following: (i) sustained development of renewable generation capacity, (ii) driving commercialisation of electrolysis technology, (iii) deploying enabling infrastructure and addressing water scarcity issues, (iv) including investments in desalination plants to remove water supply bottlenecks.

[11] https://www.ofweek.com/hydrogen/2019-03/ART-180824-8440-30315713.html.

For renewable hydrogen to become a significant part of China's low carbon-energy mix, Beijing needs new and innovative national and international policies while developing appropriate market structures to spur innovation along the value chains, scaling technologies while significantly reducing costs, and deploying enabling infrastructure at scale.

#### 3.2.2. Matched infrastructure

If China addresses water scarcity issues, it can become a hydrogen 'export champion'. However, while China has abundant renewable energy resources, freshwater resources vary significantly amongst the regions, challenging the likelihood of its emerging as an international supplier. Furthermore, increasing industrialisation will pose growing threats to China's access to adequate freshwater resources, further stressing its water infrastructure. Hence, China could be forced to import renewable hydrogen, even if it could theoretically meet its domestic demand without turning to foreign markets. Alternatively, hydrogen production can be focused on China's southwest, where rich renewable resources are available, and water resources are less constrained. However, China has to build extensive pipelines (around 2,500 km) to funnel hydrogen to demand centres in the east. Our analysis shows that in the long term, domestic renewable hydrogen production and transportation (by pipeline) could become competitive at around US$3–US$4/kgH2. Imports from Australia would cost around US$4–US$5/kgH2 based on ammonia shipping and reconversion to hydrogen.

Nevertheless, water constraints might make it more feasible to forgo extensive infrastructure development and import hydrogen from neighbouring countries instead. For example, resource-rich regions in southwestern China could consider exporting renewable hydrogen to neighbouring countries, like India. Due to its infrastructure challenges throughout its vast area, India will likely employ a mix of on-grid and large-scale grid solutions to produce renewable hydrogen. But to support its highly dense population, especially in the region neighbouring China, India may also need to import large quantities of hydrogen.

#### 3.2.3. Technology economic analysis and regulations: monitoring; standards; health, security, environment, etc.

In general, China's hydrogen production process is not economical, the overall cost is high, environmental risks exist, and hydrogen production efficiency from renewable energy is still low. In the hydrogen storage link, the balance between hydrogen storage density, safety, and hydrogen storage cost has not been resolved. In the hydrogen use link, the localisation degree of crucial core technologies is low, the cost of hydrogen application is high, and infrastructure such as hydrogen refuelling stations cannot balance revenue and expenditure through economies of scale.

Industry regulations, standards, and institutional mechanisms will be challenged to meet the hydrogen energy industry's rapid development. The industry-wide supervision system and testing standard system regarding the safety, quality, storage, transportation, and application of hydrogen are also not sound. The approval procedures and operational supervision standards for hydrogen energy infrastructure construction are imperfect.

According to the study 'Uncovering the True Cost of Hydrogen Production Routes Using Life Cycle Monetization' (Al-Qahtani et al., 2021), in the TCH[12] production, the average monetised environmental impacts account for significant fractions of the TCH for fossil-based routes (76% in steam methane reforming [SMR], 57% in SMR with carbon capture and storage [CCS], 62% in methane pyrolysis, 88% in coal gasification, and 78% in coal gasification with CCS). Meanwhile, the direct production costs (levelized cost of hydrogen) dominate the TCH in the electrolytic routes (86%, 77%, 86% for nuclear, solar, and wind electrolysis, respectively). Furthermore, the externalities account for 68% and 81% of the TCH for biomass gasification with and without CCS, respectively.

#### 3.2.4. Mechanism and subsidy policies, etc.

Industry regulations, standards, and institutional mechanisms cannot meet the needs of the rapid pace of the hydrogen energy industry. The industry-wide supervision and testing standard systems regarding the safety, quality, storage, transportation, and application of hydrogen are not clear. In addition, the approval procedures and operational supervision standards for hydrogen energy infrastructure construction are incomplete. In particular, the policy system for constructing the hydrogen refuelling stations is relatively old, and the construction standards, regulations, and policy systems are fairly old or missing, making the approval of hydrogen refuelling stations complex and always need a long time.

## 4. Methodologies

We adopted a combination of technical and economic analyses, surveys, and senior expert interviews. The technical and economic analyses mainly focused on the future cost reduction for different technologies. The analyses also compared different countries or markets. Also, there include comparisons of the hydrogen energy development strategies, plans, technology path selections, policies, etc. of the main hydrogen energy countries. In addition, senior expert interviews were conducted among leading representative experts in the hydrogen energy industry to see their views on the future. Finally, we also participated in and organised several hydrogen energy–related seminars to collect the latest information.

## 5. Expected Results and Deliverables: Hydrogen Industry Perspective in China

### 5.1. Technology Development Pathway

[12] TCH = total cost of the assessed H2 production routes.

China needs to carefully study the choice and positioning of the two technical routes of hydrogen energy and storage batteries. As a low-carbon technology route with potential for commercialisation in the future, hydrogen energy will compete with battery systems in the transportation field. The most suitable application scenarios and their economics should be evaluated from the perspective of the entire energy system (Tu, 2020).

The rapid development of electric vehicles in the Chinese market has brought people confidence. Because the advantages of hydrogen fuel-cell vehicles in heavy-duty and long-distance transportation complement the short-distance urban mobility functions of electric vehicles, people quickly targeted hydrogen fuel.

### 5.2. Industry Chain

China has accelerated its deployment in crucial industrial chain links, such as hydrogen production, storage, transportation, and application, and has initially formed a relatively complete hydrogen industrial chain.

China has a reasonably mature-scaled technology of hydrogen production and purification upstream, including hydrogen production from fossil raw materials, industrial by-products hydrogen, and a more clean long-term development direction (renewable energy source electrolysis of water to produce hydrogen).

In the midstream, large-scale safe storage and transport of hydrogen are now the main bottleneck in the commercial application of hydrogen energy in China. High-pressure gaseous hydrogen storage is the main technology direction, such as hydrogen storage tanks for vehicles, transportation hydrogen storage tanks, stationary storage hydrogen equipment (hydrogen refuelling station), etc. In addition, liquid hydrogen tanker and large-scale transport, such as pipelines, is under development.

On the downstream, on hydrogen application, China has a concentration of about 90–95 hydrogen energy consumption. Regarding industrial raw materials, such as petrochemicals and steel and metallurgy, the market scale of hydrogen consumption as an energy source is still small. Fuel cells, hydrogen health, and hydrogen agriculture are expected to become the future's growth point of hydrogen energy consumption.

From the perspective of the hydrogen industry chain, China is rich in by-product hydrogen. The potential capacity of power generation and hydrogen production such as wind, solar, water, and nuclear is about 3.4 million tonnes per year. The source of hydrogen is guaranteed. In addition, the rapid decline in the cost of solar and wind energy has also made it possible to produce green hydrogen in the long run. According to the International Energy Agency, from 2010 to 2018, the global cost of photovoltaic power generation has dropped by an average of 82%; in some areas, renewable power has achieved parity. With the cost reduction brought about by the advancement of hydrogen fuel-cell technology and scale, the current typical commercial cost of the fuel cell is about US$230/kW. By increasing the production scale of the plant from 1,000 units/year to 100,000 units/year, the cost can be reduced to US$50/kW. China's local governments are looking for new economic growth points. Energy companies are facing the pressure of energy transition and are exploring ways to diversify and use clean and low-carbon energy. Traditional auto companies are struggling to find breakthroughs in the face of the declining industry chain.

### 5.3. Solutions for the Infrastructure

For the end users, the consumption and utilisation of hydrogen energy can be divided into transport utilisation and stationary utilisation, both realised through fuel-cell technology. Transportation applications include hydrogen-powered cars, ships, rail trains, etc.; stationary applications include energy storage systems, cogeneration systems, etc. According to the two ways of utilisation, the industrialisation route of hydrogen energy can be divided into fuel route and energy storage and comprehensive utilisation. For hydrogen infrastructure solutions, systematic demonstrations in various application fields must be carried out and actively explore business models for large-scale development of hydrogen energy. Especially for infrastructure, China needs flexible solutions with different measures to multiple local conditions. It is necessary to avoid wasting a large amount of funds caused by the homogenisation of hydrogen energy development in various places and change the practice of blind subsidies in the early development of electric vehicles. Some cities or projects with conditions should be selected, tried first, and steadily promote industrialisation and infrastructure deployment.

## 6. Policy Recommendations

1) It is necessary to plan the targets and positioning of hydrogen energy development based on national conditions: (i) scientifically position the role of hydrogen energy in national long-term policies and strategies, (ii) set up major special projects, (iii) formulate strategic plans to develop the entire hydrogen energy system and development routes in various segments, (iv) grasp the rhythm of hydrogen energy end user's applications, and (v) prevent low-level, repetitive construction and production capacity excess risk.

2) China should improve the system of laws and regulations and break through the barriers of the policy; further clarify the hydrogen energy authorities; unify the planning and approval process; and accelerate the construction of a comprehensive system of standards, measurement, testing, and certification guarantees. It should also improve the supervision mechanism of hydrogen refuelling stations, clarify the supervision principles and responsibilities of these refuelling stations, and deploy hydrogen refuelling stations.

3) China should develop the hydrogen energy industry under the premise of autonomous and controllable technology. It should also overcome the core technology and economy of hydrogen energy. Furthermore, it must carefully study the choice and positioning of the two technical routes of hydrogen energy and storage batteries. Some of China's hydrogen energy technologies have reached the world's advanced level, but the shortcomings are still evident from the perspective of the industrial chain. Therefore, large-scale backbone enterprises, scientific research institutes, and 'highly sophisticated and specialised' small and medium-

sized enterprises are encouraged to develop core materials. The R&D and collaborative innovation of materials, equipment, and key components will accelerate the formation of mass production technology with completely independent intellectual property rights and create an independent ecological chain.

4) China should carry out systematic demonstrations in various application fields and actively explore business models for large-scale development of hydrogen energy, including flexible infrastructure solutions. Furthermore, it should encourage energy companies to take the lead in establishing a stable and convenient hydrogen energy supply system, and innovate the application of hydrogen energy in commercialising green hydrogen. It should also develop hydrogen energy demonstration applications according to local conditions and refer to the experience of Japan, Germany, and other countries to promote the comprehensive hydrogen application industry in China’s balanced development.

5) China should clarify the development direction of using non-fossil energy electrolysed water to produce ‘green hydrogen’ as the main source of raw materials. The cost of wind power and photovoltaics in China has dropped rapidly, and future growth potential is still great. Thus, the development of hydrogen production from renewable energy based on wind power and photovoltaics should be the primary direction to support the development of hydrogen energy.

6) Related departments of China’s government should further assess the uncertainty of the development of certified grey hydrogen and green hydrogen. At present, there are many technical options for hydrogen production in China, including coal-based hydrogen plus carbon capture, usage, and storage (CCUS), industrial by-product hydrogen, and renewable energy hydrogen production. However, each type of hydrogen production poses uncertainties.

7) It is necessary to explore the use of hydrogen energy to solve the low-carbon development of China's steel and chemical industries. Whether the low-carbon clean route of China's steel industry can be solved by hydrogen reduction is crucial for the country.

8) International cooperation in hydrogen energy is still crucial in the future. China should actively cooperate and look for a win-win. Chinese companies should (i) use an open and cooperative attitude to connect with global superior innovation resources; (ii) actively explore cross-border cooperation with internationally renowned hydrogen energy industry chain–related companies, R&D institutions, etc.; and (iii) strengthen the introduction and training of talents in the hydrogen energy industry by drawing on foreign advantages and strong R&D support to improve core competitiveness.

9) China has eight regional electricity grids. Six grids belong to the state grid，the other two are in the China Southern Power Grid and the Inner Mongolia Power (Group) Co. Ltd. The government should consider how to position, plan, and deploy green hydrogen in these regional girds to meet carbon peak and carbon neutrality targets in the electricity/energy transition process.

10) China should actively involve in the international collaboration of hydrogen standards. As a result, the international community can accept green hydrogen mainly from renewable energy. Therefore, the government should develop green hydrogen step by step, first, with the abundant curtailed-wind and curtailed-solar energy as the zero cost can be used to make green hydrogen energy.

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# Chapter 8

# Feasibility Study of Large-scale Development of Hydrogen Energy Industry in China from the Perspective of Safety Laws and Regulations

Wang Jianfu

Hydrogen demand in China has risen quickly in recent years; more than 20 million tonnes in 2020, it has reached number one in the world. Under the goal of 'Carbon Neutral' and 'Carbon Peak', the annual demand for hydrogen in China is expected to jump from 37.15 million tonnes in 2030 to 130 million tonnes in 2060. Hydrogen energy will assume more prominence as a zero-carbon energy and industrial raw material. Therefore, it requires that the laws, regulations, and standards need to match safety requirements, while not curbing its large-scale application. There are many regulations in the hydrogen energy industry chain of 'production, storage, transportation, and use' in China. Some of the requirements are more stringent, such as the restriction on land property in the process of producing hydrogen. Some regulations need to be improved, such as the lack of requirements for long-distance hydrogen pipelines. The international experience can be used for reference in the following directions: the process and manufacturing requirements of hydrogen pipelines in the United States, hydrogen energy safety management in the European Union, safety checks in Japan, and hydrogen laws in the Republic of Korea. Priority has been given to the development of the examination and approval system of hydrogen energy testing and hydrogen energy filling stations in many provinces of China. The above experience shows that China should improve the top-level design as soon as possible and speed up the technical basic research to support the continuous improvement of safety standards. Finally, a sound regulatory system is needed to promote hydrogen energy to play a more important role in the process of decarbonising economy in China.

Keywords: hydrogen energy, safety, regulation, large-scale application.

The large-scale development of the hydrogen energy industry is based on safety guarantees; hence, it should be guided and restrained by laws and regulations, and constantly adjusted and improved to promote its healthy and sustainable development. Only by ensuring the safe use of hydrogen (especially green hydrogen) can it play an important role in energy conservation and carbon reduction in transportation, industry and other fields, so as to replace fossil energy, reduce carbon emissions, and achieve China's goals of 'carbon peak' and 'carbon neutrality'. This chapter analyses the current situation and obstacles of laws, regulations, and standard systems related to hydrogen safety in China; summarises the experience and related practices at home and abroad; and makes suggestions on promoting the development of hydrogen energy industry from the perspective of safety.

## 1. Current Situation and Obstacles of Laws and Regulations System

The current laws and regulations in China include *Law on Work Safety*, *Law on Special Equipment Safety*, *Regulations on Safety Supervision for Special Equipment*, *Administrative Regulations on Road Transportation of Hazardous Goods*, *Rules for Transport of Hazardous Goods by Waterway*, *Regulations on the Safety Protection of Railway Transport,* and *Law on Safety of Hazardous Chemicals (Exposure Draft)*, which are different in effectiveness and scope of application, but can restrict the safety of hydrogen energy to varying degrees. In addition, although in Article 115 of the Energy Law (Exposure Draft) enacted in April 2020, hydrogen energy has been stripped from the category of hazardous chemicals and attributed to energy, the current application of hydrogen energy in China falls within the category of hazardous chemicals.

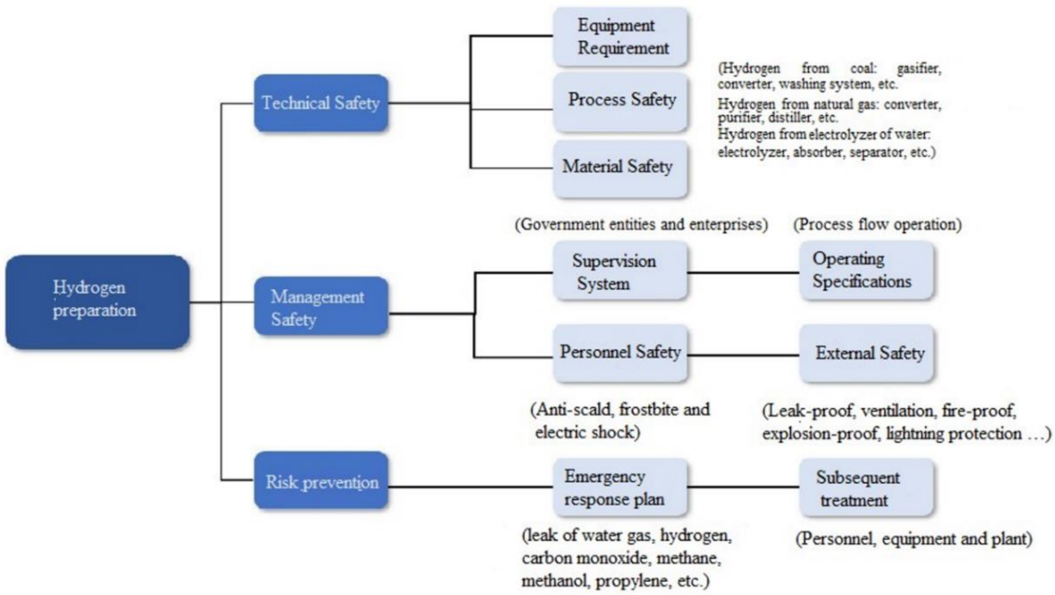
China's standards related to hydrogen energy, such as the *Essential Requirements for the Safety of Hydrogen Systems* and the *Code for Design of Hydrogen Stations*, put forward requirements for safe application of hydrogen energy vis-à-vis preparation, storage, transportation, and filling. However, compared with the rapid development of the industry, these standards are slightly backwards and most of them have been laid down for 10+ years and cannot better support the development of the industry. In the future, China should put forward high requirements and new legislation for technical safety, management safety, and risk prevention to match the large-scale development of the hydrogen energy industry.

### 1.1. There are laws to follow in the safety of hydrogen energy preparation and land properties and safe distance restrict the industrial development.

#### 1.1.1. Requirements of safety laws, regulations, and standard systems in hydrogen energy preparation

The *Bluepaper on the Development of China's Hydrogen Energy Industry* (2018) demonstrated that 62% of China's hydrogen sources are coal and industrial by-product, 19% are natural gas, and a small part are water electrolysis. With the accelerated application of hydrogen energy in the field of transportation, hydrogen can be generated in hydrogen filling stations in the future.**Error! Reference source not found.** According to the characteristics of hydrogen energy preparation, the safety requirements of several main hydrogen production modes in China are analysed from perspectives of technology, management, and risk prevention in Figure 8.1. In Technical Safety: fire and explosion protection of production equipment (gasifier, reformer, electrolyser, etc.); the preparation process and flow are safe and reliable; in Management Safety: safety control of flammable and toxic gases generated in the production process, safe distance between facilities, establishment of safety supervision authorities, etc.; in Risk Prevention: disposal methods for flammable and explosive gas leakage, and treatment methods for any accident in personnel and equipment or plant.**Error! Reference source not found.**

**Figure 8.1: Requirements of Safety Laws, Regulations, and Standard Systems in Hydrogen Energy Preparation**




Source: Author.

### 1.1.2. Current safety laws, regulations, and standard systems for hydrogen production

**a) There are many categories of laws and regulations, which can play a guidance role.**

At present, there are many safety laws and regulations in China for hydrogen energy preparation. The main content and characteristics are shown below:

**Table 8.1: Main Content of China's Laws, Regulations, and Standards System for Hydrogen Production**

| Safety system | Specific requirement | Relevant laws and regulations | Properties | Main Content of Laws, Regulations and Standards |
|---|---|---|---|---|
| Technical safety | Equipment Requirement | Law on work safety (China law, 2014) | Legislation | Technology and material safety protection Supporting requirements for safety facilities |
| | | Basic safety requirements for hydrogen systems (SAC, 2014) | National standards | Equipped with relief device, flame arrester, safety control system, etc. |
| | Process Safety | Law on work safety Fire protection law Code for design of hydrogen stations (SAC, 2014) | Legislation National standards | Process safety protection Fire Protection Design and Construction Requirements of Building Works The pressure difference between hydrogen and oxygen is less than 0.5kPa. |
| | Material safety | Supervision Regulation on Safety Technology for Stationary Pressure Vessel (GQSIQ, 2013) | Legislation | Requirements for fireproof materials, physical and chemical properties such as resistance to hydrogen embrittlement, resistance to hydrogen corrosion and compatibility with medium |
| | | Basic safety requirements for hydrogen systems Evaluation method of resistance to hydrogen-induced cracking of pipeline steel and pressure vessel steel (SAC, 2015) Test method for hydrogen embrittlement of copper (SAC, 2013) | National standards | Compatibility, Failure Mode, Machinability, Toughness, Plasticity, Manufacturability, Resistance to Hydrogen Penetration, Low Susceptibility to Hydrogen Embrittlement Test Method for Material Strength, Stiffness and Other Characteristics of Hydrogen Containers |
| | | Hydrogen embrittlement test of plating process (SAC, 2013) Low hydrogen embrittlement forged cadmium (titanium quality inspection) of high-strength steel part (CN-HB, 1986) Low hydrogen embrittlement forged cadmium (titanium process) of high-strength steel part(CN-HB, 1986) Specification for stress relief before plating and dehydrogenation after plating | Industry standard | Safety Test of Plating Process Material |

| | | | | |
|---|---|---|---|---|
| | | (CN-HB, 1998) | | |
| Management Safety | Supervision System | Law on work safety<br>Fire protection law<br>Regulations on Safety Management of Hazardous Chemicals (SAC, 2013) | Legislation | Establish Safety Responsibility System, Government Supervision and Administration<br>Regulations on License of Work Safety |
| | | Basic safety requirements for hydrogen systems | National standards | Land for hydrogen production and chemical industry and fire resistance rating |
| | Operating Specifications | Law on work safety<br>Fire protection law<br>Basic safety requirements for hydrogen systems | Legislation<br>National standards | Fire Safety Practice<br>Certified Safety Engineer |
| | Personnel Safety | | | Training and Evaluation of Safety Operators |
| | External Safety | | | Fire Safety System |
| | | | | Fire break outside the station ≥12m, inside the station ≥8m<br>The clear distance between hydrogen compressors is ≥1.5m and the distance between hydrogen purifiers is ≥1m. |
| Risk prevention | Emergency response plan | Fire Protection Law | Legislation | Firefighting and emergency evacuation plan |
| | | Basic safety requirements for hydrogen systems | National standards | Install an alarm device for detecting leakage and over-pressure in the hydrogen production process. Eliminate the leaked hydrogen in time after accident. |
| | Subsequent processing | Law on work safety | Legislation | Emergency Rescue, Investigation and Treatment of Work Safety Accident |
| | | Basic safety requirements for hydrogen systems<br>Code for design of electrical installation for atmosphere of fire and explosion (SAC, 2014) | National standards | The leaked hydrogen shall be eliminated in time after an accident has occurred. The selection of accident exhaust fan shall conform to the *Code for Design of Electrical Installation for Atmosphere of Fire and Explosion* (GB50058). |

Source: Author.

**From the perspective of technical safety,** the *Work Safety Law* (revised in 2014) required producers and operators to adopt new processes, new technologies, new materials, or new equipment, and to understand and master their safety technical characteristics and take effective safeguard measures. Safety facilities must also be constructed and put into service at the same time during the reconstruction and expansion of enterprises.

The *Fire Protection Law* (revised in 2019) clearly stipulated that the design and construction of building works completed by hydrogen energy production enterprises must conform to the national technical standards for fire protection. The *Supervision Regulation on Safety Technology for Stationary Pressure Vessel* stipulated that the mechanical properties, physical properties, and compatibility with media of materials should be considered for pressure vessels meant to be used for hydrogen energy preparation. Specific safety requirements are proposed for the chemical composition and mechanical properties of reactor materials (metal and nonmetal). The law on work safety is used to guide fire protection design in hydrogen production construction projects.

**From the perspective of management safety,** the *Law on Work Safety* has provisions regarding employee rights and obligations in work safety, supervision, and management of work safety: for example, establishing an accountability system for safe production, carrying out training and evaluation, and clarifying the governmental responsibilities of supervision and administration. For enterprises with more than 100 employees, the *Law on Work Safety* stipulates work safety management institutions or full-time work safety management personnel, and requires them to have certified safety engineers. The *Fire Protection Law* (revised in 2019) clearly stipulates that fire control management and supervision enterprises, for example, should implement the responsibility system for fire safety and formulate their own systems and safety procedures. The *Regulations on Safety Management of Hazardous Chemicals* clearly regulate the full operation process of production, storage, and use of hazardous chemicals; for example, before production of hazardous chemicals, production enterprises should follow the provisions of *Regulations on License of Work Safety*; in addition, it stipulated that production enterprises must be on chemical land or their premises shall be located in an chemical industry park. In fire protection law, government management, safe production responsibility, and other management systems required for production and operation are clearly formulated.

**From the perspective of risk prevention,** the *Law on Work Safety* stipulates the emergency rescue, investigation, and handling of accidents; formulates emergency rescue plans; and organises regular drills. After any accident, the relevant personnel shall immediately report to the head of their unit; take effective measures quickly; organise rescue; prevent accidents from expanding; and reduce casualties and property losses. The *Fire Protection Law* (revised in 2019) stipulates that hydrogen energy production enterprises shall make relevant fire-fighting and emergency evacuation plans, and a series of laws and regulations related to fire fighting and rescue have been laid down under the Law. *The Regulations on Emergency Response to Production Safety Accidents* have provided terms of emergency preparedness and rescue regarding rescue teams, drills, and command enforcement.

**b) The Standards have identified risk factors and puts forward clear indicators.**

Relevant standards for hydrogen production include the *Essential Requirements for the Safety of Hydrogen Systems* (GB/T29729-2013), *Safety Requirements for Hydrogen Production System by Pressure Water Electrolysis*, *Code for Fire Protection Design of Buildings*, and cover the following key points to ensure the safety of hydrogen production:

**In terms of technical safety,** the Standards have specified hydrogen risk factors and stipulated that hydrogen energy preparation enterprises shall set up relief devices, flame arresters, safety control systems, etc. Further, the Standards require reasonable selection of equipment material, including compatibility, failure mode, machinability, etc.; at the same time, materials should have good toughness, plasticity, manufacturability, hydrogen permeation resistance, and low hydrogen embrittlement sensitivity. Through the requirement on performance of hydrogen equipment material, explosion and leakage can be avoided. Through hydrogen embrittlement plating tests, low-hydrogen-embrittlement forged cadmium (titanium quality inspection) of high-strength steel parts, and specification for stress relief before plating and dehydrogenation after plating, the surface mechanical properties of materials in hydrogen production systems are strictly geared to avoid hydrogen embrittlement.

**In terms of management safety,** the Standards mainly limit the nature, qualification and building layout of production enterprises. According to the management requirement on safe production of hazardous chemicals, hydrogen production must be situated on land available for the chemical industry or located in a chemical park. In addition, the fire resistance rating of hydrogen production stations must not be lower than Level II, and plants must be in a single-storey building, with the highest part having vent holes. Pressure relief facilities must be set up in any plant with explosion hazards; the hydrogen compression plant shall be a semi-open building structure; there shall be no fewer than 2 emergency exits; and the fire break outside the hydrogen production station shall be ≥12m and the fire break inside the station shall be ≥8m. The Standards also require arranging hydrogen production equipment as follows: equipment for hydrogen and oxygen preparation cannot exist in the same plant; the distance between hydrogen production compressors must be ≥1.5m; the distance between hydrogen purifiers must be ≥1m; the distance between bottles for hydrogen production must be larger than the net width of the channel; and belt drive and electrical equipment for hydrogen production shall be grounded for fire prevention and removal of static electricity.

**In terms of safety protection,** the Standards require hydrogen leak detection capability: combustible gas detection and alarm devices shall be set up in areas with fire and explosion hazards in the hydrogen production system, while air concentration detection and alarm devices shall be set up at the highest place or where hydrogen is most likely to accumulate in the water electrolysis hydrogen production house, and leakage detectors shall be set up at the air inlet and outlet. The Standards further require installing an alarm device for detecting leakage and over-pressure in the hydrogen production process. The leaked hydrogen shall be eliminated in time after an accident has occurred. The selection of accident exhaust fans shall conform to the *Code for Design of Electrical Installation for*

*Atmosphere of Fire and Explosion* (GB50058). Finally, the Standards also require operators to wear electrostatic protective clothing, and that operators shall be regularly trained and evaluated.

**Table 8.2: Safety Requirement for Hydrogen Production Station**

| **Safe fire break of hydrogen production station** | | | |
|---|---|---|---|
| **Inside/outside** | | | **Safe distance (m)** |
| Buildings (Outside the station) | Fire-resistant rating | Level 1 and Level | 12 |
| | | Level 3 | 14 |
| | | Level 4 | 16 |
| | Civil buildings | | 25 |
| | Important public buildings | | 50 |
| Hydrogen production room (Inside the station) | Primary station | | 15 |
| | Secondary station | | 10 |
| | Tertiary station | | 8 |

Source: Author.

### 1.1.3. Main obstacles to safety laws, regulations, and standards systems for hydrogen production

Through research on application of the aforementioned laws, regulations, and standard systems in the field of hydrogen production, the following obstacles are common with the hydrogen production process:

1) **Lack of focus on the safety of preparation process.** The prevailing Chinese laws, regulations, and standard systems attach importance to standardising the physical and chemical properties of materials in terms of technical safety to avoid leakage and fire; however, there is a lack of focus on the safety technical indicators of the hydrogen energy preparation process and the hazards response plan in management. It is only mentioned in the *Law on Work Safety* that the new process needs supporting safety equipment. For example, hydrogen production from natural gas requires the reformer to prevent leakage, and meet the temperature and pressure requirements of safe reaction and collection during hydrogen production from coal. However, the relevant standards focus on hydrogen embrittlement or hydrogen corrosion more on the back end of the production line, i.e. the material requirements in the storage stage, and lack guidance on the safety risks of the production process itself.
2) **Lack of specialised laws and regulations on hydrogen energy production supervision.** For the present, professional categories of certified safety engineers exclude control of hydrogen energy, which has been deleted from the scope of hazardous chemicals. China's relevant laws on safety evaluation, safety review, safe

construction, safe acceptance, rescue, punishment and safety certificates fail to cover the hydrogen energy industry chain, and the supervision and enforcement of hydrogen energy are still absent at this stage.

3) **Restriction on number of safety controllers is easing.** According to Chinese law, any enterprise with 100+ employees shall have full-time safety controllers. Given the future trend of hydrogen production, restriction to 100 employees may be too loose to regulate the development of the industry.

4) **Requirement for land properties is too strict.** For the present, hydrogen production (including green hydrogen produced with renewable energy) in chemical industry parks as required by China's *Regulations on Safety Management of Hazardous Chemicals* has become the foundation and orientation of the hydrogen energy industry's development. It is determined according to the distribution characteristics of renewable energy resources in China that hydrogen energy in the future will mainly come from large-scale production in renewable energy bases, while the land properties have limited the development of this model.

5) **The safe fire break is too long**. For the present, in the *Essential Requirements for the Safety of Hydrogen Systems*, the minimum safe fire break outside the station is 12 metres. Due to the limitation of distance, it is difficult to miniaturise the 'integrated station' in China and thus it is difficult to popularise and apply it on a large scale in cities and other regions with scarce land resources.

### 1.2. The hydrogen energy storage and transportation are under increased supervision and strict audit, and their material and technical safety standards available still have shortcomings.

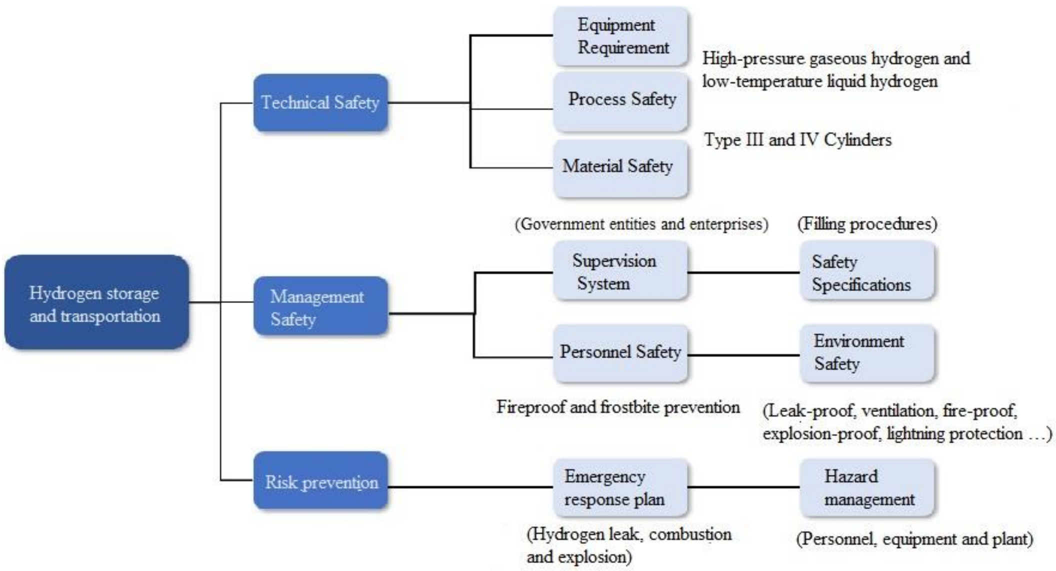
#### 1.2.1. Requirements of safety laws, regulations and standard systems in hydrogen energy storage and transportation

As an intermediate process in preparation and use, the storage and transportation of hydrogen energy is of great importance. Safe storage and transportation are closely related to the large-scale, wide-range and mobile use of hydrogen energy in China. For the present, there are no series of standards for high-pressure (35MPa or above) gaseous hydrogen transportation, liquid hydrogen transportation, piping hydrogen transportation, etc. in China, so it is required to refer to relevant regulations on transportation of inflammable and explosive hazards.

**Hydrogen storage is based on technical safety.** At present, China's hydrogen storage mode is mainly employing high-pressure technology, which is relatively mature; the pressure is generally less than 70MPa, the compression energy consumption is high, and the potential safety hazards are mainly reflected in the reliability risk and leakage danger of material available for hydrogen storage. In addition, the supplementary means of liquid hydrogen storage requires higher equipment and material conditions. At present, most hydrogen storage cylinders in China are Type III (metal liner), compared with Type IV. Type III cylinders with metal liners will heat up faster in the process of filling, and, due to high material density, the hydrogen storage capacity of Type III is lower than that of Type IV. Globally, Type IV (polymer liner) has represented the trend. Therefore, China's safety demand for hydrogen energy storage is mainly based on new materials, technologies, and the promotion of safe storage technology. Hydrogen energy is mainly transported through long tube trailers in China at present, and piping transport is still at the demonstration stage. The safety requirement for long tube trailers is kept consistent with hydrogen storage. There may be great potential space for pipeline hydrogen transportation in the future. Pipeline hydrogen transmission can be divided into pure hydrogen pipelines and natural gas hydrogen-mixed pipelines. Safety regulations mainly focus on reliable material, leakage detection systems, and standardised management system.

Standards for hydrogen pipelines mentioned in China include GB50177 *Code for Design of Hydrogen Stations* and GB4962 *Technical Regulations for Safety of Hydrogen Use*. GB50177 is applicable to the design of hydrogen piping in newly built, rebuilt, and expanded hydrogen stations, hydrogen supply stations, plant areas, and workshops, which has been described in detail in 9.1.1.2. GB4962 has specified the safety technical requirements of gaseous hydrogen in the process of use, replacement, storage, compression and filling, discharge, firefighting, emergency management, and safety protection. It is suitable for all workplaces on the ground after gaseous hydrogen production, but not for liquid hydrogen, gaseous hydrogen on water, aviation hydrogen use and on-board hydrogen supply systems, and for which the corresponding process in hydrogen production can be taken for reference. The above standards are not applicable to buried long-distance hydrogen pipelines. At present, there is no standard system applicable for long-distance hydrogen pipelines in China.

**Figure 8.2: Requirements of Safety Laws, Regulations and Standard Systems in Hydrogen Energy Storage and Transportation**




Source: Author.

### 1.2.2. Current situation of safety laws, regulations and standard system for storage and transportation

#### a) Common safety laws and regulations are mainly applied for storage and transportation, which are under increased supervision and strict audit

**Table 8.3: Main Content of China's Laws, Regulations and Standards System for Hydrogen Energy Storage and Transportation**

| Safety system | Specific requirement | Relevant laws and regulations | Properties | Main Content of Laws, Regulations and Standards |
|---|---|---|---|---|
| Technical safety | Equipment Requirement | Special Equipment Safety Law<br>Regulations on Road Transportation of Hazardous Cargo<br>- | Legislation | Comply with safety technical specifications.<br>Equipped with special containers such as tank- type and van-type vehicles or pressure vessels and safety protection, environmental protection and firefighting facilities and equipment; there are no equipment safety regulations for long-distance piping of hydrogen for the present. |
| | | Basic safety requirements for hydrogen systems<br>Requirement for storage and transportation of liquid hydrogen (SAC, 2021) | National standards | Stationary gaseous hydrogen storage tanks shall be provided with safety accessories such as pressure gauge, safety release device, hydrogen leak alarm, purge replacement interfaces, etc.<br>There shall be a hydrogen escape pipe at the top and a discharge outlet at the bottom. The liquid hydrogen tanker and tank container must be equipped with an electrostatic grounding device.<br>The liquid hydrogen receiver port of the tanker shall be equipped with a 10 micron filter. |
| | Process safety | Non-available for the present | Non-available for the present | Type III Cylinder, Type IV Cylinder, etc. |
| | Material safety | Supervision Regulation on Safety Technology for Stationary Pressure Vessel<br>Pressure Vessel Painting and Transport Packaging | Legislation | Rust removal, anti-corrosion, protective film, etc.<br>Tensile strength, impact absorbed energy, elongation after breaking, etc.<br>There is no requirement on material for long- distance piping of hydrogen |

| | | | | |
|---|---|---|---|---|
| | | | | for the present. |
| | | Essential Requirements for the Safety of Hydrogen Systems | National standards | The liquid hydrogen tank is well insulated. |
| Management Safety | Supervision System | Law on work safety Regulations on Road Transportation of Hazardous Cargo Fire Protection Law Regulations on Safety Management of Hazardous Chemicals | Laws and Regulations | Establish a special safety management system Assign full-time safety management personnel during transportation<br>The Transportation Administration is responsible for transportation license and safety administration (hazardous chemicals). |
| | Operation Safety | Special Equipment Safety Law<br>Liquid Hydrogen Storage and Transportation Requirement<br>Regulations on Safety Management of Hazardous Chemicals Code for Design of Electrical Installation for Atmosphere of Fire and explosion(SAC,2014) | Laws and Regulations | Safety evaluation and safety review shall be carried out for storage and handling. Corresponding safety measures shall be taken in the filling process of tankers and tank containers, and devices against tensile pull shall be provided. |
| | Personnel Safety<br>Environment Safety | | | Personnel shall be educated and trained in safety and should not take up their jobs without certification; and shall be conducted static electricity away and wear work clothes, etc. before operation. |
| | | Basic safety requirements for hydrogen systems | National standards | The place for liquid hydrogen storage tanks should be kept a corresponding safe distance from residential buildings, public roads, and warehouses. |
| Risk prevention | Emergency response plan | Fire Protection Law | Legislation | Cut off transmission of electricity, combustible gas, and combustible liquid. |
| | | Basic Safety Requirements for Hydrogen Systems Requirement for Storage and Transportation of Liquid Hydrogen | National standards | When an accident occurs in the transit of tankers or tank containers, it shall be reported to competent local authorities for handling in time and emergency response measures shall be taken in addition. |
| | | Regulations on Safety Supervision for Special | Legislation | In case of explosion or leak of pressure vessels and pressure pipes, characteristics of media shall be |

| | | | | |
|---|---|---|---|---|
| | Risk Management | Equipment | | distinguished during emergency rescue, and such explosion or leak shall be handled in strict accordance with the procedures specified in the relevant plans to avoid secondary explosion. |
| | | Basic Safety Requirements for Hydrogen Systems | National standards | Leak in the piping system of tankers and tank containers, if any, shall be timely repaired and treated. |
| | | Code for Design of Electrical Installation for Atmosphere of Fire and Explosion | | |

Source: Author.

**Technical safety is mainly governed by general regulations.** Since hydrogen energy is mainly stored and transported through long tube trailers in China, laws and regulations mostly focus on this means of transport. For the present, long piping transportation of hydrogen energy is still at the demonstration stage, and there is no specialised law related to it. In addition, the *Special Equipment Safety Law* has stipulated that the performance indicators of hydrogen storage and transportation pressure vessels shall conform to the safety technical specifications; the safety technical supervision regulations for stationary pressure vessels require that the material of storage and transportation equipment should have anti-rust, anti-corrosion and the like characteristics, as well as high tensile strength and impact resistance to absorb energy. For the present, there is no clear legal regulation on process material for hydrogen cylinders.

**Management safety is mainly under increased supervision and strict audit.** China's laws clearly define the regulatory responsibilities for hydrogen energy storage and transportation, and the Transportation Administration shall be responsible for transportation licenses and safety administration (hazardous chemicals). It is also required that the personnel responsible for the supervision and management of special equipment should be familiar with relevant laws and regulations and have corresponding expertise and work experience. It has also specified the way to set qualifications and regular inspections so as to improve the timeliness of equipment operation: the Special Equipment Safety Law stipulates that special equipment users shall, in accordance with technical safety technical specifications, request special equipment inspection agencies to perform regular inspection one month prior to the expiration of the validity period of inspection, and perform a safety evaluation and safety review in the full process of hydrogen energy storage and handling. For specific safety operation procedures, the requirement for storage and transportation of liquid hydrogen has mentioned that corresponding safety measures shall be taken in the filling process of tankers and tank containers, and devices against tensile pull shall be provided. The protection of personnel safety by laws and regulations is mainly reflected in operation procedures: personnel shall be educated and trained in safety and should not take up their jobs without certification, and shall conduct static electricity away and wear work clothes, etc. before operation. The safety protection environment is reflected in that the place for liquid hydrogen storage tanks should be kept a corresponding safe distance from residential buildings, public roads, and warehouses.

In addition, the code of conduct for operational safety includes: no transport in bad weather, prohibition of over-pressure, grounding of equipment before loading and unloading, capacity limitation, prohibition of overload, isolation of storage area from employees accommodation area, no passenger vehicles available for hydrogen transportation, keeping surroundings of hydrogen system clean, taking measures such as controlling the hydrogen filling rate and pre-cooling, preventing the wall temperature of hydrogen cylinders from exceeding the predetermined value, eliminating ignition sources in the storage and operation areas, and using road barriers and warning signs to control the storage and operation areas, transporting hydrogen in compliance with laws and regulations on transportation of hazardous (flammable) cargo. No long-distance transportation appropriate for liquid hydrogen and hydrogen slurry, and explosion-proofing is required for all the above-mentioned.

**For risk prevention, the *Specification for Special Equipment* is available for reference.** The use of special equipment should have the prescribed safe distance and safety protection measures. Buildings and ancillary facilities related to the safety of special equipment shall comply with the provisions of relevant laws and administrative regulations. This can provide legal protection for safe construction of hydrogen production stations and hydrogen filling stations. The Fire Protection Law has stipulated that when an accident occurs in the transit of tankers or tank containers, it shall be reported to competent local authorities for handling in time and emergency response measures shall be taken at the same time. The risk prevention for leaks is mainly based on detection: leak detectors shall be installed at the air inlet and the air outlet, selection of accident exhaust fans shall conform to the *Code for Design of Electrical Installation for Atmosphere of Fire and Explosion* (GB50058), an alarm device shall be installed for detecting leakage and over-pressure in the hydrogen production process and at least one of audible and visual alarms should be given, and operators shall wear electrostatic protective clothing in the process of operation and shall be regularly trained and evaluated. Transmission of electricity, combustible gas, and combustible liquid shall be cut off in case of danger. Leaks in the piping system of tankers and tank containers, if any, shall be timely repaired and treated after the danger.

### 1.2.3. Main obstacles to safety laws and regulations of storage and transportation

The development of hydrogen energy storage and transportation technology is subject to safety supervision. Although great progress has been made in technologies such as pressurised compression hydrogen storage, liquefied hydrogen storage, compound hydrogen storage, and alloy hydrogen storage, the balance among hydrogen storage density, safety, and costs has not yet been addressed and is not enough to support the large-scale commercial development of the industry. It is necessary to continuously improve the technical level and reliability in order to keep promoting the large-scale development of the hydrogen energy industry.

1) **Absence of standard systems for long-distance hydrogen pipelines.** At present, the domestic natural gas piping network has not yet launched a pilot demonstration of hydrogen mixing. Due to the particularity of hydrogen media, the problems it faces are very prominent. It is necessary to strengthen the compatibility between pipe material and hydrogen-compressed natural gas; fully consider factors such as accelerated leakage rate, enlarged combustible range, and accelerated combustion rate caused by hydrogen mixing; and comprehensively analyse the leak and combustion explosion of hydrogen-compressed natural gas. The steel of China's West-East Natural Gas Piping is Grade X70 or X80. Under high pressure (approx. 4~12MPa) for transmission, the area shrinkage rate can be reduced to 30%~60%; with 1% hydrogen mixed, greater impacts such as hydrogen embrittlement will easily occur, thus leading to pipe rupture, leak, and explosion, or similar potential safety hazards. Therefore, it is not feasible to mix hydrogen into most natural gas pipes in China, and the future development prospect remains unclear.
2) **Hydrogen storage and transportation standards are largely inadequate.** For the present, China only has promulgated safety standards and demonstrations for ordinary Type III steel cylinders, and has not yet formed safety laws and regulations or national standards and specifications for vehicle-mounted, lightweight, high-pressure hydrogen storage containers, liquid hydrogen tanks, and solid-state hydrogen storage facilities. In addition, it is not clear whether 35MPa or 70MPa is applicable for high-pressure gaseous hydrogen transportation. China's prevailing standard system restricts Type III cylinders, while the standard systems applicable for Type IV cylinders is still blank, which has certain obstacles to the future development of the industry.

## 1.3. Safety regulations such as supervision, fire prevention, business license and land use in hydrogen energy filling are absent

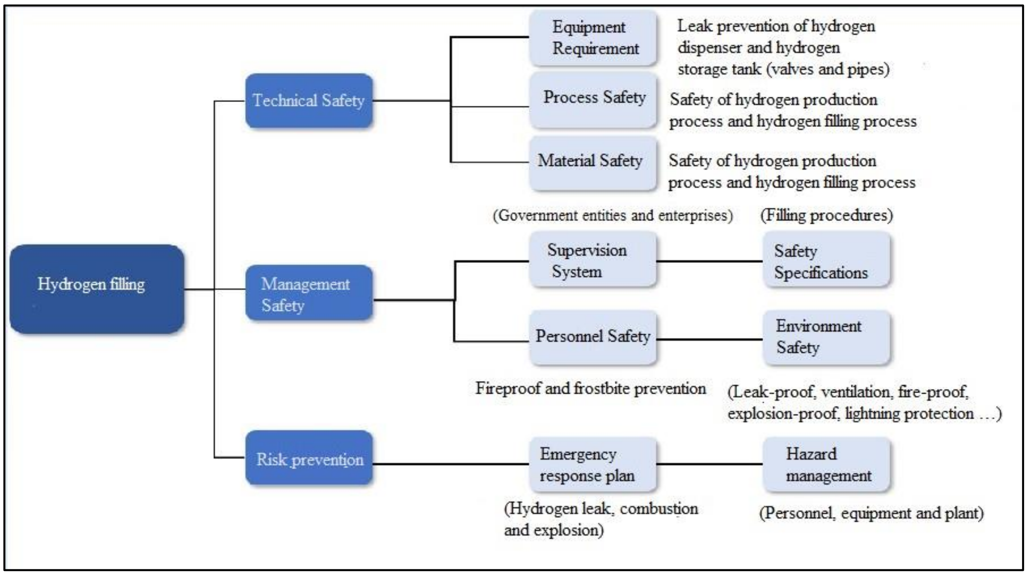
### 1.3.1. Requirements of safety laws, regulations, and standard systems in hydrogen energy filling

China's hydrogen filling stations have not yet been applied on a large scale. Those in operation are all at their demonstration stage. Relevant laws and regulations on investment, construction, and operation of general building projects that should be observed by hydrogen filling station projects are still blank; however, there are more national standards regulating construction of hydrogen filling stations. The safety requirements of hydrogen filling stations are mainly reflected in safety and fire prevention, leakage prevention, protection of personnel and protection of surrounding environment. The following apply to hydrogen leak prevention:

- hydrogen filling stations are required to have much safer storage equipment and processes;

- hydrogen filling stations should have the capability of monitoring leaks so as to acquire such specific information as their location in a timely fashion and speed and avoid any greater potential safety hazard;
- the construction layout of a hydrogen filling stations should ensure that leaked hydrogen not remain but instead dissipate to avoid burning or explosion accidents caused by an open flame; and
- hydrogen filling stations should have a high level of firefighting and the ability to extinguish fire in time.

**Figure 8.3: Requirements of Safety Laws, Regulations and Standard Systems in Hydrogen Energy Filling**




Source: Author.

### 1.3.2. Current situation of safety laws, regulations, and standard system for hydrogen filling stations

At present, China has no specialised laws and regulations applicable for hydrogen filling stations and the analysis in this chapter is mainly based on national standards.

**Table 8.4: Main Content of China's Laws, Regulations and Standards System for Hydrogen Energy Filling**

| Safety system | Specific requirement | Relevant laws and regulations | Properties | Main Content of Laws, Regulations and Standards |
|---|---|---|---|---|
| | Equipment Requirement | Code for design of hydrogen stations | National standards | Safety relief device, hydrogen escape pipes at the top of equipment, pressure measuring instrument, nitrogen purging/replacement interface, hydrogen leak detection/alarm device, etc. |

| | | | | |
|---|---|---|---|---|
| Technical safety | Process Safety | Code for design of hydrogen station<br>Safety technical code for hydrogen filling station | National standards | Hydrogen compression process requirement (long tube trailers and hydrogen pipeline)<br>Requirement for hydrogen production process within the station (water electrolysis, reforming, etc.) |
| | Material safety | Basic safety requirements for hydrogen systems | National standards | Mechanical properties of metallic material (solution treatment and heat treatment) |
| Management Safety | Supervision System | / | / | There are only local specialized hydrogen energy supervision regulations. |
| | Operation Safety | Technical specification for hydrogen filling station(SAC,2021)<br>Safety technical specification for hydrogen filling station(SAC,2021)<br>Fire Protection Law | Legislation National standards | Rated work pressure of 35MPa or 70MPa The filling flow rate is no more than 5kg/min.<br>The design pressure is 110% of the maximum working pressure, etc. |
| | Personnel Safety | | | Refer to the Fire Protection Law |
| | Environment Safety | | | |
| | | Basic safety requirements for hydrogen systems | National standards | Spacing between devices of hydrogen stations and width of fire lanes of hydrogen stations.<br>Protection of civil buildings |
| Risk prevention | Emergency response plan | Technical specification for hydrogen filling station | National standards | Over-pressure or low-pressure alarm, flame alarm detection, roof hydrogen detection, alarm when the hydrogen has reached 0.4%, and automatically turning on the exhaust fan when the hydrogen has reached 1%. |
| | Subsequent processing | Fire Protection Law | Legislation | Refer to the Fire Protection Law |

Source: Author.

There are only local specialised regulations in supervision systems for hydrogen filling stations. For specific operation matters, the *Technical Specification of Hydrogenation Station* has clearly specified the rated pressure and gas flow rate of hydrogen-filling operation environments. The external environment is mainly protected by setting a safe distance, including spacing between devices of hydrogen stations and width of fire lanes of hydrogen stations and protection of civil buildings. See Table 8.5 below for details.

For risk prevention in hydrogen filling stations, the main monitoring of leaks requires an auto alarm system to be turned on when the hydrogen concentration has reached 0.4%, and the exhaust fan to be turned on automatically when it has reached 1%. Due to lack of relevant standards for hazard management, only relevant content of the Fire Protection Law is available for reference.

**Table 8.5: Relevant Requirement for Hydrogen Filling Station**

| Buildings | | Hydrogen Filling Station | Total volume of hydrogen filling station ($m^3$) | | | |
|---|---|---|---|---|---|---|
| | | | ≤1,000 | 1,001~10,000 | 10,001~50,000 | >50,000 |
| Fire-resistant rating | Level 1 and Level 2 | 12 | 12 | 15 | 20 | 25 |
| | Level 3 | 14 | 15 | 20 | 25 | 30 |
| | Level 4 | 16 | 20 | 25 | 30 | 35 |
| Civil buildings | | 25 | 25 | 30 | 35 | 40 |
| Important public buildings | | 50 | 50 | | | |

Source: The author.

### 1.3.3. Main obstacles to safety laws and regulations of hydrogen filling stations

The following main obstacles are found in relevant laws, regulations, departmental rules, and standard systems:

1) **Strict requirements on fire breaks hinder the construction of hydrogen filling stations in mature urban centers.** The standards of hydrogenation stations on fire break and construction equipment spacing are not uniform, thus hindering the large-scale construction of hydrogen filling stations, especially in urban centers.
2) **No explicit authorities are assigned for administration or the process of examination and approval will be impeded.** Hydrogen filling stations lack similar gas service licenses issued by urban gas administrations and there is no competent equivalent authority, resulting in a limited approval process.
3) **Restrictions on land properties hinder the construction of hydrogen filling stations.** At present, land available for hydrogen filling must be either industrial or chemical land. Except for some industrial parks, hydrogenation stations should mostly be built at gas stations in cities or expressways for filling of fuel cell electric vehicles (FCEVs); restrictions on land properties hinders construction of hydrogen filling stations.

4) **The emergency response plan is incomplete and lacking a targeted guidance.** Due to the absence of specialised laws and regulations for accidental leaks, fires, explosions, and any other accidents in hydrogen filling stations, the Fire Protection Law can play a guiding role for the present, but the lack of a characteristic guiding scheme for hydrogen energy accidents also limits the development of the industry.

### 1.4. Hydrogen energy is mainly applied in the fields of transportation and industry, and the application experience and regulations are in the initial stage.

At present, hydrogen energy is mainly applied in the fields of transportation and industry, and there is no condition for wide-range household application. The transportation field is dominated by safe FCEV application, while the industrial field is dominated by metallurgy, chemicals, and oil refining. This chapter focuses on the safety problems with the above applications and the current situation of national laws, regulations, and standard systems.

#### 1.4.1. Attention should be focused on FCEV hydrogen filling temperature rises and collision hazards in the transportation field.

FCEVs are still in an emerging field with rapid technological iterations. The process of forming safety regulations and standard systems should be a process of continuous deepening of technology research and development. According to their structure, the safety needs of FCEVs are divided into that of fuel cell systems and that of the whole structure, of which the safety needs of fuel cell systems cover filling of hydrogen, supply in fuel cells, and operation of the system.

China has a large number of standards applicable for fuel cells, most of which are related to safety; Table 8.6 lists the contents.

**Table 8.6: Main Content of China's Laws, Regulations and Standards System for FCEVs**

| Safety system | Specific requirement | Relevant laws and regulations | Properties | Main Content of Laws, Regulations and Standards |
|---|---|---|---|---|
| Technical safety | Equipment Requirement | Fuel cell electric vehicle (FCEV) - Safety Requirement (SAC, 2009) | National standards | Safe Relief Device<br>Hydrogen leak detection sensor<br>Thermal insulation protection |
| | Process Safety | Safety Guide for FCEVs(CAIA, 2019) | Technical Instructions | The proton exchange membrane should have good thermal stability, chemical stability, and good mechanical stability.<br><br>The gas diffusion layer needs to avoid long burrs in manufacturing and the proton exchange membrane needs to avoid puncture in thermo-compression resulting in gas leak and |

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| | | | | danger.<br>In the preparation process of membrane electrode, proton exchange membrane may be pierced due to excessive compression of carbon paper, thus causing gas blow-by on both sides of the cathode and anode to result in danger. Therefore, thermocompression of carbon paper should be controlled to an appropriate extent according to the thickness of proton exchange membrane.<br>Thermocompression of carbon paper should be controlled to an appropriate extent according to the thickness of proton exchange membrane.<br>The electrode plate requires high conductivity, high thermal conductivity, and high strength to ensure the safety of fuel cells during the full life cycle. |
| | | | | The end plate of fuel cell needs certain strength and good insulation. |
| | Material safety | Proton exchange membrane fuel cell (SAC, 2017) | National standards | Safety technical requirements such as proton conductivity and tensile rate |
| Management Safety | Regulatory Architecture | | National ministries and commissions | Ministry of Communications |
| | Operation Safety | FCEV Safety Requirements<br>Fuel cell electric vehicles - refueling receptacle<br>On-board hydrogen system of FCEV - Technical requirements - Safety requirements of FCEVs | National standards | Reminder of low residual amount of hydrogen<br>The receptacle shall be dust-proof and pollution-proof. The operating pressure of grounded receptacle does not exceed 35MPa and the operating environment temperature ranges from -40℃ to 60℃. |
| | Personnel Safety | | | Hydrogen leak alarm device (2% concentration, audible and visual alarm) |
| | Environment Safety | | | Leaked gas should not be discharged to passenger cabin, luggage cabin and cargo- hold.<br>Hydrogen leak test in confined space |
| Risk prevention | Emergency response plan | FCEV Safety Requirement | | Cut off power, close solenoid valve and eliminate open flame in case of hydrogen leak. |
| | Risk Management | FCEV Safety Requirement | National standards | Reasonable ventilation and accelerated diffusion. |

Source: Author.

The above FCEV safety standard systems have covered the full process from equipment and material and process safety to filling parameters and use safety, but lacked any specialised rules. Compared with laws and regulations, standards are weaker in implementation and their applicability should be improved gradually with the progress of technology. Therefore, there is a need for safety regulations and standards for FCEVs in the transportation field to keep pace with the times, mainly due to the following:

**Mismatching between the hydrogen filling pressure and the actual demand.** China's current standard GB/T 26779-2011 *Fuel Cell Electric Vehicles - Refueling Receptacle* gives the safety indicators of hydrogen filling for fuel cells with pressure of 35MPa or below, while there are hydrogen filling systems under each pressure gradient of 11MPa~70MPa in the world. China's standards cannot match the future technical demand and there is room for revision.

**The temperature rise control strategy of hydrogen filling should be improved.** Hydrogen temperatures are extremely susceptible to rising during filling; when the filling speed is too fast, temperature rise is accelerated and the natural cooling speed is slow. In relevant standards, the filling temperature range is required to be -40℃~60℃, but there is no specific guidance applicable. The temperature rise can be significantly reduced by pre-cooling when filling hydrogen, but the temperature rise will remain under high flow rate. Therefore, it is necessary to adopt pressure limits, flow limits, or other safety guidelines to avoid excessive temperature rise.

**Regulators lack attention to collision safety.** As safety tests on hydrogen storage tanks is of particular importance in the event of a FCEV collision, any such traffic accident caused by this may lead to greater safety problems, and it is worthwhile for regulators to adopt stronger regulatory schemes to ensure the safe operation of FCEVs.

### 1.4.2. Hydrogen energy substitution in the industrial field involves technological innovation, and supporting standards and specifications have failed to catch up.

The chemical properties of hydrogen are mostly employed in industry, i.e. as a reducing agent. Although the energy performance of hydrogen has been initially confirmed, supporting regulatory policies and mechanisms have not yet been adjusted. Industry accounts for 70% of China's carbon emissions, with the chemical sector accounting for the largest share, according to data from the Energy Conservation and Environmental Protection Institute of CCID Research Institute. This is mainly due to carbon and carbon-containing molecules having acted as irreplaceable reducing agents in chemical processes. Therefore, the chemical industry is one of the more difficult areas to reduce emissions. Under the background of 'carbon peak' and 'carbon neutral', higher requirements have been put forward for the transformation of the chemical industry. The chemical industry is both the largest source of hydrogen production and an important user. Promoting blue hydrogen and green hydrogen to replace carbon in the chemical industry (such as exploring the development of hydrogen metallurgy) is an important path to achieve the goal of 'carbon peak' and 'carbon neutral' in China.

a) **The hydrogen metallurgy industry is still in its infancy, and safety regulations should be gradually explored.**

The present research on global hydrogen metallurgy projects is divided into three steps: the first is to establish a pilot plant for a feasibility study of large-scale application of hydrogen energy for industrial smelting before 2025; the second is to use hydrogen generated from coke oven gas, chemicals, and other by-products for industrial production by 2030; the third is to realise industrialised production of green and economic hydrogen by 2050, and launch high-purity steel hydrogen smelting with hydrogen energy, which is mainly generated from electrolysed water that used hydropower, wind power, and nuclear power. The hydrogen smelting technology of China is still in the initial stage of research and development. Most enterprises are still in the stage of project planning. Only a few have set the goal of producing hydrogen from clean energy for the purpose of smelting and most still use coke oven gas and chemical by-products as a hydrogen source. For the present, China lacks top-level design in terms of specialised planning, policy systems, standard systems, and safety specifications supporting hydrogen metallurgy. The main obstacles are detailed as follows:

**Lack of examination and approval regulations to guide construction.** Taking ferrous metal smelting as an example, the widely used blast furnace iron-making mode is mainly mixed smelting of solid coke and crude ore. This mode cannot match the operating condition of hydrogen metallurgy, and it is necessary to reshape smelting modes, plant construction, and safeguards. Therefore, many steel mills will be transformed or rebuilt, and their safety regulations should be redesigned. In this process, technical experts shall be assigned to make continuous study and demonstration, and national guiding standards or stricter laws and regulations shall be launched to give full play to the strictness of the examination and approval process to ensure the safety of the hydrogen metallurgy process.

**Inexperience in establishment of regulatory system and mode.** With the gradual development of hydrogen metallurgy in China in the future, enterprises will face safety problems in the process of operation. It is necessary for regulatory authorities to adopt the regulatory modes, ideas, and principles that keep pace with the times to further standardise the safe operation of hydrogen metallurgy enterprises. Hydrogen metallurgy is still in its infancy in China, and there is no practical historical experience for reference at the regulatory level.

**Lack of personnel safety training.** Study of any other energy source such as oil and natural gas shows that regular operator training and evaluation are an important part of safety work. Many accidents come from improper operation, carelessness, etc. Though safety training on hydrogen metallurgy operators is essential, it is all but absent in China.

**Lack of risk prevention mechanism.** It is difficult to formulate hazard prevention regulations accommodating every safety risk in the hydrogen metallurgy process due to a lack of actual operation data and experience.

**b) Work safety laws and regulations of synthetic ammonia have limited specification for hydrogen energy.**

The prevailing laws and standards on safe production of synthetic ammonia include the *Access Conditions for Synthetic Ammonia Industry* issued by the Ministry of Industry and Information Technology in 2012; local laws and regulations include the *Guidelines for Safety Standardization for Synthetic Ammonia Production Enterprises* (AQ T3017-2008) issued by Shanxi province in 2008. Both are designed to regulate access to synthetic ammonia and standardise operations, but the relevant expressions concerning hydrogen energy are insufficient. The regulatory system requirements for the large-scale application of hydrogen energy in the field of synthetic ammonia are mainly reflected in the following fields:

**Safety of synthetic ammonia equipment: control of synthetic tower material and inlet and outlet temperature**. The synthesis tower is subjected to high temperature and high pressure, and hydrogen is flammable and explosive. The temperature and tightness of the inlet and outlet should be well controlled to avoid explosion. The synthetic tower is mostly made of steel. Under a high-temperature environment, the synthetic tower is vulnerable to corrosion and hydrogen embrittlement due to the influence of hydrogen and ammonia. Therefore, the synthetic tower material should be strictly regulated and reference can be made to laws and regulations on hydrogen energy transportation.

**Safe production of synthetic ammonia: fire, explosion, and virus prevention**. It is necessary to keep improving the awareness of personnel on safety precautions, formulate and follow strict operating procedures, rules, and regulations, and strengthen management on hydrogen. For example, adopting mature, reliable, and safe technology can fundamentally improve production; properly controlling the temperature and pressure of containers and preventing open fire sources from approaching any combustible material can prevent accidents; monitor all variables in the production process, set combustible gas alarm, $H_2$ and $H_2S$ detection alarm, and automatic alarm for leakage. The formulation of safety regulations for synthetic ammonia can refer to the relevant contents of *Code for Electrical Design of Explosion and Fire Hazardous Environmental Installations*.

**c) Absence of specification on hydrogen energy in laws, regulations, and standards on safe production of methanol**

At present, methanol is mainly synthesised by hydrogenation after coal gasification in China. In the process of producing methanol from coal, the ignition points of raw coal, hydrogen, and any intermediate product are very low, and explosions will occur in lengthy circumstances of high temperature and high pressure. This should be regulated. China's prevailing laws and standards mainly focus on regulating transportation and the use of methanol, and there are few regulations on the key part related to hydrogen in methanol production. In GB18218-2000 *Identification of Major Hazard Installations for Hazardous Chemicals*, major concerns are identified for hazardous substances during methanol production and storage. The requirements for a safety regulatory system for the large-scale application of hydrogen energy in the field of methanol production are mainly reflected in the following fields:

**Effective allocation of production equipment.** In the process of methanol production, fire risk is classified as Category A; in order to reduce the incidence of potential safety hazards, it is necessary to optimise the allocation of production equipment. For example, production equipment is arranged in the open air, compressed plants are designed as Level-I fire-resistant buildings, the roofing is made of lightweight material, and the pressure relief area is strictly tested to ensure compliance with the specific explosion-proof regulation of plant building. In addition, the flooring is designed with material generating no spark and an accident ventilation system is installed indoors. Natural ventilation holes are designed on the roof. Once carbon monoxide concentration within the plant has risen to 20mg/$m^3$ or H2 concentration has risen to 4%, the indoor accident ventilation system should be opened automatically. Mechanical exhaust systems and combustible gas alarms shall be installed in rectification pump houses and refrigeration stations. In case of a safety accident, an alarm shall be given immediately.

**Strict precautions against leakage of converter.** The main materials at the converter inlet are steam and crude gas, while gases at the converter outlet are carbon dioxide, carbon monoxide, hydrogen, and methane, and the temperature of outlet gas is 450℃~590℃. If the converter leaked in the production process, then gas would leak to cause an accident such as a fire and poisoning. Therefore, in order to ensure the normal operation of a converter and avoid leakage, relevant personnel must control the water-to-steam ratio within the range of 0.5~2.0; the content of hydrogen sulfide in the crude gas entering the furnace shall be controlled to ensure that the content of hydrogen sulfide is higher than 300ppm so as to avoid affecting the activity of conversion catalyst and causing reverse sulfidation.

**d) Laws and regulations on hydrogen refining should be improved in hydrogen storage, reactor, and fire prevention.**

**A safe transition is required between hazardous chemical management regulation and energy legislation.** Hydrogen is used as chemical material to hydrocrack and reform heavy oil under high pressure; this is the main application of hydrogen refining. Article 24 of *Regulations on Safety Management of Hazardous Chemicals* states that hazardous chemicals (including hydrogen for industrial use) shall be stored in dedicated warehouses, specialised places, or specialised storage (hereinafter referred to as specialised warehouses), and shall be managed by full-time personnel. This legislation has strict binding significance in the hydrogen chemical industry. With hydrogen energy included in governance of energy law, whether the hydrogen energy storage management mode of chemical enterprises will be adjusted remains unclear. The legislation on hydrogen energy, if it cannot achieve a good transition, will have an impact on the safe production of hydrogen in chemical enterprises.

**Lack of special safety laws, regulations, and standards for hydrogen refining.** The existing hydrocracking system is a process in which hydrogen can cause heavy oil to undergo hydrogenation, cracking, and isomerisation under the action of a catalyst under higher pressure and high temperature (100~150 atmospheric pressure, approximately 400℃) for converting to light oil (gasoline, kerosene, diesel oil or material for catalytic cracking to produce olefins). The difference between hydrocracking and catalytic cracking is that the reaction of catalytic cracking is accompanied by hydrocarbon hydrogenation. The yield of liquid product from hydrocracking is over 98% and the quality of hydrocracking is far higher than that of catalytic cracking. Hydrocracking, though having a large number of benefits, is not as widely used as catalytic cracking, since it has to be operated under high pressure, requires more alloy steel, consumes more hydrogen, and needs more investment. Safeguards are reflected in relevant laws and regulations against leakage and explosions during the high temperature and high-pressure reaction, and mainly in the following legal requirements:

a) Requirements on stiffness and strength of reactor material and characteristics of alloy steel;
b) Requirements on air tightness of high-pressure system and emergency management for leakage;
c) Technical specification for safe start and stop of catalytic reactor:
d) Emergency plan for emergency shutdown of reactor (circulating hydrogen);
e) Safety regulations for fire prevention and emergency treatment;
f) Precautions against spontaneous combustion and emergency treatment for catalyst and reactant (FeS, $H_2S$, etc.); and
g) Poisoning prevention and emergency treatment of catalyst and reactant ($Ni(CO)_4$, $H_2S$, etc.).

In addition to laws and regulations, there are many standards in China for regulating safe operation of chemical enterprises; however, the content on hydrogen safety is obviously insufficient. For example, it is required in Section 4.1.10: Fire Break in the *Code for Fire Protection Design of Petrochemical Enterprises* (GB50160-2018) that the fire break for combustible liquid be 50~90m and that, for process facilities, it be 10~90m. This section has no regulation on the safety of high-pressure gaseous hydrogen used by some chemical enterprises; the requirement for combustible emission gases in Section 4.2.2 is mainly reflected in the specifications for alkane, since liquefied petroleum gas and the like have higher density than air and are easy to deposit on the surface.

By contrast, hydrogen has extremely low density and is a potential safety hazard when remaining in any dead corner of the roof during diffusion. There is no reference to the arrangement of exhaust equipment on the top of buildings in Section 4.2.2; Section 4.3: Access Road imposes the corresponding requirement according to the transportation capacity of hazardous chemicals. The regulatory requirement mentioned in the Standard under the storage capacity of 50,000$m^3$ and 120,000$m^3$ are more applicable for oil and gas storage and transportation, and cannot fully adapt to the transportation characteristics of high-pressure gas hydrogen and liquid hydrogen industries, and correspondingly cannot match the road safety specifications during hydrogen transportation. The fire break of buildings arranged is given in Section 4.3, in which combustible gas, liquefied hydrocarbon, and combustible liquid fall into separate categories, and, due to significant difference between the physical and chemical characteristics of hydrogen and alkane, hydrogen is more necessary to be classified as a single category under the background that liquefied hydrocarbon is classified into a separate category.

At present, the requirement on the arrangement of safe distance for hydrogenation stations and hydrogen production equipment is common in transportation fields, but the specification for safe distance of hydrogen-using equipment in the chemical industry is absent, making it necessary to study this.

## 2. Reference from foreign experience

With the wide application of hydrogen energy, countries and international organisations have done a lot of work on its safe development: for example, ISO/TC197 Hydrogen Energy Technical Committee, established in 1990 with 22 participating members and 13 observing members, which is mainly responsible for formulation and revision of international standards in hydrogen production, hydrogen storage and transportation, hydrogen-related tests, and hydrogen energy utilisation. IA-Hysafe organises the International Conference for Hydrogen Safety biennially to provide an open platform for display and discussion of latest research. Laboratories and associations organised by each country have also contributed to the technology and standard of hydrogen safety, including Japanese HySUT, Japanese HyTReC, Sandia National Laboratories of the US, the European Union's FCH2JU, Northern Ireland's HySAFER, Canada's PowerTech, etc.

### 2.1. The US has established the concept of hydrogen safety and the standard for piping and tank availability for our reference.

The main goal of the US development of hydrogen energy is reserve of strategic technology in the medium and long term and realisation of energy diversity and flexibility. The annual output of hydrogen in the US exceeds 10 million tonnes, representing about 15% of global supply; there are about 2,500 kilometres of hydrogen pipelines and 46 hydrogenation stations. The US Department of Energy in the *Hydrogen Program Plan 2020* that it is committed to technological research and development of the full industrial chain of hydrogen energy, and will intensify demonstration and deployment in order to realise scale.**Error! Reference source not found.** According to the US National Laboratory, the demand for hydrogen energy in the US will increase to 41 million tonnes per year by 2050, representing 14% of the total energy consumption in the future.

Hydrogen safety accidents still occur in the US. In April 2020, an explosion occurred in a hydrogen fuel plant in Longview, North Carolina, causing damage to 60 houses nearby. Based on the strong demand for hydrogen safety, a series of laws, regulations, and standard systems have been deployed in the US, including the *National Hydrogen Energy Road-map* issued by the Department of Energy in 2002, the Energy Policy Act enacted in July 2005, and the *Hydrogen and Fuel Cell Program* issued by the Obama administration in September 2011, all of which outline the national hydrogen safety concept, which is to **confirm which hazardous sources of hydrogen can be used**.**Error! Reference source not found.** The Department of Energy has proposed a broad concept of hydrogen safety, that is, not only concerning hydrogen, but also handling its relationship with ignition sources (sparks and heat) and oxidants (oxygen, etc.), thus expanding on China's safety precaution ideas.

Ventilation has been fully considered in construction of US hydrogen filling stations and natural ventilation holes have been arranged on the top of buildings.

In addition to safety concepts, the US has formulated a series of safety laws and regulations, mainly including material management and traffic control. Management of material for hydrogen energy in the US is similar to that of hazardous chemicals for hydrogen energy in China; in order to avoid any accident in the full industrial chain such as production, transportation, loading, unloading, and storage of hydrogen (and other hazardous chemicals), the US has formulated the *Hazardous Materials Code*, which has clearly stipulated safe operation, response plans, training, and supervision regarding hazardous chemicals in all processes.

In the field of transportation, the US has established the National Fire Administration (USFA) for fire research, precautions against hazard, publicity, and education, etc. In order to ensure the safe application of hydrogen energy, USFA has promulgated laws, regulations, and standard systems such as Hydrogen Technical Regulations (NFPA2), and the Use and Technical Standards of Compressed Gas in Portable and Fixed Containers (NAPF55).**Error! Reference source not found.** For example, the type of hydrogen filling station is limited to a stationary one, thus avoiding the risk of a leak caused by movement of equipment; hydrogen in stations is supplied from a designated source outside so as to reduce the potential safety hazard; and the strategic choice of hydrogen transportation is mainly long tube trailers, while a small part is transported with liquid hydrogen tankers. In order to avoid accidents in the hydrogen filling process, laws and regulations require shutting down the engine, no smoking, no use of any mobile phone, and no open flame during hydrogenation. In order to avoid any large-scale lethal effect of emergencies, the US has performed tests on hydrogen systems, fuel tank leaks, simulations of garage leakages, and on tank drops.

It can be seen through study on hydrogen safety regulations that the US holds a more cautious attitude towards the development of hydrogen energy and has more restrictions on safety. Some safety measures, such as emphasis on explosion and leak prevention, are worthwhile to learn from.

**Table 8.7: US Hydrogen Safety Standard Systems (Excerpts of Key Points)**

| Standard No. | English Name/Chinese Name | Main content |
|---|---|---|
| ANSI/AIIA G- 095-2004 | Guide for safety of hydrogen systems(US-ANSI, 2017) | Close to *the Essential Requirements for the Safety of Hydrogen Systems* of China. |
| ANSI/ASME B31.12-2019 | Hydrogen piping and pipelines(ANSI/ASME B31.12-2019) | Requirement for process materials: pipe heat treatment and thermoforming inspection and test. Safety requirements for pipes manufacturing and assembling (bolts and seals). Detection and prevention of gas leakage. Allowable stress and quality factors of metal pipes. |
| CSA B51-14(R2019) | Boiler and pressure vessel (CSA, 2019) | Close to China's *Supervision Regulation on Safety Technology for Stationary Pressure Vessel*. |
| ANSI/CSA HGV 2-2014(R2019) | Standard hydrogen vehicle fuel containers(CSA, 2019) | Application conditions: Requirements for mass production, material, design, manufacture, marking and test of compressed hydrogen storage tanks for fuel cell road vehicles. Permanently attached to the vehicle. The operating temperature ranges from -40℃ to 85℃, the capacity is less than 1,000 liters and the operating pressure does not exceed 70MPa.<br>Mainly specified the testing requirements that materials need to meet:<br>Deformation of material within different pressure and tension ranges, stress ratio under different wall thickness conditions and product test. |
| ANSI/CSA HGV 4.1-2020 | Hydrogen dispensing systems.(ANSI, 2020) | Applicable to standards for safe operation, substantial and durable construction, and performance test of mechanical and electrical characteristics of vehicle hydrogen distribution system. Applicable conditions: operating pressures of 25MPa, 35MPa, 50MPa and 70MPa. |
| | | Scope of management: standardize the metering, registration, control, and management of hydrogen fuel cell vehicle filling, and put forward preventive measures against vehicle hydrogen over- filling and vehicle hydrogen storage tank over-pressure. |

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|---|---|---|
| CSA ANSI/CSA HGV 4.5-2013(R2018) | Prioritization device for filling of hydrogen-powered automobile (CSA, 2018) | The operating temperature of filling equipment is -40℃~60℃, and use of screws, nuts and bolts shall comply with relevant standards;<br>The use of equipment must be inspected per ASTM Standards or can be proved to meet the conditions;<br>All movable parts shall be replaceable at any time and can be easily replaced; manual/automatic valves shall comply with the CSA requirements;<br>The operators who install the filling equipment should be certified by automobile manufacturers and have been qualified accordingly (it has not made explicit that which qualification is required), and China has a similar situation, so it is necessary to specify the safety qualification (license) required for hydrogen operation worldwide. The temperature in the hydrogen filling room is limited to 25℃~30℃. |
| CSA HPIT 1-2015 | Compressed Hydrogen Powered Industrial (CSA, 2015) | Minimum requirement for material, design, manufacture, and test of newly produced compressed hydrogen fuel system component has been specified. These containers are only used to store compressed hydrogen installed in hydrogen powered industrial truck applications or other heavy industrial applications. |
| | Gaseous Hydrogen Powered Industrial Truck/Heavy-duty Vehicle/Light-duty Surface Vessel Filling Agreement (CSA, 2015) | Filling operation procedures, filling time limit, cut-off time, emergency stop, fuel surplus monitoring;<br>The inner diameter range of hydrogen piping is determined according to the velocity, pressure, and enthalpy of hydrogen at the outlet; |

| | | |
|---|---|---|
| SAE/USCAR-5- 5:<br>2019-02-27 | Avoidance of Hydrogen Embrittlement of Steel (SAE, 2019) | Hydrogen embrittlement of steel, i.e. brittle fracture that may be caused under pressure, is the result of hydrogen absorption in the process of cleaning, phosphate coating and electroplating;<br>The susceptibility to hydrogen brittleness can increase with the stress (applied internally or externally) and material strength. The condition for increasing the risk of hydrogen embrittlement of steel has defined the decompression procedure needed to minimize the risk of hydrogen embrittlement. |

Source: Processed by author from Mao, Z.Q. (2020).

This chapter excerpts some key content from numerous standards for reference. The above standards have specifications on equipment, material properties, operation procedures, etc., especially with regard to ANSI/ASME B31.12-2014 on hydrogen piping and pipelines, and ANSI/CSA HGV 2-2014 (R2019) on FCEV hydrogen storage tanks. China has no safety standard applicable in these two fields. According to the summary of construction and operation experience of the existing 2,500 km hydrogen pipeline, the US has formulated the *Standard of Hydrogen Piping and Pipelines*; as the temperature changes in different seasons, the safety of the pipe material is analysed and the safe temperature range is formulated in accordance with the existing material level, which is worth incorporating into China's equivalents. The storage and transportation of hydrogen energy represents almost 30% of the cost of the full industrial chain, and the high-pressure range is conducive to promoting the economy of hydrogen energy. In view of this, the US has formulated the *Standard Hydrogen Energy Storage Tank*, setting the operating pressure to be 70MPa, which is higher than the 20MPa limit defined by the prevailing standard in China. Of course, raising the operating pressure also requires the technical support of hydrogen storage equipment and material. Through the close cooperation between enterprises and the government, the technology and standards in the US have been upgraded simultaneously and created preconditions for large-scale application. Through research and analysis, it can be seen that the American fuel cell industry adopts a standard-first approach, which is consistent with the research of many scholars on the durability of fuel cells. For example, Nilesh Ade and other scholars have studied the durability of proton exchange membrane fuel cells (PEMFC) and analysed the safety hazards of explosions. After that, some scholars analysed the technical methods of how to improve the economics of hydrogen refueling stations within a safe range, which provided a reference for the large-scale development of hydrogen energy by the US Department of Energy.

## 2.2. The EU hydrogen energy regulations have every detail in place, focusing on safety management and hazard detection.

The development of EU hydrogen energy is mainly to replace fossil fuels, reduce carbon emissions, and make a greater effort to develop new energy sources. In the *European Hydrogen Energy Strategy* released in July 2020, safe application of hydrogen energy was mentioned nine times, demonstrating that the EU attached greater importance to safety. The main characteristics of safety legislation are sound legal systems, detailed content, and few cross-references, while the legal system related to hydrogen energy development is mainly mandatory. In addition, for codes in the same field, there will be many details required in EU Regulations, and words like 'see relevant standards for specific provisions' rarely appear.

**Mandatory environmental impact assessment.** The main laws and regulations related to production and use of hydrogen energy include 85/337/EEC *Environmental Impact Assessment Act for Public and Private Projects*, 2008/1/EC *Concerning Integrated Pollution Prevention and Control*, 2004/35/EC *Environmental Liability with Regard to Prevention and Remedying of Environmental Damage*, and European Hydrogen Energy Strategy (2020), of which 85/337/EEC clearly pointed out that, before a new project is approved, an environmental impact assessment of any major project must be performed; further, hydrogen filling stations are mandated to perform environmental impact assessments. **Error! Reference source not found.**

**Attach greater importance to the safety management of practitioners.** EU legislation attached greater importance to production safety, and there are regulations applicable to each production section in particular. In Germany, a safety controller shall be assigned if a factory has employed 20 people; in the EU, it is required to make an emergency response plan and designate a staff member to be in charge of accident prevention. In contrast, China has no safety regulations specifically for employees in the hydrogen field and the current personnel safety regulations have been promulgated and implemented as part of relevant legislation.

**Attach importance to inspection and test of hydrogen transportation.** The laws and regulations of the European Union, Germany, and China on hydrogen transportation are similar, and most of them focus on road transportation safety, which is also in line with the actual situation of the European Union. Directives 94/55/EC and 96/35/EC are special regulations for the technical indicators of hazardous goods transportation and the safeguard of operators. It is required in 96/96/EC that regular inspection and test are mandatory for all motor vehicles and drivers for cargo transport. In pipeline transportation, laws of EU and Germany require strict environmental impact assessment on related building projects. In addition, they must comply with prevailing national engineering and safety laws and regulations.**Error! Reference source not found.**

**Table 8.8: Main Content of EU Hydrogen Safety Laws and Regulations**

| Standard No. | English Name/Chinese Name | Main content |
|---|---|---|
| BS EN 10229: 1998 | Evaluation of resistance of steel products to hydrogen induced cracking (HIC) (EU, 1998) | Steel, hydrogen, visual inspection (test), cracking, corrosion test, sample preparation, accelerated corrosion test, test equipment, split test, mathematical calculation, and test sample |
| CEN 1251:2019 | Cryogenic vessels- transportable vacuum insulated vessels of not more than 1000 litres volume - Part 1: Basic Requirements; Part 2: Design, fabrication, inspection, and test (EU, 2019) | Requirements for mechanical loading, chemical effects, thermal conditions, material properties, design, fabrication, inspection, and final acceptance test |
| CEN 13648 | Cryogenic Vessels - Safety devices for protection against excessive pressure: Part 1: Safety valves for cryogenic equipment; Part 2: Safety devices for bursting disc of cryogenic equipment ((EU, 2000)) | Focus on safety test of equipment |
| CEN 13530<br><br>UNE-EN 13458-2/AC-2007 | Cryogenic Vessels - Large Transportable(EU, 2000)<br>Vacuum Insulated Vessels<br>Part 1: Basic Requirements; Part 2: Design, fabrication, and test(EU, 2004) | |
| CEN14197 | Cryogenic Vessels - Static non-vacuum insulated vessels: Part 1: Basic Requirements; Part 2: Design, fabrication, inspection, and test; Part 3: Operational requirements. (EU, 2007) | Requirements for construction, marking and test of static non- vacuum insulated vessels, portable/stationary fuel cell systems. |
| EN62282-5-1- 2007 | Portable fuel cell appliances-Safety (EU, 2007) | |
| EN62282-3-1- 2007 | Stationary fuel cell appliances-Safety (EU, 2010) | |

Source: Processed by author from Mao, Z.Q. (2020).

### 2.3. Strong enforcement of safety regulations and support guarantee with advanced detection technologies in Japan

Since Japan has high population density and small land space, it is difficult to avoid densely populated areas for the construction of hydrogen energy industry. Therefore, the implementation of the safety policies, laws, and regulations is very urgent. In Japan, the main intentions for safe application of hydrogen energy lie in the following aspects: (a) alleviating the energy crisis and reducing dependence on oil and natural gas; (b) improving the energy supply side structure and increasing the diversity of the energy structure; (c) promoting fuel cell vehicles; and (d) exporting hydrogen energy safety technologies to the world and becoming the technological leader of the industry.

**Table 8.9. Laws, Regulations, and Standards Related to Hydrogen Safety in Japan**

| Category | | Name | Main Contents |
|---|---|---|---|
| Regulations | | Hydrogen fuel cell safety regulations Vessel safety regulations (Japan, 1994) | The basic technical requirements for hydrogen system safety, electrical system safety, drive system and fuel system safety have been formulated.<br>In 2014, Japan extended the safety upper limit for the one-time charging pressure of the on-board hydrogen storage tanks of fuel cell vehicles, increasing from 70 MPa to 87.5 MPa. |
| Laws | | High pressure gas security law (Japan, 1994) | The technical specifications, periodic inspections, and seismic design of general high-pressure gas equipment are applicable to high-pressure hydrogen. The high-pressure hydrogen safety requirements for hydrogen fuel cell vehicles, as well as safety management on the marks and scrappage are added in the latest version in 2017. |
| Standards | JIS C8822-2008 | General safety specifications for small polymer electrolyte fuel cell systems (Japan, 2008) | |
| | JIS K0512-1995 | Hydrogen (Japan, 1995) | Analysis of the basic characteristics of hydrogen used in industry and transportation, determination of oxygen content, storage precautions, etc. (When storage according to the storage method, attentions should be paid to the following: (1) Vessels must be chained to prevent it from tipping over; (2) The vessels should be placed in a well-ventilated and fire-free place, and stored at a temperature below 40°C. |

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| | | | 10. Treatment method. Hydrogen has a wide explosion range of 4.1% to 74.2% in the air, it is highly flammable, easy to leak, and has a low ignition temperature and difficult to see flames, etc. When collecting and testing samples, with consider these nature; in terms of safety, attentions should be paid to the following: (1) The vessel must be chained to prevent it from tipping over. (2) Use the prescribed tools to open and close the valves of vessels quietly. If it sprays out suddenly, there is a risk of fire. (3) When handling hydrogen, a warning of no combustion should be displayed. (4) Be careful not to leak hydrogen from the gas flow paths such as sample introduction pipes, measuring instrument, etc. The connection parts must be checked of leak with soapy water. (5) When performing the operations of 6.5.1 and 6.6.1, use a tipper fixed on the ground. In addition, when performing the operation of 6.6.2, perform the gas replacement completely, pay attention to backfire. (6) Fully ventilate to prevent the exhaust gas from the analyzer staying in the room. In addition, the exhaust is carried out under safe conditions without flames, mechanical sparks, high temperature objects, electric sparks, and static electricity. |
| | JISC 8822:2008 | Safety standards for small solid polymer fuel cell systems (Japan, 2008) | Scope of application: The standard covers the overall safety criteria of the system, performance maintenance and management, etc. of the fixed and portable small solid polymer fuel cell systems (hereinafter referred to as fuel cell systems), their structures, materials, functions, setting standards, displays, markings, instructions for use, etc. Material requirements: Corrosion-resistant materials or coatings; when the outer contour materials such as synthetic resin are placed in the air of 80C±3C for 1 hour and then naturally cooled, there should be no cracks, rupture or other abnormalities. The materials of equipment parts must not contain PCB, asbestos or asbestos material; in terms of mechanical requirements, all parts should have |

| | | | |
|---|---|---|---|
| | | | a safe structure, which can resist distortion, strain and other damages; Control over temperature change:<br>The temperature at the touch area is below 70C.<br>Requirement for fuel cell stacks: a) Have a structure that can sufficiently withstand the stresses caused by assumed pressure, vibration, heat, etc. b) Have corrosion resistance in the intended use environment. c) Have electrical safety in the intended use environment.<br>The heat preservation materials and thermal insulation materials adjacent to the gas passage, burning parts and electrical components shall be tested according to 5. in the Table 17 of HSS 2093. They shall not burn and must extinguish the fire within 10 seconds.<br>When testing the insulation strength of the fuel cell stacks under the conditions 1) or 2) specified below, we must do the following: 1) charge the DC voltage or 1 time the AC voltage (500 V when it is lower than 500 V) to 1.5 times the maximum working voltage, continuously for 10 minutes between earth. 2) When the rated voltage is 150 V or less, the voltage is 1,000 V to the ground, and when the rated voltage is greater than 150 V, apply a 1,500 V AC voltage to the ground continuously for one minute.<br>In the power generation unit, set up an automatic stop device under the conditions listed in the following: a) when fuel pressure or temperature in the fuel system and the heavy system has increased significantly; b) When the flame of the resetter burner goes out; c) When a gas leak is detected; d) When the control device is abnormal; e) When the control power supply voltage drops significantly; f) When the fuel cell stack has overcurrent; g) When the voltage generated by the fuel cell stack is abnormal; h) When the temperature of the fuel cell stack has increased significantly. |

Processed by author from Mao, Z.Q. (2020).

At present, regulations related to hydrogen energy safety include high-pressure gas security laws (rules for security of general high-pressure gas, security of vessels, specific equipment inspection, and security of joint enterprises), fire protection laws, construction standard laws, labour safety and health laws, etc. The main standards include Japanese Industrial Standards (JIS), International Standard ISO/TC197, High Pressure Gas Security Association, Japan Petroleum Energy Technology Center, and the Japan Industrial and Medical Gas Association.

**Strict regulations and strong enforcement.** An important feature of Japan's legislation is strong operability, which is mainly reflected by the clear and specific legal provisions, and the timely promulgation of supporting regulations. After enacting a new energy law, the Japanese government will promptly formulate related supporting regulations in the form of 'implementation orders', 'implementation rules', etc., in order to regulate related issues in a more specific and detailed manner. For example, Japan enacted the *Law on Special Measures to Promote the Utilization of New Energy* in April 1997. To ensure its implementation, in June of the same year, the government enacted the *Enforcement Order of Law on Special Measures to Promote the Utilization of New Energy*. Although the above-mentioned laws are not closely related to hydrogen energy safety, they have certain reference significance for the formulation and implementation of hydrogen energy safety regulations in China.

**Strict standards and thoughtful consideration.** As regards standards and specifications, Japan has regulated the safety technology of hydrogen refueling stations. A hydrogen refueling station has a combination of large-capacity and high-pressure hydrogen storage cylinders, high-pressure compressors, and hydrogen unloading facilities. Construction of hydrogen refueling stations in gas stations is allowed in Japan; in other words, oil and hydrogen mixing stations are allowed. Further, containerised natural gas or hydrogen production devices using propane as raw material in hydrogen refueling stations, or those used in online hydrogen production, are allowed. The safe distance between hydrogen refueling stations and surrounding buildings is only required to be in accordance with provisions of the *Safety Law on High Pressure Gas*, and the distance from residential houses and various public facilities should be no less than 8 metres. Hydrogen refueling stations, residential houses, and public facilities are installed with 10 cm-thick separation walls.

**Table 8.10: Comparison of Major Safety Distances**

| Comparison of major safety distances planned by various countries (unit: m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Categories | Requirements on control | | China | US | Germany | Japan | UK |
| In-station distance | Constraint distance | Open fire in the station | 12~14* | 12 | 1~5 | 8 | 5 |
| | Layout distance | Distance between hydrogen equipment | 3~15 | /** | 0.5~1 | / | / |
| | | Distance between hydrogen and non-hydrogen equipment | 4~8 | / | 2 | / | / |
| | Protective distance | Equipment and road | 2~5 | 3 | / | 3 | 8 |
| | | Plant/ warehouse | 5~15 | 0 (2h***) | 5 | / | / |
| Outer-station distance | Out-station distance | Buildings outside the station | 12~50 | 2 (2H) | / | / | / |
| | | Open fire outside the station | 20~40 | 3~4.6 | / | / | 8 |
| Note:* Open flame is valued according to gas (oil) water heater/gas kitchen in the station: ** Due to introduction of risk assessment from abroad, some values are not mandatory and are determined based on the assessment result: ***Fire resistance time duration subject to American standards is not less than 2h. | | | | | | | |

Source: Author.

**Advanced safety detection technology.** Japan's FCEVs apply 70MPa high-pressure hydrogen. The maximum outlet pressure of a refueling station hydrogen compressor and a storage bottle are up to 90MPa. Reliability and safety performance testing of hydrogen storage bottle manufacturing is very important. 70MPa and 90MPa hydrogen storage bottles usually adopt a three-layer structure: the surface layer applies glass fibre composite material, the middle layer is made of carbon fibre composite material, the inner layer of type III bottles is made of aluminium alloy liner, and the inner layer of type IV bottles is made of plastic liner. Hydrogen storage bottle design and manufacturing technology should be tested by hydraulic blasting, gunshot, fire, etc.; bottles should be given an automobile crash test.

For hydrogen refueling stations, the main safety technical measures include installation of high-sensitivity leak detectors in strategic locations, timely alerts when the volume concentration is higher than 1, and multiple flame detectors with alarms. Buildings such as high-pressure hydrogen storage rooms and compressor rooms should consider factors for dispersing hydrogen after leakages, and adopting a roof design that is both rainproof and prone to vent air. The roof design of outdoor hydrogenation units should be conducive to diffusion of hydrogen to high altitudes.

First, as the highest requirement for hydrogen-usage safety, Japan's laws and regulations are demanding; second, as guidelines for practice, Japan's standards are comprehensive, elaborate and strong in execution; and last, as the main means to ensure safety, the development of technologies and detection means interworking to ensure continuous improve and to make sure that safety parameters of the entire process of hydrogen energy use are distinctive.

### 2.4. Republic of Korea formulates full-process regulations to provide rules and guidance for industrial development

On 4 February 2020, the Republic of Korea (henceforth, Korea) government officially launched the world's first hydrogen law, the *Safety Management Law on Promotion of Hydrogen Economy and Hydrogen Safety* (hereinafter referred to as the Hydrogen Law), which provides strong support for safety management of hydrogen energy supply and facilities. The Hydrogen Law formulated the entire process of regulations and systems, established a hydrogen safety agency, stipulated strict access and business change conditions, and clearly required establishment of a safety administrator.**Error! Reference source not found.**

**Whole-process laws and regulations.** Korea's Hydrogen Law enforces strict laws and regulations throughout the entire process of operating a hydrogen energy business, ranging from operating permits to project declarations to completion inspections.

**Establishment of a hydrogen safety agency.** To regulate management boundaries and responsible parties for hydrogen safety, Korea has established a specialised agency responsible for hydrogen safety. The Minister of Industry, Commerce, Industry and Energy designated organisations, teams, or legal persons related to hydrogen project safety as specialised hydrogen safety organisations. The hydrogen safety organisation's work focuses on research and development of hydrogen safety technology, including through international cooperation; education and training on hydrogen safety; and boosting the importance of hydrogen safety.

**Strict access and business change conditions.** Articles 36 to 40 of Korea's Hydrogen Law stipulate that a report should be submitted to the mayor regarding access permits and changes to business permits. Commencement, suspension, and resumption of projects also need to be declared with causes being explained. High-level administrative approval strictly regulates access and operating timeliness of hydrogen energy. At the same time, it stipulates that specific requirements should be declared when major events such as ownership inheritance and bankruptcy auctions occur that would affect business activities.

**Strict safety guarantee on filling of hydrogen.** The hydrogen filling process has a high potential safety hazard. Korea's Hydrogen Law has clarified the scope and process of this work. Article 49 mentions that a mobile pressure vessel and gas cylinder filling unit shall meet the following conditions and obtain permission of the department responsible for safety supervision and management of special equipment before it can engage in filling activities. The filling unit shall establish an inspection and recording system before and after filling, and it is forbidden to fill mobile pressure vessels and gas cylinders that do not meet requirements of safety technical specifications. The gas cylinder filling unit shall provide users with cylinders that conform to the safety technical specifications, guide them on their safe use, register them, and apply for regular declarations in a timely manner.

**Assign a security administrator.** Korea's Hydrogen Law clearly stipulates that a safety administrator must be assigned to operate a hydrogen business. As the principal party, the security administrator is mainly responsible for fulfilling responsibilities and ensuring safety, and guarding against danger of hydrogen supplies. The appointment of corporate security officers must be reported to the mayor, county guard, or district director. At the same time, when safety officers are unable to perform their duties due to other matters including retirement, travel or illness, they need to submit declarations 30 days in advance to ensure the smooth transition of safety protection work.

Study of Korea's Hydrogen Law reveals that its work on hydrogen energy security is mainly to establish strict administrative approval procedures, strict business scope definitions, prudent business changes, and continuous improvement of safety concepts. The above management experience is worth learning.

## 3. Related domestic practices

Safety is one of the main constraints to the development of the hydrogen energy industry, and it is also a topic receiving relatively high public concern. At present, China is deficient in laws and regulations on the safety of the entire hydrogen energy industry chain and shows unclear regulatory authorities. Some cities regard hydrogen as a hazardous chemical and are supervised by the city management department. With rapid development of the domestic hydrogen energy industry, various places have continuously attempted to promulgate regulations on the safe operation and supervision of hydrogen energy. As the most important part of the hydrogen energy application field, FCEV safety particularly stands out.

### 3.1. All relevant agencies are actively carrying out research on hydrogen energy development strategies in a bid to provide directions for industrial safety

The hydrogen energy industry has just started in China, but national strategic plans have not yet been issued. At present, the strategic level studies that have been carried out include those on infrastructure and fuel cell development; further, more than 20 provinces, cities, and regions across the country have carried out hydrogen energy industry development research. Studies of various kinds have clarified the goal of industrial development, presented strategy paths, and come up with development suggestions.

It is worth mentioning that the major strategic project of the Chinese Academy of Engineering, i.e. 'China's strategic study on hydrogen energy and fuel cell development', carries out special research on five fronts, namely the role of hydrogen energy and fuel cells in advancing energy revolution, hydrogen production and supply industry development strategy research, fuel cell industry development strategy, strategic research on development of hydrogen use industry and China's hydrogen energy and fuel cell development policy recommendations. This research covers development of the entire hydrogen energy industry chain and provides orientations for promotion of scientific development of China's hydrogen energy and fuel cell industry.**Error! Reference source not found.**

### 3.2. Implementation of several hydrogen energy testing centers indicates a major step forward for industrial development

At present, construction of the hydrogen energy testing center is gradually implemented, which mainly includes the National Hydrogen Energy Center, the National Hydrogen Vehicle Research and Testing Public Service Platform, the Great Wall Hydrogen Energy Testing Technology Center, the Future Science City Hydrogen Energy Technology Collaborative Innovation Platform, the Kunshan Innovation Research of Nanjing University Institute of Testing and Inspection Center, and Shanghai Shenli Technology Co., Ltd. Testing Center. The main body of investment coverage from research institutes to automobile manufacturers and from research and development to applications also reflects urgent needs of industrial development. Although most of the hydrogen energy testing centers at this stage are dedicated to testing of fuel cell vehicles including fuel cell testing, hydrogen storage safety testing, new energy vehicle testing and so on, the completion of major testing centers will vigorously promote formation of a more comprehensive hydrogen energy detection test method and a complete evaluation system in China, and will propel development of the domestic hydrogen energy industry.

#### 3.2.1. Establishment of the National Hydrogen Power Quality Supervision and Inspection Center has achieved a breakthrough from scratch

The National Hydrogen Power Quality Supervision and Inspection Center is the first national hydrogen energy testing organisation in China. The center was built by China General Technology Group and China Automotive Engineering Research Institute Co., Ltd. with an investment of CNYU500 million and is in Yufu Industrial Development Zone, Liangjiang New District, Chongqing.

Main inspection content: it focuses on inspection and testing, prioritises testing content of fuel cell stacks, fuel cell systems and key components, hydrogen storage systems, hydrogen energy power systems, fuel cell vehicles and other fields, and centers on hydrogen energy applications. Based on three main technical lines of safety, greenness and experience, it attempts to create a comprehensive service platform for hydrogen energy power testing and evaluation that integrates testing and certification, standard systems, evaluation research, application promotion, and industrial incubation.

After the project is completed, it will serve hydrogen energy industry clusters in Southwest China, the overall country, and the world, and will become a fair and authoritative third-party technical testing service. It will have a profound impact on promotion of the development of hydrogen energy power industry.

### 3.2.2. As a domestic automobile manufacturer and supplier, Great Wall Motor's Hydrogen Energy Testing Center leads development of the industry

The Great Wall Hydrogen Energy Testing Technology Center was established by Great Wall Motor Co., Ltd. It is the world's largest battery testing device application company. With potent hardware strength and influence, it will become an important base for fuel cell enterprise testing. The center was brought online in Baoding in 2018 with a total input of US$570 million. It is committed to hydrogen storage safety testing, fuel cell testing, system performance testing, vehicle performance testing, and life cycle testing.

It is worth mentioning that the Great Wall Hydrogen Energy Testing Center has a 105 MW power hydrogen core ring test used to verify the safety of the entire vehicle, including the impact of liquid, gas, and eventually hydrogen, as well as a dropping and shooting test. Safety can be ensured through the entire inspection system. This is also a first in China. The establishment of the center will provide better support for development of China's fuel cell vehicle industry.

### 3.2.3. The future science city hydrogen energy technology collaborative innovation platform to promote coordinated development of technology and industry in the hydrogen energy field

In 2019, the Beijing Future Science City Hydrogen Energy Technology Collaborative Innovation Platform began giving full play to its advantages of major scientific research institutes in the field of hydrogen energy; further, it cooperated with Beijing Aerospace Experimental Technology Institute (Aerospace 101), Beijing Science and Technology Cooperation Center, and China Special Equipment Testing and Research Institute and the Zhongguancun Huadian Energy and Power Industry Alliance to announce the opening of Beijing's hydrogen energy equipment test and detection capabilities and to promote the coordinated development of technology and industrial entities in the hydrogen energy field. This also marks an important step taken towards the promotion and safe application of hydrogen energy equipment.

The platform focuses on the hydrogen energy equipment test and detection base of the Aerospace 101 Institute, supports the construction of hydrogen energy equipment test and detection capabilities, and has built the first 95 megapascal (MPa) level high-pressure hydrogen energy equipment test and test platform in China. It is equipped with fire, fatigue, leakage and reliability performance assessment test and type test capabilities of various hydrogen storage vessels, valves and other components under the hydrogen media and is the first domestic rapid charging and discharging test system for hydrogen storage tanks above 70MPa.

### 3.2.4. State Power Investment Corporation builds a hydrogen energy technology company to roundly promote research and development and testing of hydrogen energy applications

State Power Investment Corporation Hydrogen Energy Technology Development Co., Ltd. was established in 2019. Its main business scope includes research, development and production of core hydrogen fuel cell technologies, research and development of key technologies and materials for hydrogen energy production and storage, research, development and production of hydrogen energy power systems, research and development and services of hydrogen fuel cell testing and inspection technology and hydrogen safety technology research, etc.

After less than 2 years of development, the company has attained remarkable achievements in research and development of hydrogen fuel cells. The 100-kilowatt power metal bipolar plate hydrogen fuel cell stack launched by the company has realised fuel localisation of key raw materials and core components of batteries. As regards hydrogen energy demonstration projects, a transportation demonstration project is being carried out. At the same time, it is also working with Zhejiang University to carry out research on natural gas pipeline hydrogenation material verification, which will provide support for the model project of natural gas hydrogenation.

Moreover, other testing centres such as the Testing and Inspecting Center of Kunshan Innovation Research Institute of Nanjing University, the Testing Center of Shanghai Shenli Technology Co., Ltd., and the New Energy Vehicle Testing Center of China Automobile Center all focus on testing of fuel cells and new energy vehicles.

**Table 8.11: Status on Establishment of Hydrogen-Energy-Related Testing Centers**

| Item | Test content | Investment subject | Location | Start Time | Land Occupation | Total Investment |
|---|---|---|---|---|---|---|
| Kunshan Innovation Research of Nanjing University Institute of Testing and Inspection Center | Fuel cell testing, new solar cell testing, biomass fuel testing, lighting electrical product testing, environmental testing | Nanjing University, Kunshan | Kunshan | 2016 | 3 mu | Unknown |
| Future Science City Hydrogen Energy Technology Collaborative Innovation Platform | Fire, fatigue, leakage and reliability performance assessment tests of various hydrogen storage vessels, valves and other components under hydrogen media | The 101st Research Institute of China Aerospace Science and Technology Corporation, China Special Inspection Institute, Institute of Physics and Chemistry, Chinese Academy of Sciences | Beijing | 2017 | Unknown | (Military enterprise) |
| Great Wall Hydrogen Energy Testing Technology Center | Hydrogen storage safety testing, performance testing of fuel battery, system performance testing, vehicle performance testing | Great Wall Motor | Baoding | Completed in June 2018 | 50 mu | 570 million yuan |
| Shanghai Shenli Technology Co., Ltd. Testing Center | Fuel cell stacks and modules, fuel cell system testing | Shenli Technology | Shanghai | Obtained CNAS certification on 14 August 2018 | Unknown | Unknown |
| China Automotive Center New Energy Vehicle Inspection Center | More than 20 comprehensive test buildings including fuel cells, power batteries, electric drive assemblies, electromagnetic compatibility, new energy vehicles, etc. | China Automotive Center | Tianjin | 25 May 2020 | 308 mu | 1.99 billion yuan |

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|---|---|---|---|---|---|---|
| National Hydrogen Vehicle Research and Testing Public Service Platform | A total of ten laboratories of parts, systems, and vehicles | Rugao Economic and Technological Development Zone and Shanghai Motor Vehicle Testing and Certification Technology Research Center Co., Ltd. | Rugao | 15 September 2020 | 44 mu | 260 million yuan |
| National Hydrogen Energy Center | Technical consulting services of fuel cell stack, fuel cell system and key components, hydrogen storage system, hydrogen power system, fuel cell vehicles | China General Technology Group, China Automotive Engineering Research Institute Co., Ltd. | Chongqing | 16 September 2020 | 190 mu | 500 million yuan |

Source: Author.

### 3.3. National standards related to hydrogen energy safety are being formulated and modified at a faster rate, hoping that standardisation will guarantee the development of the industry.

Standardisation is very crucial to the development of the industry. China's current hydrogen energy technology standard system consists of eight standard sub-systems, one of which is the hydrogen safety standard. Through years of hard work, more than 100 national standards for hydrogen energy have been issued, with 30 standards concerning safety. The first national standard for hydrogen energy is GB/T 29729-2013 *Basic Requirements for Hydrogen System Safety*. As the first systematic national standard for hydrogen system safety, it plays an active role in promoting the development of hydrogen energy technology and enhancing its recognition in the market and society. In addition to national standards, industry standards, regional standards, and community standards have also been gradually established and improved. At present, a series of national standards are being revised. They are mainly standards related to hydrogen fuel cells and hydrogen vehicle, such as terminology for proton exchange fuel cells, standard system for proton exchange membrane fuel cells, proton exchange membrane fuel cell stacks, portable proton exchange membrane fuel cells, stationary proton exchange membrane fuel cell power generation systems, technical and testing specifications for motors and their controllers in electric vehicles, technical requirements for hydrogen production by hydrogen energy-water electrolysis, and technical specification of hydrogen purification systems on pressure swing adsorption, etc.

Although there are not so many special standards for hydrogen energy safety as other standards, and they are mainly concentrated on the relevant standards of the fuel cell vehicle application, given the particularity of hydrogen, great importance is attached to standardisation in the industrial development process. With the rapid development of the industry, relevant safety standards will be formulated and revised constantly.

### 3.4. Pioneering explorations in the safety approval of hydrogen refueling stations have been carried out with remarkable achievements in many cities.

In addition to the existing relevant national standards and regulations, currently, more than 10 cities in China have issued regulatory documents concerning the construction of hydrogen refueling stations, and the infrastructure of hydrogen fuel cell vehicles, including Foshan, Zhangjiakou, Wuhan, Weifang, and Wuhai, Fuzhou, Yueyang, Laohekou, Changchun, and Baoding City. Some of them are concerned with hydrogen energy safety. Although they may be similar or different in some ways, and they may not be perfect, they still provide a groundbreaking reference for the construction of hydrogen refueling stations in China, particularly in terms of their safe operation, management, and supervision.

**Table 8.12. Documents on the Management of Hydrogen Refueling Stations in China and the Key Points Concerning Safety**

| Time of release | Name of document | Key points concerning safety |
|---|---|---|
| March 2018 | Interim Measures for the Approval and Management of Hydrogen Refueling Stations in Wuhan Economic and Technological Development Zone (Hann an District) (Wu Jingkai [ 2018 ] No. 24 ) (Wuhan, 2018) | 4 . Report for project construction. ( 5 ) Review of safety conditions and design of safety facilities: hydrogen refueling station projects shall refer to urban g as projects. The project construction units shall entrust a qualified safety evaluation agency to carry out safety pre-evaluation in accordance with the 'Three Simultaneousness' Supervision and Management Measures for Construction Project Safety Facilities, and safety pre- evaluation reports should be prepared. |
| August 2018 | Interim Measures for the Administration of Hydrogen Refueling Stations in Foshan City (Draft for Comments) (Foshan, 2018) | Chapter III Operation and Safety Management: Provisions concerning safety ranging from system to operation are mentioned in 13 items through Article 9 to Article 21. |
| May 2019 | Opinions from Weifang Municipal People's Government Office on Doing a Good Job in the Planning, Construction, Operation and Management of Hydrogen Refueling Stations in the City (Weifang government office [ 2019 ] No. 61 ) ( Weifang, 2019) | 5 . Effectively strengthen the safety management of hydrogen refueling stations, referring to improving the safety system, increasing staff, standardizing operation records, and imp roving emergency response capabilities. |
| July 2019 | Interim Administrative Approach for Temporary business license of Automobile Hydrogen Refueling Stations ( Draft for Comments) (Shanghai, 2019) | Details are mentioned regarding the application, acceptance, review, approval, certificate issuance, and relevant supervision and management of business license for auto mobile hydrogen refueling stations in Shanghai city. |
| August 2019 | The People's Government of Laohekou City in Hubei issued the Administrative Measures for Hydrogen Refueling Stations in Laohekou City (for Trial Implementation) (Laohekou, 2019) | Chapter VI Operation and Safety Management: Provisions concerning Safety management system, safety distance, safety warning, safety assessment are mentioned in 18 items through Article 24 to Article 41. |
| January 2020 | Administrative Procedures for Hydrogen Refueling Stations in Wuhai City ( Trial) ( 2019 - 2022) (Wuhai, 2019) | Chapter IV Operation and Safety Management: Provisions concerning Safety are mentioned in 4 items through Article 14 to Article 17 , referring to carrying out safety inspections on hydrogen systems, fire and safety facilities, electrical facilities, and ventilation devices, according to Technical Specifications for Hydrogen Refueling Stations . |
| May 2020 | Program for Hydrogen Energy Industry Safety Supervision and Management in Zhangjiakou City (Zhangjiakou, 2020) | There are 9 chapters and 90 articles in the program, covering the safety management of the entire industry chain, referring to the company's own safety management, key points of safe operation, and the management responsibilities of various regulatory agencies. |
| October 2020 | Notice of the People' s Government of Changchun City on Issuing the Interim Measures for the Administration of Automobile | In Article 12, Article 13, and Article 15, it is made clear that details such as the Security Officer at all levels, the safety management system of auto mobile hydrogen refueling stations, and the hydrogen hazard risk notification board |

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| | Hydrogen Refueling Stations in Changchun City (Changchun Municipal Regulation [2020] No. 1) (Changchun, 2020) | should be unveiled to the public, and the safety operation specifications should be posted in an eye-catching place, etc. |
| October 2020 | Opinions of the Baoding Municipal People's Government Office on Doing a Good Job in the Approval and Management of Hydrogen Refueling Station Projects (Baoding, 2020) | 2 . Review of project planning and design program and plan of land use ( 6 ) Design for safety conditions and safety facilities. The hydrogen refueling station project shall be carried out in accordance with the 'Three Simultaneous' Supervision and Management Measures for Construction Project Safety Facilities with reference to urban gas projects, and the safety pre-evaluation of its construction projects will be conducted. Also safety pre-evaluation reports and safety facility design documents will be prepared. |
| November 2020 | Interim Measures for the Construction, Operation and Management of Hydrogen Refueling Stations in Fuzhou City ( Fuzhou Municipal government Office [ 2020 ] No. 109 ) (Fuzhou, 2020) | The measures have repeatedly mentioned safe production, training, and operation, and proposed the establishment and improvement of relevant safety management systems for hydrogen refueling stations. |
| December 2020 | Interim Measures for the Construction and Management of Hydrogen Refueling Stations in Yueyang City (Yueyang, 2020) | In Article 7 and 12 , security review work of hydrogen refueling station construction project is mentioned, Namely, the operation and management of hydrogen refueling stations shall comply with the Safety Technical Requirements for Hydrogen Storage Devices for Hydrogen Refueling Station s( GB/ T 3 4583 — 2017 ) , Hydrogen Station Safety Technical Specification s( GB/ T 34584 - 2017 ) and relevant national standard s . |

Source: Authors.

#### 3.4.1. The first local management document for hydrogen refueling stations was issued in Wuhan, and its safety approval and supervision system is worth promoting.

Wuhan has taken the lead in the development of hydrogen energy in China. It not only abounds with industrial by-product hydrogen, but also gains some advantage in key core technologies such as membrane electrodes, storage and transportation, efficient production, and FCEV power systems. In addition, it also has a strong foundation in technology and industrialisation.

Refueling stations are the key infrastructure for the development of the hydrogen vehicle industry. Regarding site selection, construction approval, and other procedures, there are no normative or guiding documents issued by local governments at all levels. To promote the development of the hydrogen energy industry and speed up the construction of supporting infrastructure, Wuhan Economic and Technological Development Zone (Hannan District) made a good try in approving and supervising hydrogen refueling stations in 2018. It issued the Interim Provisions for the Approval and Management of Hydrogen Refueling Stations in Wuhan Economic and Technological Development Zone (Hannan District). This document clarifies the approval and management procedures and regulatory department concerning site selection, reporting, construction, and operation of hydrogen refueling station projects.

Regarding hydrogen energy safety, the document proposes that hydrogen refueling station projects shall refer to urban gas projects. The project construction units shall entrust a qualified safety evaluation agency to carry out safety pre-evaluation in accordance with the 'Three Simultaneousness' Supervision and Management Measures for Construction Project Safety Facilities, and safety pre-evaluation reports should be prepared. Meanwhile, design concerning the safety facilities of the construction project should be carried out by entrusting a qualified design unit, and safety facility design documents should be compiled. Safety pre-evaluation reports and facility design documents should be submitted to the district safety supervision bureau for the record. Although the measure only sets forth brief provisions on the safety of hydrogen refueling stations, and it does not cover the entire industry chain and related management systems, it has been developed from scratch, and it means a big step forward for standardising infrastructure construction in the hydrogen energy field. It can provide valuable reference for other cities.

### 3.4.2. Foshan City has made a pioneering exploration on the safety of hydrogen refueling stations and issued the first Interim Measures for the Administration of Hydrogen Refueling Stations in China

Foshan's hydrogen energy industry began in 2014. After 6 years of development, it has taken the lead in China in introducing the Canadian Ballard production line for commercial vehicles; introducing and implementing support and preferential policies; putting 16 hydrogen refueling stations into service; and establishing a standard innovation base for the hydrogen energy industry. However, various problems emerged in the development process of Foshan's hydrogen energy industry, such as the production, preparation, and refilling of hydrogen. Fortunately, progress has been made in identifying and solving problems. It is worth mentioning that Foshan has made pioneering explorations in hydrogen energy safety management. China's first 'Interim Measures for the Administration of Hydrogen Refueling Stations' was issued in Foshan in August 2018. It made clear regulations on administrative approval, safety system construction, and safety management.

**In terms of administrative examination and approval and competent authorities,** Foshan City has borrowed from the natural gas administrative examination and approval model and established a model of housing construction taking the lead in administrative examination and approval. It filled the gap in the approval process of hydrogen refueling stations. It maintained that the Housing and Urban-Rural Construction Administration should be responsible for the city's industry management of hydrogen refueling stations and also the guidance and supervision of the construction approval, business license and safety supervision of hydrogen refueling stations in various districts. The housing and construction department at the people's government district level specifically implements the approval of the construction of hydrogen refueling stations, the issuance of business licences, operation supervision and safety management.

**In terms of the construction of safety system,** it not only proposed that someone should be responsible for the safe operation of hydrogen refueling stations, but it also clearly stated that the operating entity must establish a sound safety management system, safety production responsibility system, risk management system, and emergency response plans. Emergency drills should be carried out, with special drills at least once a quarter, comprehensive emergency drills at least once a year. The safety management system of the hydrogen refueling station shall include, but is not limited to, operation site safety management, fire safety management, equipment safety management, staff safety management, safety inspection management, the accident reporting and handling process, the regular inspection system, and security work management. A series of regulations above provide both guidelines and guarantees for the safe operation of hydrogen refueling stations.

### 3.4.3. Zhangjiakou City has issued China's first approach for the safe supervision and management of hydrogen energy, setting a good example.

As a national demonstration zone with renewable energy and the host city of the 2022 Winter Olympics, Zhangjiakou City has seen rapid development and taken the lead in the hydrogen energy industry in recent years. Targeting green, low-carbon, and sustainable development, Zhangjiakou City provide transportation services for the Winter Olympics with hydrogen fuel cell vehicles. According to Zhangjiakou's hydrogen energy industry plan, by 2022, hydrogen fuel cell vehicles will have been put into demonstration operation in batches in the Zhangjiakou competition area and the main urban area in order to meet the transportation needs of the Winter Olympics. It is planned to promote more than 2,000 vehicles with hydrogen fuel cell for city buses and passenger and logistics services.

Safety issues occurred inevitably along with the rapid development of the hydrogen energy industry and they cannot be ignored. In order to prevent and defuse major risks and ensure the safe and stable development of the hydrogen energy industry, Zhangjiakou City issued the first *Safety Supervision and Management Approach for the Hydrogen Energy Industry* in May 2020. There are nine chapters and 90 articles in this approach. The biggest highlight is that it is concerned with the safety management of the entire industry chain, including the company's own safety management, the key points of safety operation, and the management responsibilities of various regulatory departments.

**In terms of safety management of hydrogen-related enterprises,** the *Safety Supervision and Management Approach* covers the key points of safety management of the entire industrial chain from the production, storage, transportation, refueling, to the use of hydrogen energy. In reference to the *Law of the People's Republic of China on Safety Production*, it put forward requirements for the safety management of hydrogen energy companies in the entire production and operation process ranging from hydrogen energy industry planning, license application, staffing, personnel qualifications, three systems, emergency plans and drills, personnel training, and equipment maintenance, etc. For example, it made clear statements about the safety distance between the hydrogen production enterprise and the facilities outside the plant, as well as the architectural characteristics and fire resistance limits of the buildings.

**For hydrogen energy storage, hydrogen gas tanks and vessels are the equipment mainly used.** Hydrogen gas tanks should be limited in their height and water seal level to prevent hydrogen from escaping. Hydrogen vessels should be put under proper pressure with safety devices installed to prevent overpressure explosions.

**Safety requirements are also put forward for the transportation of hydrogen.** Corresponding qualifications are demanded in the design and manufacture of hydrogen energy vehicles. The users should register and regularly inspect the vehicles in accordance with the regulations. Qualified safety management personnel, drivers, escorts, and operators should be equipped correspondingly. Also, some necessary safety protection equipment is needed for daily operation.

**Regarding the safe operation and control of the hydrogen refueling system,** it is required that the site selection of hydrogen refueling stations should meet the requirements of planning and safety. The hydrogen refueling stations should take measures to prevent hydrogen leakage, avoid static sparks and open flames, and ensure that all electrical instruments should be explosion-proof.

**In terms of the safety requirements for the use of hydrogen energy,** it is proposed that electric vehicles fueled by gaseous hydrogen cells should comply with the relevant national mandatory standards for motor vehicles and the safety requirements for electric vehicles. They should work hard to avoid over-temperature and over-pressure of hydrogen storage tanks, hydrogen leakage. Hydrogen leak detectors should be installed and make measures to prevent static electricity.

**In terms of the supervision and management of hydrogen energy,** clear divisions about their respective management functions in the hydrogen energy industry chain are made among 13 relevant supervision and management departments, namely the department of administrative approval, market supervision, ecological environment, transportation, housing construction, urban management, and emergency management and so on. All departments are required to strengthen the supervision of hydrogen energy according to their responsibility division to ensure the safe, stable, and efficient operation of the hydrogen energy industry.

## 4. Propositions on policy

Due to the particularity of hydrogen, the safe development of the hydrogen energy industry is particularly important. The safe utilisation of hydrogen energy runs through all links of the entire industrial chain, from preparation, storage, transportation, refueling, to the application of hydrogen, and it is a prerequisite and necessary condition for the healthy development of the hydrogen energy industry. International and domestic application practices have proved that as long as hydrogen energy is used in production and storage in accordance with laws, regulations and standards, the safety of hydrogen energy can be guaranteed. This chapter makes propositions on how to improve the legal system, technical standards, and specifications; accelerate the production, learning, research, and application; and improve safety testing capabilities, etc.

### 4.1. To speed up top-level design and establish safety laws and regulations for the entire hydrogen energy industry chain

At present, it is not yet clear what role hydrogen energy plays, and this will restrict it from playing its due role in the energy revolution. Besides, there is no systematic development goal and implementation path for the hydrogen energy and fuel cell industry, which is not conducive to maximising the utility of existing industrial factors and building a policy guarantee system for industrial development. Thus, it is proposed to speed up the top-level design, formulate a national development blueprint for hydrogen energy industry, and clarify the role of hydrogen energy in industrial development.

Meanwhile, the development of the hydrogen energy industry can only refer to the safety regulations of gas-related hazardous chemicals in the current legislative system. However, those regulations cannot play a specific role in the safe development of hydrogen energy, not to mention meeting the needs of hydrogen energy development. Thus, it is proposed to learn from the advanced experience of Japan, Korea, and other countries. That is to say, efforts should be made to speed up the top-level design, and accelerate the formulation of mandatory laws and regulations for the safe development of the hydrogen energy industry so that it can cover all links of the hydrogen energy industry chain, from the safety regulations of hydrogen production devices and equipment, the safety performance testing for devices of hydrogen storage and transportation, and all links involving safety in hydrogen energy applications. In addition, much attention should be paid to the safety of hydrogen production and its working personnel. It is proposed to set up institutions for the research, development, guidance, and supervision of hydrogen energy with specific provisions about their functions and powers as well as their operating procedures, and add provisions to guarantee the safety of the employees and their working environment in hydrogen energy industry by developing relevant supporting systems.

### 4.2. To accelerate the formulation and revision of the hydrogen energy safety standard system to provide support for industrial development

By comparing with the relevant EU regulations, it was found that the latter provide clear detailed requirements for the specifications in the same field. By contrast, in China's standard specifications, there are rarely such detailed requirements for technical indicators in the production process. As a result, they cannot standardise industry development. This also explains why, in China, industry standards used to account for the main proportion of hydrogen production standards in the past. Taking FCEVs as an example, Japan has established an advanced and complete standards system in the field of hydrogen energy for vehicles. In China, there is as much enthusiasm for the development of FCEV as in Japan, but there is no such completeness in the national mandatory standards related to FCEV safety, with some standards also lacking advancement.

It is proposed to continuously modify and improve the relevant safety standard system in China's hydrogen energy industry on the basis of systematic research in safety technology and learning from foreign advanced standards, so as to provide support for industrial development. Relevant businesses and enterprises should be encouraged to

participate in the formulation and revision of norms and standards for hydrogen energy. Systems should be established to monitor the industry, and safety inspection institutions should be established. In addition, it is necessary to explore an innovation-driven legal and regulatory standard system applicable to the development of new technologies and crafts, and the development of new business forms and models.

### 4.3. To strengthen basic research in hydrogen safety technology to provide intellectual support for industrial development

The research of hydrogen energy safety technology mainly focuses on the basic areas of fuel cell safety, hydrogen behavior, and material compatibility of hydrogen-related equipment. China should broaden the depth and breadth of research on the safety technology of the whole industry chain, with a focus on safety and reliability testing methods and certification of related equipment, materials, and components. At the same time, simulated analysis should be made about all accident scenarios in fuel cell safety, vehicle safety, and hydrogen storage tank safety application processes. It is proposed to give full play to the initiatives of local governments and enterprises, encourage qualified regions and enterprises to build hydrogen energy testing and research institutions, and gradually form a research system with the State Key Laboratory of Hydrogen Safety as the main body and the active participation of social science and technology forces.

In addition, it is proposed to strengthen technological research and development and cooperation among departments, promote the deep integration and penetration between all links of the industry chain, link up key 'materials-core components-integrated control-terminal applications', lower industry barriers, and strengthen the coordinated development of the entire industry chain.

### 4.4. To further clarify the safety supervision mechanism and promote the rapid development of the industry

It is proposed to clarify the competent authority of the hydrogen energy industry, establish a complete procedure of hydrogen energy infrastructure approval, construction, and acceptance; strengthen the main agents' safety risk awareness and safety supervision in the production, storage and transportation, refueling, and utilisation of hydrogen; and formulate feasible safety risk prevention and control measures, safety accident prevention mechanisms, and safety emergency response mechanisms. We should build a hydrogen energy operation monitoring system to implement real-time monitoring, analysis and early warning of hydrogen storage and transportation facilities and hydrogen refueling stations. The guiding policies and supporting laws and regulations should be issued at a faster rate to ensure that they play restraining and standardising roles.

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| **Nomenclature** | |
|---|---|
| **ANSI** | American National Standards Institute |
| **ASME** | The American Society of Mechanical Engineers |
| **CHEI** | China's Hydrogen Energy Industry |
| **CSA** | Canadian Standards Association |
| **CN-HB** | Industrial standards of the people's Republic of China |
| **FCV** | Fuel cell vehicles |
| **FCH2JU** | Fuel Cells and Hydrogen 2 Joint Undertaking |
| **GAQSIQ** | General Administration of Quality Supervision, Inspection and Quarantine of the people's Republic of China |
| **HETC** | Hydrogen Energy Technical Committee |
| **HySUT** | Hydrogen Supply and Applied Technology Research Association |
| **HyTReC** | Hydrogen Energy Test and Research Center |
| **HySAFER** | International Association for Hydrogen Safety |
| **HFCP** | Hydrogen and Fuel Cell Program |
| **IA-Hysafe** | International Association for Hydrogen Safety |
| **ISO** | International Organization for Standardization |
| **JIS** | Japanese Industrial Standards |
| **JISC** | Japanese Industrial Standards Committee |
| **NFPA2** | Technical specification for hydrogen energy |
| **PEMFC** | Proton Exchange Membrane Fuel Cell |
| **SAE** | Society of Automotive Engineers |
| **SAC** | Standardization Administration of China |
| **SCCC** | Standing Committee of the Chinese people's Congress |
| **USFA** | United States Fire Administration |
| **USCAR** | The United States Council for Automotive Research |

# Chapter 9

# Green Hydrogen Standard in China: Standard and Evaluation of Low-Carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen

Wei Liu, Yanming Wan , Yalin Xiong, and Pengbo Gao

With the proposal of carbon neutral goals in various countries, the deepening of global action on climate change and the acceleration of green economy recovery in the post epidemic era, building a low-carbon and clean hydrogen supply system has gradually become a global consensus. In order to promote the development of the clean hydrogen market, the standards of green hydrogen have been discussed worldwide. The quantitative definition of different hydrogen production methods based on the emission methods of life cycle greenhouse gases is gradually being recognised by the industry. China issued the 'Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen' in December 2020. This is the first formal green hydrogen standard worldwide, which provides calculation methods for greenhouse gases of different hydrogen production paths. This chapter discusses the major green hydrogen standards initiatives in the world, analyses the key factors of the global green hydrogen standards, and introduces how to establish the quantitative standards and evaluation system of low-carbon hydrogen, clean hydrogen, and renewable hydrogen by using the method in China.

**Keywords:** carbon neutral, green hydrogen standard, low-carbon hydrogen, clean hydrogen, renewable hydrogen, life cycle assessment

## 1. Introduction

In recent years, under the active promotion of major economies such as the European Union (EU), Japan, Republic of Korea, and China, hydrogen energy has gradually become the new international focus and has achieved rapid development. In 2020, 11 regions or countries including the EU, Germany, Spain, and Canada formulated hydrogen energy development strategies. By the end of 2020, 16 of the 27 countries, whose gross domestic product accounted for 52% of global gross domestic product, had drawn up comprehensive national hydrogen energy strategies, and 11 countries were still drafting their national hydrogen energy strategies (NEDO, 2015; Pivovar, Rustagi, and Satyapal, 2018; Alberto, 2020; Hydrogen Council, 2017; Li et al., 2020; Anika, Matej, and Doria, 2021). Many countries also formulated ambitious strategic goals for green hydrogen. For example, the EU plans to install 2x40 gigawatts (GW) of renewable hydrogen electrolytic tanks each of which is capable of producing 1,000 kilograms of renewable hydrogen annually by 2030 (FCH, 2019; Hydrogen Europe, 2020).

As the world’s second largest economy, China has formed a key driving force for controlling global climate and building a community with a shared future for mankind with the announcement of the carbon peak and carbon neutral goal vision: China will enhance its nationally self-determined contributions, adopt more powerful policies and measures, and strive to reach the peak of carbon dioxide emissions by 2030 with carbon neutrality achieved by 2060. In the same year, China issued the ‘Notice on Carrying out Fuel Cell Vehicle Demonstration Applications’ to encourage the use of low-carbon hydrogen and clean hydrogen (Ministry of Finance, 2020). As of the end of 2020, according to news reports in the mass media, about 28 renewable energy hydrogen production projects have been signed in China. China's vision of achieving carbon neutrality sends a clear signal to the world and injects new vitality into the global response to climate change and green recovery. The growing demand for low-carbon and clean hydrogen is expected to promote international hydrogen trade between hydrogen importers and exporters (White et al., 2021; Newborough and Cooley, 2020; Federal Government of Germany, 2020). It is well known that hydrogen is a secondary energy source. In fact, not all hydrogen is good for reducing carbon emissions. The prerequisite for promoting international hydrogen trade is to clarify hydrogen-related quality indicators, especially the origin of hydrogen. The precise definition of ‘hydrogen’ is crucial to the hydrogen trade. Hydrogen can be produced by a variety of processes and energy sources, including production from coal, production from natural gas, production from electrolysis of water, and so on (Grigoriev et al., 2020; IEA, 2019; Arnepalli and Tiwari, 2011; Olabi et al., 2020). For ease of description, the clean energy industry often classifies hydrogen by colour, such as grey hydrogen, blue hydrogen, and green hydrogen (Noussan et al., 2020; IRENA, 2019, 2020). However, the above classification method is difficult to distinguish all types of hydrogen production processes clearly and quantitatively, and even for the same hydrogen production process (such as hydrogen production by electrolysis of water), it is often difficult to define the product by one colour. Therefore, with the introduction of carbon neutrality targets in various countries, the quantitative definition of different hydrogen production methods based on life cycle greenhouse gas (GHG) emissions has gradually been recognised by the industry.

To facilitate the policymaking and trade of green hydrogen, relevant international standards are being discussed across governments, industries, and academia. Recently, the ‘Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen’ proposed by the China Hydrogen Alliance was officially issued (T/CAB 0078-2020). This is the first time in the world that carbon emissions of hydrogen have been quantified on the basis of official standards. This chapter explores how low-carbon hydrogen and green hydrogen has been defined and confirmed in China, providing experience and reference for other nations or organisations and laying a foundation for mutual recognition of international low carbon green standards.

## 2. Green Hydrogen Standard Initiatives Worldwide

It should be noted that hydrogen energy can only take a great leap by relying on a unified platform of global energy governance and worldwide market. Therefore, it is necessary to establish and improve the international standard system on hydrogen quality, with the calculation cost of carbon emissions, cross-border compatibility, and mutual recognition taken into account. The initiatives to develop green hydrogen can be found mostly in Europe, as shown in Table 9.1. Key factors were investigated by international standardisation agencies (e.g. CEN CLC JTC 6) and certification bodies, including the outcomes of certain projects and projects under consultation in the areas of energy and climate policy (e.g. EU CertifHy, L'Association Française pour l'Hydrogène et les Piles à Combustible (AFHYPAC), and the governments of California and the United Kingdom) (Abad and Dodds, 2020; Fuel Cells Bulletin, 2017; CEN/CENELEC, 2018).

In terms of these green hydrogen initiatives, there are four key points involved.

(1) The definition of green hydrogen. On the one hand, it refers to whether the hydrogen source must be limited to renewable energy; and on the other hand, it involves whether the definition of green hydrogen is based on the quantification of the life cycle GHG emissions or whether the definition is based on the qualification of hydrogen production technology and hydrogen source.

(2) System boundary. Based on the definition of quantification of life cycle GHG emissions, there are many options for carbon emission accounting boundaries, such as the point of production and the point of use.

(3) Baseline GHG threshold. Major countries choose hydrogen production carbon emissions (such as steam methane reforming, SMR) or well-to-wheel gasoline vehicle carbon emissions as the benchmark according to the system boundary and national conditions.

(4) Qualification level. According to the carbon reduction target or air pollution reduction target in national policies, GHG emissions are further quantified so that the green hydrocarbon emission threshold can be obtained.

**Table 9.1: Green Hydrogen Characterisation Initiatives Worldwide**

| Body (Country) | Main Policy Objective | Qualifying Technical Route | Baseline GHG Threshold | Qualification Level | System Boundary |
|---|---|---|---|---|---|
| CertifHy (EU wide) | Reduction of GHG emissions | Any technical route of hydrogen production from renewable energy with a threshold of 99.5% purity | GHG emissions from SMR of natural gas to hydrogen | A reduction of 60% GHG emissions compared to hydrogen produced using SMR (< 36.4gCO2eq/MJH2 ) | Point of production |
| AFHYPAC (France) | Deployment of Renewable energy | Any technical route of hydrogen production from renewable energy | None | Must be 100% renewable | Point of production |
| BEIS (United Kingdom) | Reduction of CO2 emissions | Technology Neutral) | Never determined | To be determined. | Point of production |
| California Low Carbon Fuel Standard | Reduction of GHG emissions. Third of vehicle hydrogen produced from renewable energy | Renewable electrolysis, catalytic cracking or SMR of biomethane or thermochemical conversion of biomass, including MSW | WTW emissions from new gasoline vehicles | 30% lower GHG and 50% lower NOX emissions for fuel cell vehicles | Point of use |
| CEN/CENELEC CLS JCT 6 (International) | Terminology, GO. interfaces, operational management, safety, training and education | Adopted from CertifHy | Adopted from CertifHy | Adopted from CertifHy | Point of production |

AFHYPAC = L'Association Française pour l'Hydrogène et les Piles à Combustible, BEIS = Department for Business, Industry & Industrial Strategy, CEN/CENELEC = European Committee for Standardization and the European Committee for Electrotechnical Standardization, EU = European Union, GHG = greenhouse gas, GO =guarantees of origin, MSW = municipal solid waste, SMR = steam methane reforming, WTW = well to wheel.
Source: Authors based on Abad and Dodds (2020).

### 2.1. Definition of Green Hydrogen

A set of approaches and criteria have been enforced to define green hydrogen, but it is not harmonised on the qualifying feedstock, renewable or not, and technological pathways. When it comes to grey or renewable hydrogen, the opinion is consistent, where grey hydrogen is typically understood as one produced from fossil fuel feedstock. However, in terms of renewable hydrogen from renewable sources, the case is different. Regarding green hydrogen, some initiatives such as AFHYPAC categorise it as the same as renewable hydrogen, while others such as CertifHy add more criteria, i.e. any renewable pathway meeting 99.5% purity threshold is considered as green hydrogen. However, several initiatives choose a more technology-neutral way, paying more attention to GHG emissions, thus emphasising the environment impact. For example, biomethane SMR can be accepted by the California Low Carbon Fuel Standard, and nuclear power by the UK Department for Business, Industry & Industrial Strategy, as long as the carbon emissions are sufficiently low.

With the intention of resolving disparities in different interpretations and improving applicability, the definition of hydrogen energy based on GHG intensity is gaining acceptance. The EU is developing an EU-wide framework involving the definition of a green hydrogen standard under the CertifHy project financed by the Fuel Cells and Hydrogen Joint Undertaking. An emissions threshold of 36.4 g $CO_{2eq}$/MJ $H_2$ on the point of production is proposed. When the threshold is met, hydrogen produced from renewables is defined as green hydrogen, while the counterpart forms non-renewables as low carbon hydrogen. In addition to categorising the hydrogen, carbon intensity based method, as a quantified measurement, enhances the interchangeability of hydrogen from different pathways or across different countries, when carbon related cost is considered.

However, it is conceivable that such a method requires more details of the hydrogen supply and consumption, and parameters should be set up, such as system boundary, emissions benchmarks, and reduction threshold, which brings more counting and regulation burdens.

### 2.2. System Boundary

Based on the principle of reducing GHG emissions, there are different system boundaries and accounting methods for low-carbon clean hydrogen. The system boundaries used in existing plans can be divided into two categories: the point of production and the point of use. From the perspective of the system boundary, the calculation of the 'factory point' does not require considering downstream emissions such as storage, transportation, loading and unloading, and supply, nor the fuel loss caused by fuel leakage, thus resulting in higher operability; the system boundary for the 'consumption point' calculation is much wider and can more accurately estimate the emissions of a specific route, although the management cost is high. In addition, the underlying basis for hydrogen purity, pressure, state, and carbon accounting standards are also different.

The EU CertifHy project is the longest-running project on guarantees of origin (GO) green hydrogen certification., and it has explored and launched the GO green hydrogen certification. The project is based on the life cycle carbon emission evaluation method. For the hydrogen products that leave the factory, the required purity is equal to or greater than 99.5% with the required pressure being equal to or greater than 30 Bar. If the requirements are not met, the carbon emissions during the purification or pressurisation process should be included.

The system boundary used in existing initiatives can be classified into two categories: the point of production and the point of use. The system boundary is of the hydrogen supply chain, whose components are involved in calculating GHG emissions. The point of use scheme, for example, the California Low Carbon Fuel Standard, covers the whole supply chain from production of feedstock to the delivery of hydrogen to the filling station, to the end customer. The point of production scheme excludes downstream emissions from storage, transportation, supply, and fuel losses due to boil-offs and leakages. Additionally, none of the schemes include emissions involved in constructing and decommissioning hydrogen production plants and other capital infrastructure.

The factors that have impact on both schemes include: (i) the feedstock and any land use changes, (ii) energy inputs (e.g. the electricity emission intensity), (iii) the efficiency of the selected production technologies, and (iv) any additional processes (e.g. compression, liquefaction) to bring the product to specification. In the point of use scheme, the downstream emissions are involved and depend on the type of end-use, such as heating, industrial processes, or transport modes.

### 2.3. Emissions Benchmark and/or Baseline GHG Threshold

The benchmark plays an important role in bridging the gap between the current and future energy structures, thus promoting energy transition. How to select emissions benchmarks is another issue that lacks consensus, since it is closely related to system boundary, hydrogen supply, and consumption structure. However, the hydrogen supply and consumption structure is not identical from case to case. When the system boundary is point of production, the selection of the benchmark depends on the hydrogen supply structure. For instance, steam methane reforming (SMR) is the dominating pathway of hydrogen supply in Europe, especially in the commercial hydrogen market, where the proportion of hydrogen produced by natural gas is more than 95%. As a result, the use of the carbon intensity of SMR as a benchmark, such as CertifHy, has been widely enforced in Europe. When the system boundary is point of end-use, the selection of the benchmark depends on the hydrogen consumption structure. The California Low Carbon Fuel Standard uses the well-to-wheel oil consumption intensity as a benchmark, since they pay more attention to the application of hydrogen energy in the transportation area.

### 2.4. Reduction Threshold and/or Qualification Level

Reduction threshold reflects ambition of policy objectives, although practicability must be considered. Reduction threshold and/or qualification level are directly related to the benchmark.

As mentioned earlier, the most representative SMR hydrogen production process with 91 $gCO_{2eq}/MJ_{H2}$ is used as the benchmark in Europe. CertifHy clarifies the green hydrogen carbon emissions intensity threshold as 36.4 g $CO_{2eq}$/MJ $H_2$, which is a reduction of 60% compared to hydrogen produced using SMR, according to the 2020 emissions reduction requirements in the EU Renewable Energy Act. As a result, hydrogen is divided into non-low-carbon hydrogen and low-carbon hydrogen. Non-low-carbon hydrogen is grey hydrogen, while low-carbon hydrogen includes both green hydrogen produced by renewable energy and non-renewable hydrogen produced by non-renewable energy.

In California, the Low Carbon Fuel Standard was adopted in 2009 to contribute to state GHG emissions reduction goals under the Global Warming Solutions Act of 2006. The program incentivises the adoption of low-carbon transportation fuels based on the fuel's lifecycle GHG emissions per unit of energy – or carbon intensity as rated by the programme. Hydrogen, as important low-carbon transportation fuel in medium and heavy duty vehicles, is included under the California standard. Senate Bill 1505 Environmental Standards has a requirement that 33% of hydrogen fuel must come from renewable sources, with an emissions reduction requirement of 30% reduction of GHG and 50% reduction of nitrogen oxide.

## 3. Green Hydrogen Standard in China

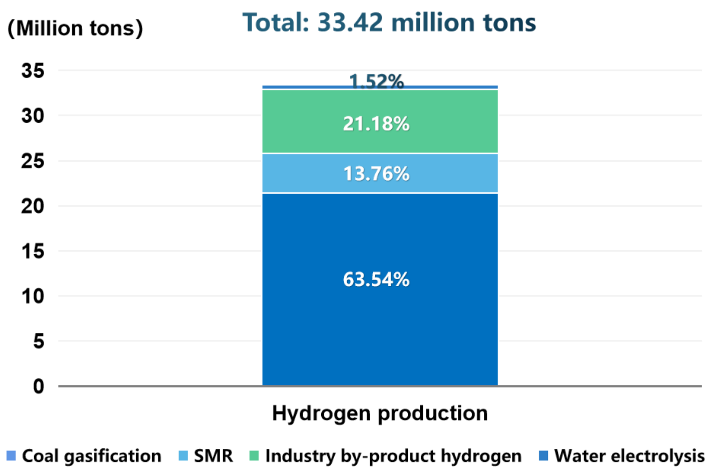
The discussion and practice of international green hydrogen standards have provided valuable experience for China's standard formulation. The formulation of China's green hydrogen standard should also be based on national conditions with international standards considered.

### 3.1. Status of Hydrogen Energy Production in China

To formulate national or regional green hydrogen standards, the first step is to define the hydrogen supply and consumption structure of the region or country. In the process of formulating China's green hydrogen standard, we followed such experience. The hydrogen supply and consumption structure in China has been investigated based on the statistics with analysis method. First, based on the statistics of the workload conditions of production enterprises in all industries, hydrogen from traditional industries was investigated. The scope of this study includes petrochemical, chemical, and coking industries, including intermediate hydrogen raw materials for refining, petrochemical, synthetic ammonia (nitrogen fertiliser), methanol, modern coal chemical industry, and chlor-alkali, as well as by-product hydrogen from the coking and semi-coking industries. In total, it accounts for more than 95% of the industry's total hydrogen production capacity. In addition, according to the sales of electrolytic cell equipment in China, the capacity of hydrogen production by water electrolysis is also estimated.

According to statistics from the China Hydrogen Alliance, China's current hydrogen production capacity is about 41 million tons annually, and the output is about 33.42 million tons (CHA, 2020a). In terms of the raw materials used for production, they mainly include fossil energy such as coal and natural gas, and industrial by-product gas. Coal to hydrogen production is the largest, reaching 21.24 million tons, annually accounting for 63.54%, followed by industrial by-product hydrogen and natural gas hydrogen production, with an annual output of 7.08 million tons (of which coking and semi-coking by-product gas is 6.04 million tons) and an annual output of 4.6 million tons, respectively. The output of hydrogen production by water electrolysis is only 500,000 tons annually.

**Figure 9.1: Hydrogen Production Structure in China**




SMR = steam methane reforming.
Source: CHA (2020a), authorized by CHA.

### 3.2. Baseline GHG Threshold in China

Through the above research results, it can be found that China's hydrogen supply structure is dominated by coal to hydrogen. Based on this actual situation, we choose the carbon emissions of hydrogen from coal as the benchmark. This section mainly uses actual case data in China as the accounting basis for calculating the carbon emissions from coal to hydrogen and the carbon emissions from coal to hydrogen with carbon capture and storage (CCS).

According to the process flow, the hydrogen production system is divided into three stages: the raw material acquisition stage, the raw material transportation stage, and the hydrogen production stage (Ren, Zhou, and Ou, 2020; Dufour et al., 2011). The system boundary is divided as shown in Figure 9.2. The description of the system and its boundary is as follows:

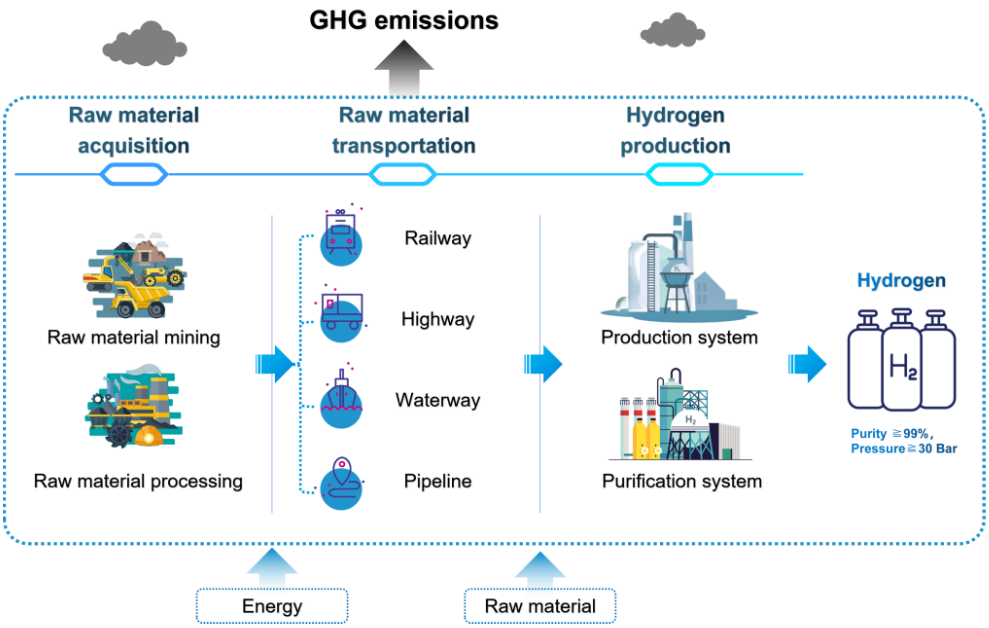
1) The system includes all links from raw material mining and transportation to hydrogen production.
2) In the system, raw materials include coal, natural gas, water, and methanol, and energy includes primary energy (coal, natural gas, diesel) and secondary energy (electricity).

3) The total material consumption of the system includes the material consumption in raw material extraction, transportation, and hydrogen production. The total energy consumption of the system includes the energy consumption corresponding to the material consumption and the energy consumption corresponding to the production process. The total greenhouse gas emissions of the system include the greenhouse gas emissions corresponding to the material consumption (GHG emissions from raw material production), GHG emissions during transportation, GHG emissions during production, and GHG emissions corresponding to energy consumption (GHG emissions corresponding to electricity consumption).

4) The GHG emissions from activities such as factory construction, equipment manufacturing, and transportation tool manufacturing are not considered.

5) The six GHGs specified in Appendix A of the Kyoto Protocol are: carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride ($SF_6$). The GHG produced in the hydrogen production process is mainly $CO_2$. In addition to $CO_2$, the GHGs produced in the process of hydrogen production and transportation also include $CH_4$ and $N_2O$. According to the Intergovernmental Panel on Climate Change's Fourth Assessment Report, 1 ton of $CH_4$ is equivalent to 25 tons of $CO_2$ in terms of 100-year global warming potential, so $GWP_{CH_4}$ = 25; 1 ton of $N_2O$ in the 100-year time scale is equivalent to 298 tons of $CO_2$, so $GWP_{N_2O}$ = 298.

**Figure 9.2: System Boundary of GHG Emissions in China**




GHG = greenhouse gas.
Source:CHA (2020b), authorized by CHA.

The GHG emissions per unit mass of hydrogen produced by the hydrogen production system (hereinafter referred to as the hydrogen production GHG emissions) is equal to the sum of the GHG emissions during the raw material acquisition stage, the raw material transportation stage, and the hydrogen production stage, which is calculated according to equation (1):

$$e = \frac{(E_1 + E_2 + E_3)}{AD_{H_2}} \times \vartheta \qquad (1)$$

where:

e —— GHG emissions from hydrogen production, in kilograms of carbon dioxide equivalent per kilogram of hydrogen ($kgCO_2e/kgH_2$)

$E_1$ —— GHG emissions during the raw material acquisition stage, in kilograms of carbon dioxide equivalent ($kgCO_2e$)

$E_2$ —— GHG emissions during the raw material transportation stage, in $kgCO_2e$

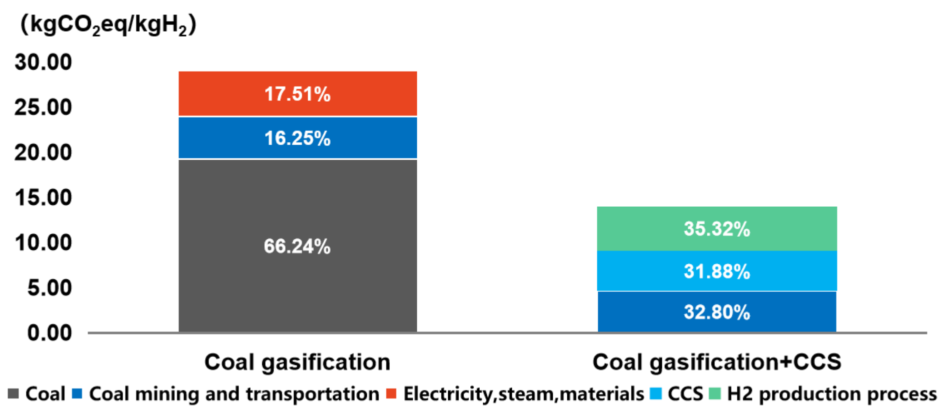
$E_3$ —— GHG emissions during the hydrogen production stage, in $kgCO_2e$

$\theta$ —— Distribution coefficient based on energy production method, that is, the ratio of the energy of product hydrogen to the total energy of product hydrogen and by-products, %

$AD_{H_2}$ —— The production volume of hydrogen within the accounting period, in kilograms (kg).

Figure 9.3 shows the GHG emissions of hydrogen production form coal gasification and hydrogen production form coal gasification with CCS. The corresponding hydrogen production GHG emissions are 29.02 $kgCO_2e/kgH_2$ and 13.99 $kgCO_2e/kgH_2$, respectively.

**Figure 9.3: Hydrogen Production Structure in China**



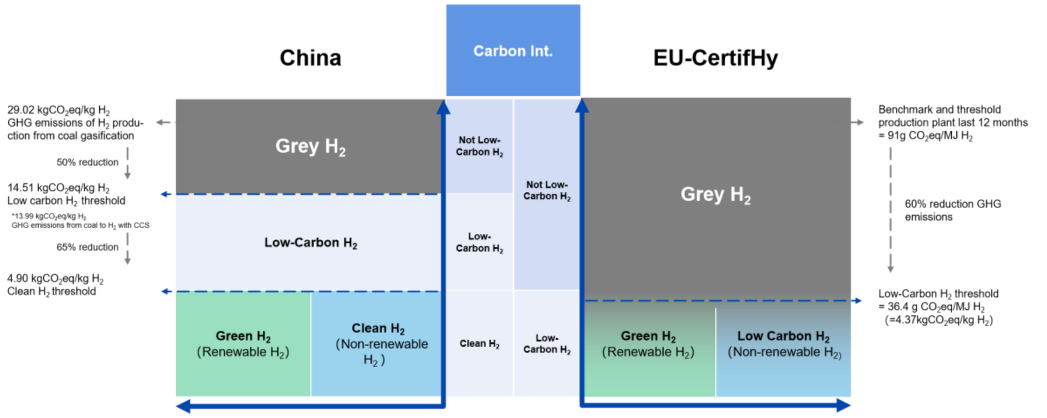

CCS = carbon capture and storage.
GHG emissions of $H_2$ production process include coal, electricity, steam, and other materials
Source: Authors.

### 3.3. Definition of Low-Carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen

In order to clarify the definitions and the quality criteria of hydrogen from different pathways or sources in China, the Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen*,* proposed by China Hydrogen Alliance, was implemented on 29 December 2020. This standard uses the life cycle assessment method to establish the quantitative evaluation system of low-carbon hydrogen, clean hydrogen, and renewable hydrogen, and promotes the sustainable development of a hydrogen energy industry chain from the source. For the first time in the world, carbon emissions of hydrogen have been quantified in an official standard.

The proposed standard is in line with the CertifHy project in Europe in methodology. Specifically, the 'point of production' scheme is adopted to reduce the calculation and administrative cost, the same as in CertifHy. However, the selection of benchmark and threshold varies with the current status of hydrogen supply and development needs in China being considered. The standard proposed two thresholds to categorise the GHG emissions of hydrogen into three intervals, instead of one threshold and two intervals as in CertifHy. This is mainly on account of the current situation of China's carbon emissions levels. In order to make a smooth transition of China's carbon reduction mission, the standard puts forward two thresholds: low-carbon hydrogen threshold and clean hydrogen threshold. The low-carbon hydrogen benchmark is based on the GHG emissions of hydrogen production from coal gasification, which is 29.02 $kgCO_2eq/kgH_2$. According to the carbon reduction requirement of 50% in the 'National Plan For Tackling Climate Change 2014–2020', the low-carbon hydrogen threshold is set at 14.51 $kgCO_2eq/kgH_2$, which is reduced by 50% compared with hydrogen production from coal gasification. The clean hydrogen benchmark is 13.99 $kgCO_2eq/kgH_2$, which is the GHG emissions of hydrogen production from coal gasification with CCS. According to the carbon reduction demand of 65% in 'Energy Supply and Consumption Revolution Strategy 2016–2030', the clean hydrogen threshold is set at 4.90 $kgCO_2eq/kgH_2$, which is reduced by 65% compared with hydrogen production from coal gasification with CCS. In addition, it should be pointed out that the renewable hydrogen in the standard is equivalent to green hydrogen, which means the GHG emissions threshold is lower than 4.90 $kgCO_2eq/kgH_2$, at the same time, raw materials for hydrogen production are derived from renewable energy sources. The threshold of clean hydrogen or renewable hydrogen aligns with the threshold in the low carbon hydrogen or green hydrogen in CertifHy. The comparison between CertifHy and the proposed standard is shown in Figure 9.4.

**Figure 9.4: The Comparison Between CertifHy and the Proposed Standard in China**




EU = European Union.

Sources: Authors based on CHA (2020b) and CertifHy.

The utilisation of two thresholds and three intervals is based on the actual situation in China, and is both creative and practical. This is because hydrogen mainly comes from coal with higher carbon emissions in China than in Europe. The median threshold in the initial stage is conducive to guiding the transition from high-carbon hydrogen production to low-carbon hydrogen production, such as CCS technology and renewable energy electrolysis of water, and realise the clean and low-carbon transformation of the hydrogen energy industry and the energy industry.

### 4. Qualification Assessment

In the standard, a qualification assessment process is also presented from which the producer can be given certification that it is qualified to produce certain kinds of hydrogen. There are several main steps in the whole governing process of certification. The first step is the certification application where the applicant needs to file a formal application to the regulating body, and prepare related documents, including the hydrogen production flow chart of the applicant unit, main equipment, hydrogen production life cycle assessment report, production raw materials list, and main energy types and sources. The second step is document verification and on-site verification, where the regulating body reviews the documents submitted above and checks the authenticity of the production appliances to confirm whether the applicant meets the requirements of low-carbon hydrogen and clean hydrogen or renewable hydrogen. After the verification, the regulating body will issue an evaluation conclusion and file it on the service platform. Once the application is approved, the producer gets the respective certification and could give the hydrogen it produces with a corresponding label. Then, the hydrogen and its certification label could be traded, together or separately.

## 5. Conclusion and Recommendations

Building a clean and beautiful world requires down-to-earth action. Low-carbon and clean hydrogen energy will bring more space and opportunities for cooperation between countries. Promoting the formulation of a global low-carbon clean hydrogen standard as soon as possible will lay the foundation for cooperation in international hydrogen trade. Different organisations have put forward different initiatives related to green hydrogen energy. The European Union and China proposed their own green hydrogen standards based on the steam methane reforming hydrogen production process and the coal gasification hydrogen production process, which fully embodies the system thinking of 'harmonious but different' – carbon emissions calculation method, hydrogen quality, and the system boundary are consistent, but the local mainstream hydrogen production processes and carbon neutrality goals are fully respected, further accelerating the pace of unifying the global low-carbon clean hydrogen indicators.

In the future, China should undertake more work around the standard. The first is to strengthen policy support and start the basic capacity building of the low-carbon clean hydrogen market. The second is to carry out mutual recognition of indicators with Europe, Japan, Australia, and other countries to promote the global unification of green hydrogen standards and facilitate international hydrogen trade.

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# Chapter 10

# Curtailed Electricity Surplus from Renewables for Hydrogen: Economic and Environmental Analysis

Youngho Chang[13] and Han Phoumin[14]

This study examines how well producing hydrogen via electrolysis from curtailed electricity from renewables could fulfil environmental benefits against the cost of producing hydrogen via electrolysis in the context of the Association of Southeast Asian Nations (ASEAN) and the East Asia Summit (EAS). The cost of producing hydrogen via electrolysis ranges from less than US$2 per kg$H_2$ when the electrolyser load factor is 1,500 hours or above to US$10 per kg$H_2$ or even higher when the electrolyser load factor is 500 hours or lower. The amount of $CO_2$ emissions abated by hydrogen produced from curtailed electricity from renewables ranges from about 130 million tonnes to about 150 million tonnes for ASEAN and from about 18,000 million tonnes to about 19,000 million tonnes for EAS. Applying prevailing carbon prices to the $CO_2$ emissions abated, the possible monetised benefits of hydrogen produced via electrolysis from curtailed electricity from renewables range from about US$0.25 per kg$H_2$ to about US$9.00 per kg $H_2$ for ASEAN and from about US$0.50 per kg$H_2$ to about US$15.00 per kg $H_2$ for EAS. The results of the cost-benefit analysis suggest that the price of carbon needs to be about US$10 per tonne of $CO_2$ to justify hydrogen produced via electrolysis from curtailed electricity from renewables for both ASEAN and EAS. The results also suggest that high electrolyser load factors make hydrogen produced via electrolysis from curtailed electricity from renewables cost-competitive even under low carbon prices.

**Keywords**: Hydrogen, Curtailed electricity, Cost-benefit analysis, Carbon price, Electrolyser load factor, $CO_2$ emissions; ASEAN; EAS.

## 1. Introduction

Hydrogen can be a reliable source of energy provided a dependable supply at a reasonable price. Hydrogen is not found in nature and is classified as, grey (or brown), blue, and green depending on how it is produced.

The two methods to produce hydrogen are reformation, as with natural gas, and electrolysis. The former is still based on fossil fuels, making it not a sustainable solution. The latter can be sustainable if a reliable and environmentally friendly source of electricity is secured. Electricity generated from fossil fuels may not be desirable for electrolysis in the long term, but electricity generated from renewable sources could be desirable.

There are currently various methods of large-scale hydrogen production, namely steam reforming with carbon capture sequestration (CCS), alkaline electrolyser with stable or

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fluctuating power, lignite gasification and woody biomass generation (IEA, 2019). Steam reforming with CCS presents the lowest cost followed by lignite gasification with CCS and woody biomass gasification. The cost of alkaline electrolyser with stable power is almost three times that of steam reforming with CCS, while alkaline electrolyser with fluctuating power costs almost six times of that of steaming reforming with CCS. For the alkaline electrolyser, feed cost is the main source of the high cost and followed by CAPEX and OPEX (IEA, 2019).

When electricity generated from renewable sources does not have corresponding demand, it causes negative net load. Net load is defined as the difference between forecasted load and expected electricity production from variable generation sources. The load structure of a typical spring day in California shows there are four typical ramping possibilities, namely at 4:00 a.m., 7:00 a.m., 4:00 p.m. and after sunset (or around 6:00 p.m.). The 4:00 p.m. possibility is the most significant daily ramp (CAIS), 2017).

Curtailing renewables is one way of solving the oversupply problem, despite electricity being wasted (CAISO, 2017). To utilise this opportunity is using cheap or free ‘otherwise curtailed’ electricity (IRENA, 2019).

One of the ways to mitigate oversupply is to increase demand; in other words, to offer consumers time-of-use rates, to increase energy storage, and to increase the ability of power plants to respond more quickly to changes in generation levels. The inherent variability of renewables such as wind or solar is an impediment to their effective use. Hydrogen fuel and electric power generation could be integrated at a wind farm. This allows flexibility of shifting production to best match resource availability given system operational needs and market factors. In times of excess electricity production from wind farms (i.e., the Belly of the Duck curve), instead of curtailing the electricity as is commonly done, this excess electricity can be utilised to produce hydrogen through electrolysis.

This study evaluates whether curtailed electricity from renewables, in the context of the Association of Southeast Asian Nations (ASEAN) and the East Asia Summit (EAS), can be used to produce hydrogen and how well it could serve these objectives in terms of economic and environmental perspectives. It estimates how much hydrogen is to be produced from curtailed electricity from variable renewables in the ASEAN and EAS regions.

The hydrogen produced would replace fossil fuels and, hence, reduce $CO_2$ emissions in the region. The amount of $CO_2$ emissions abated is treated as possible environmental benefits to be monetised by applying a prevailing carbon price in the US, the European Union (EU), or Singapore to the amount of emissions abated per unit of hydrogen produced from utilising curtailed electricity generated from renewables. This study surveys the cost of producing hydrogen through electrolysis in the literature and adopts a few estimates to examine the monetised environmental benefit against the cost of producing hydrogen via electrolysis.

There seems to be no study that applies a cost-benefit analysis to curtailed electricity for producing hydrogen against possible monetised benefits accrued from abated carbon dioxide emissions due to the produced hydrogen replacing fossil fuels. A few studies present the cost of producing hydrogen (Proost, 2019 and IEA, 2019), but there are no extensions to compare the cost of producing hydrogen from curtailed electricity to possible monetised benefits from abated carbon dioxide emissions. Such a novel application of a cost-benefit analysis is to be the contribution of this study to the literature.

The rest of this study is structured as follows. Section 2 reviews the types of hydrogen production, various cost estimates of hydrogen production from variable renewables, and environmental implications of hydrogen production from variable renewables via electrolysis. Section 3 presents details of methodology applied in the study such as the cost estimation of producing hydrogen from curtailed electricity from variable renewables via electrolysis, the benefit estimation of producing hydrogen from curtailed electricity from renewables via electrolysis in the ASEAN and EAS regions, and estimates of carbon prices. Section 4 discusses results and draws policy implications based on the results of the cost-benefit analysis conducted. Section 5 concludes this study.

## 2. Hydrogen: Variable Renewables and Environmental Implications

### 2.1. Hydrogen and Variable Renewables

There are three types of hydrogen by production methods: grey or brown, blue, and green hydrogen. Grey hydrogen is typically produced in a process called steam methane reformation, while brown hydrogen is produced from the coal (or ignite) gasification. Blue hydrogen is produced mainly from natural gas but with CCS technology. Green hydrogen is produced by a process called electrolysis in which a unit called an electrolyser that is powered splits water into hydrogen and oxygen using non-carbon-emitting electricity (DNV GL, 2020). Electrolysers can assume various sizes, such as a small, appliance-size piece of equipment to a large-scale, central production facility. The former is good for small-scale distributed hydrogen production, while the latter is good for an electricity grid that is directly linked to renewable or non-carbon-emitting electricity generation technology (US Department of Energy, n.d.).

Apart from the types of hydrogen by production methods, there are various methods of large-scale hydrogen production, namely steam reforming with CCS, alkaline electrolysers with stable or fluctuating power, lignite gasification, and woody biomass generation (IEA, 2019). Steam reforming with CCS presents the lowest cost, followed by lignite gasification with CCS and woody biomass gasification. The cost of alkaline electrolysers with stable power is almost three times that of steam reforming with CCS, while using alkaline electrolysers with fluctuating power costs almost six times that of steaming reforming with CCS. For the alkaline electrolyser, feed is the main source of the high cost, followed by capital and operation expenditure (IEA, 2019). For making electrolysis a viable source of hydrogen, it is critical to reduce the capital cost of the electrolyser unit and the balance of the system, and to improve energy efficiency for converting electricity to hydrogen. Cost is the key determinant for the wide adoption of electrolysers. However, electrolysis could be a promising option for hydrogen production where renewable resources are used as the sources of electricity.

Hydrogen can play two key roles in the global economy, namely as a booster that accelerates more usage of renewable electricity and a channel that helps the global economy decarbonise. First, hydrogen can boost renewable energy by functioning as storage and a reliable source of cleaner energy. Second, hydrogen production via electrolysis can lead to zero carbon dioxide emissions depending on how electricity is generated, which could present a pathway to a net zero future. Green hydrogen has huge implications for storing energy generated from renewables such as wind and solar energy. Green hydrogen has been active in a few states in the US, such as California and Utah (Mitsubishi Heavy Industries, 2020). Considering the sheer volumes of decarbonising needed in the electricity sector, however, green hydrogen is not expected to be fully utilised in the near future. As a result, blue hydrogen must be fully developed and utilised before green hydrogen works at full scale (Dickel, 2020).

Hydrogen has been cost-competitive and hailed as a low-carbon option. The Hydrogen Council pegs the 2020 cost of producing hydrogen via electrolysis from dedicated offshore wind in Europe to be on average US$6/kg$H_2$; it projects the cost to be US$2.6/kg$H_2$ in 2030. The breakdown of the drop in the cost is as follows: decreases in the capital cost (US$2.6), improvement in efficiency (US$0.4), decreases in the operations and maintenance cost (US$0.2), and decreases in the levelised cost of electricity of offshore wind (US$1.3) (Hydrogen Council, 2020).

Table 10.1 presents the estimated costs of producing hydrogen by various sources in the EU.

**Table 10.1: Estimates of Hydrogen Production Costs in the European Union**

| Types of Hydrogen | Costs (EUR/kg$H_2$) | Costs (EUR/MWh) |
|---|---|---|
| Grey (Fossil Fuel Hydrogen) | 1.5 | 44.9 |
| Blue (Low-Carbon Hydrogen) | 2.0 | 59.9 |
| Green (Clean Hydrogen) | 2.5 – 5.5 | 74.9 – 164.7 |

Source: Authors' compilation of data from Barnes and Yafimava (2020), Lambert (2020).

Compared to grey hydrogen, green hydrogen is still more expensive, as shown in Table 10.1. Green hydrogen in the EU is expected to cost-competitive by 2030, but it depends on not only the capital cost of electrolysers but also the electrolyser load factors, along with the cost of electricity from renewable sources (Barnes and Yafimava, 2020).

Hydrogen fuel can be integrated with electric power generation at the site of variable renewables, such as a wind farm. This allows production to be shifted to best match resource availability under system operational needs and market factors. When excess electricity is produced, it is possible to use it to produce hydrogen through electrolysis rather than curtailing it (US Department of Energy, n.d.).

The source of the required electricity has become critical in determining the benefits and economic viability of producing hydrogen via electrolysis. This includes the cost and efficiency of the electrolysis along with the amount of emissions coming from electricity generation. The current power grid of most countries is not suitable for providing the electricity needed to run the electrolysis sustainably because carbon dioxide and other greenhouse gases are released as long as fossil fuels are used. When hydrogen is produced via electrolysis with renewable sources from the grid or separate from the grid, such pathways will lead to virtually zero emissions of carbon dioxide and other greenhouse gases.

The pathway to hydrogen competitiveness requires developing more efficient fossil fuel-based electricity production with CCS as a short-term goal and decreasing the cost of generating electricity from renewable sources as a long-term goal. Using curtailed electricity to produce hydrogen via electrolysis is a solution to meet the long-term goal.

The Hydrogen Council identified seven roles hydrogen can play in providing the sustainable pathway to the transformation of energy sector in the global economy. First, it enables large-scale renewable energy to be integrated in power generation. Second, it helps energy be distributed across sectors and regions. Third, it spurs energy system resilience. Fourth, it decarbonises transportation. Fifth, it decarbonises industrial energy use. Sixth, it promotes the decarbonisation of heat and power in the building sector. Seventh, it provides clean feedstock for industry (Hydrogen Council, 2017). Hydrogen works as an energy carrier and storage facility in energy transition (DNV GL, 2018). Hydrogen is expected to be a transformative role in energy transition as a catalyst to decarbonise natural gas and accelerate uptake of CCS in producing blue hydrogen (DNV, 2020). Solar photovoltaic and wind energy are expected to dominate in power generation and capture 62% of variable renewable share by 2050. Natural gas is expected to be the largest energy source in this decade and remain as the dominant source until 2050. These confirm the place of hydrogen in energy transition and the status of hydrogen in the energy system (DNV, 2020).

### 2.2. Hydrogen and Environmental Implications

Apart from helping the energy transition of the global economy, hydrogen is suggested as a key factor in the global economy to meet the temperature target set by the Paris Agreement (DNV, 2020). As mentioned in section 2.1, hydrogen can bring environmental benefits in providing a sustainable pathway to the transformation of energy sector in the global economy. First, hydrogen enables large-scale renewable energy to integrate in power generation so that it helps the global economy abate carbon dioxide emissions by displacing fossil fuels in power generation. Second, hydrogen helps decarbonises transportation, industrial energy use and heat and power in the building sector so that it displaces carbon-emitting fuels in sectors like transportation, industry, and the building sector (Hydrogen Council, 2017).

The variable nature of renewable energy sources causes surplus in electricity supply at certain times and makes wasting the excess supply inevitable (CAISO, 2017; IRENA, 2019). The production of hydrogen from curtailed electricity via electrolysis is expected to replace power generation from fossil fuels with renewable energy and hence reduce carbon dioxide emissions. Compared to the baseline case, the amount of carbon emissions in ASEAN countries can be reduced from 28% to 64% following the rates of fossil fuels replaced (Phoumin et al., 2021).

There are many studies on how hydrogen will help the global transition to a non-carbon emission economy with good cost estimates of hydrogen production via electrolysis. Along with cost studies, there are a few studies that present how hydrogen produced from variable renewables can help reduce carbon dioxide emissions. However, whether the expected reduction in carbon emissions by producing hydrogen via electrolysis from variable renewables is cost-effective against the accrued environmental benefits is not extensively studied.

Hydrogen produced from curtailed electricity from variable renewables abates carbon dioxide emissions, which can be monetised by a carbon price. By utilising a cost-benefit analysis, this study examines the cost-effectiveness of producing hydrogen from curtailed electricity from variable renewables via electrolysis and takes the ASEAN hydrogen study (Phoumin et al., 2021) and extends it to the EAS region as a basis for estimating environmental benefits. Such an analytical framework can be applied to other regions provided a similar hydrogen production study exists. This would give at least some indication of the cost-competitiveness of producing hydrogen from curtailed electricity via electrolysis.

## 3. Methodology

The costs for using curtailed electricity from renewables for producing hydrogen are estimated using itemised cost inputs such as capitalisation expense (CAPEX), operating expense (OPEX), and feed cost, while the estimation of benefits is done by expected abatement of carbon dioxide emissions due to reduced usage of fossil fuels in the energy mix. The expected abatement of carbon dioxide emissions is monetised by applying current prices of carbon in the US, the EU or Singapore to the abated amount.

The cost-benefit analysis constructs a few scenarios with different costs of producing hydrogen via electrolysis in the market and discusses how carbon prices affect using the curtailed electricity surplus from renewables for producing hydrogen.

### 3.1. Cost Estimates of Producing Hydrogen from Curtailed Electricity via Electrolysis

There are various technical and economic factors in determining the cost of producing hydrogen via electrolysis. The electrolyser stack bears 50% and 60% of the CAPEX costs of alkaline and polymer electrolyte membranes, respectively. The power electronics, gas-conditioning, and plant components bear most of the rest of the costs. Apart from these factors, conversion efficiency, electricity costs, and annual OPEX are other key factors (IEA, 2019).

With more load hours of operation, the impact of CAPEX on the costs decreases but the electricity becomes the key cost component. For example, with CAPEX of US$450/kWe and a zero cost of electricity, the levelled cost of hydrogen could be about US$5/kg$H_2$ to less than US$1/kg$H_2$ over full load hours (IEA, 2019). This illustrates how the curtailed electricity from renewable can be a competitive way of producing hydrogen.

Running the electrolyser at high full load hours and paying for the additional electricity can actually be cheaper than just relying on surplus electricity with low full load hours. The relationship between electricity costs and operating hours becomes apparent when looking at electrolysers that use grid electricity for hydrogen production (IEA, 2019). Very low cost electricity is generally available only for a few hours within a year, which implies a low utilisation of the electrolyser and high hydrogen costs that reflect CAPEX costs. With increasing hours, electricity costs increase, but the higher utilisation of the electrolyser leads to a decline in the cost of producing a unit of hydrogen up to an optimum level at around 3,000 to 6,000 equivalent full load hours. Beyond that, higher electricity prices during peak hours lead to an increase in hydrogen unit production costs. With all these considerations, IEA (2019) asserts that 'in the near term, hydrogen production from fossil fuels will remain the most cost-competitive option in most cases.' This study aims to show producing hydrogen using curtailed electricity from renewables is a good alternative to fossil fuel-based hydrogen production.

A detailed economic assessment by the IEA, based on hourly solar and wind data over a year in five locations across different provinces, suggests hydrogen can be produced at a cost of US$ 2–2.3/kgH2. In some provinces, the lowest production costs are reached by using only solar (Qinghai) or wind (Hebei and Fujian), while in Xinjiang and Tibet performance is best with a combination of the two (IEA, 2019).

IEA (2019) has provided various cost estimates for producing hydrogen by electrolysis. As this study uses curtailed electricity for producing hydrogen, it assumed the cost of electricity is zero. The electrolyser load factor is the key determinant of the cost of producing hydrogen. If the electrolyser load factor is about 1,500 hours or higher, then the production cost could be less than US$2/kg$H_2$. If the electrolyser load factor is about 1,000 hours, then the cost could be US$2/kg$H_2$. If the electrolyser load factor becomes very low such as about 500 hours, then the cost could be higher than US$10/kg$H_2$ (Proost, 2019).

This study takes two scenarios of cost estimates following two most plausible cases of the electrolyser load factor, namely 1,000 hours and 1,500 hours. The corresponding cost estimate is US$2/kg$H_2$ and US$1/kg$H_2$, respectively. Table 10.2 presents the cost estimates of producing hydrogen from curtailed electricity from variable renewables via electrolysis that this study adopts.

**Table 10.2: Cost Estimates of Hydrogen Production by Electrolysis Load Factors**

| Electrolyser Load Factors (hours) | Costs (US$/kg$H_2$) |
|---|---|
| 1,500 | 1 |
| 1,000 | 2 |

Source: Authors' compilation of data from Proost (2019), IEA (2019).

With more load hours of operation, the impact of CAPEX on the costs decreases but the electricity becomes the key cost component. This illustrates how the curtailed electricity from renewables can be the case of a competitive way of producing hydrogen. Running the electrolyser at high full load hours and paying for the additional electricity can actually be cheaper than just relying on surplus electricity with low full load hours.

### 3.2. Estimation of Benefits from Producing Hydrogen from Curtailed Electricity in ASEAN

The power generation mix in ASEAN is estimated for business-as-usual (BAU) and various scenarios based on renewables-shares in the energy mix using the countries' energy models by applying the Long-range Energy Alternative Planning System (LEAP) software, an accounting system to project energy balance tables based on final energy consumption and energy input and/or output in the transformation sector. Final energy consumption is forecast using energy demand equations by energy and sector and future macroeconomic assumptions.

The expected reduction of carbon dioxide emissions is monetised by current carbon prices in the US, the EU, or Singapore. This study takes hydrogen production from curtailed electricity in the ASEAN and EAS regions as the basis of calculating the possible amount of the emissions of carbon dioxide abated. Applying the LEAP software to ASEAN, Phoumin et al. (2021) presented various estimates of how much hydrogen can be produced from curtailed electricity. This study also estimates how much hydrogen will be produced from curtailed electricity by extending the ASEAN study to the EAS region. Section 3.3. presents details of how much hydrogen will be produced from curtailed electricity in the EAS region.

The study constructs scenarios of how much renewables would replace total combined fossil fuel generation, i.e. by 10%, 20%, and 30% by 2050 and labels them Scenario1 for 10% replacement, Scenario2 for 20% replacement and Scenario3 for 30% replacement. Each scenario further assumes the rate of curtailed electricity is utilised to produce hydrogen, namely at 20% to 30%. Following these assumptions, the three scenarios are renamed Scenario1$H_2$, Scenario2$H_2$, and Scenario3$H_2$.

The formulas to calculate potential hydrogen production in the renewable scenarios are as follows:

Scenario1$H_2$ (Mt-$H_2$) = [Scenario1 (TWh) x (Percentage of curtailed electricity) / 48 (TWh)]

Scenario2$H_2$ (Mt-$H_2$) = [Scenario2 (TWh) x (Percentage of curtailed electricity) / 48 (TWh)]

Scenario3$H_2$ (Mt-$H_2$) = [Scenario3 (TWh) x (Percentage of curtailed electricity) / 48 (TWh)]

Mt-$H_2$ stands for million tonnes of hydrogen; TWh is terawatt-hour; the percentage of curtailed electricity is 20% or 30% of total generation from renewables. The study also applies the conversion factor of 48 kilowatt-hours (kWh) of electricity needed to produce 1 kg $H_2$ (ISES, 2020).

The potential emissions abatement is the difference between the BAU scenario and various renewable-share scenarios such as Scenario1, Scenario2, and Scenario3. Table 10.3 shows the amount of hydrogen produced from curtailed electricity by various replacement scenarios in ASEAN.

**Table 10.3: Hydrogen Produced from Curtailed Electricity in ASEAN**

(unit: million tonnes)

| | **Scenario1$H_2$** | **Scenario2$H_2$** | **Scenario3$H_2$** |
|---|---|---|---|
| Of 20% curtailed renewables | 4.23 | 5.10 | 5.97 |
| Of 30% curtailed renewables | 6.35 | 7.65 | 8.96 |

ASEAN = Association of Southeast Asian Nations.

Source: Authors' compilation of data from Phoumin et al. (2021).

Table 10.4 presents the amount of carbon dioxide emissions that can be abated by different renewables replacement scenarios in 2050 in ASEAN. The amount of carbon dioxide emissions abated ranges from about 650 million tonnes to around 800 million tonnes.

**Table 10.4: Emissions Reduction by Scenarios in 2050 in ASEAN**

(unit: million tonnes)

| | **Baseline (2017)** | **Emissions in 2050** | **Abatement in 2050** |
|---|---|---|---|
| BAU | 376 | 1,216 | - |
| Scenario1 | 376 | 568 | 648 |
| Scenario2 | 376 | 506 | 710 |
| Scenario3 | 376 | 442 | 774 |

ASEAN = Association of Southeast Asian Nations, BAU = business as usual.
Source: Authors' compilation of data from Phoumin et al. (2021).

### 3.3. Estimation of Benefits from Producing Hydrogen from Curtailed Electricity in EAS

The potential of renewable hydrogen produced using curtailed electricity in Scenario1, Scenario2, and Scenario3 is quantified according to a renewable curtailment rate of 20%–30% for the high share of renewables in 2050 in EAS. Emissions abatement, i.e. the difference between BAU and various scenarios such as Scenario1, Scenario2, and Scenario3, is calculated. The higher share of renewables under Scenario1, Scenario2, and Scenario3 could only happen if hydrogen is developed as energy storage by utilising curtailed renewable electricity. Utilising unused electricity and/or curtailed renewable electricity to produce hydrogen could be ideal to tap the maximum potential of renewables.

The higher share of renewables under various scenarios such as Scenario1, Scenario2, and Scenario3 will see a large reduction in carbon dioxide emissions, which could result in decarbonising emissions and contribute to Conference of the Parties (COP) commitments. The potential emissions abatement is the difference between the BAU scenario and various renewable-share scenarios such as Senario1, Scenario2, and Scenario3. Table 10.5 shows the amount of hydrogen produced from curtailed electricity by various replacement scenarios in EAS.

**Table 10.5: Hydrogen Produced from Curtailed Electricity in EAS**

(unit: million tonnes)

| | Scenario1 $H_2$ | Scenario2 $H_2$ | Scenario3 $H_2$ |
|---|---|---|---|
| Of 20% curtailed renewables | 72 | 76 | 80 |
| Of 30% curtailed renewables | 108 | 114 | 119 |

EAS = East Asia Summit.

Source: Authors' calculation.

Table 10.6 presents the amount of carbon dioxide emissions that can be abated by different renewable replacement scenarios in 2050 in EAS. Potential emissions abatement is 18,059 million tonnes-carbon (Mt-C), 18,527 Mt-C, and 18,994 Mt-C in Scenario1, Scenario2, and Scenario3, respectively.

**Table 10.6: Emissions Reduction by Scenarios in 2050 in EAS**

(unit: million tonnes)

| | Baseline (2017) | Emissions in 2050 | Abatement in 2050 |
|---|---|---|---|
| BAU | 18,623 | 22,266 | - |
| Scenario1 | 18,623 | 4,207 | 18,059 |
| Scenario2 | 18,623 | 3,739 | 18,527 |
| Scenario3 | 18,623 | 3,272 | 18,994 |

BAU = business as usual, EAS = East Asia Summit.

Source: Authors' calculations.

### 3.4. Carbon Prices

This study constructs a few cases with different hydrogen prices in the market. It adopts three carbon prices, namely, the Regional Greenhouse Gas Initiative (RGGI), European Union Emissions Trading System (EUETS) and a carbon tax in Singapore. For both RGGI and EUETS, the lowest and the highest carbon price are adopted. For the carbon price in Singapore, the current carbon tax is adopted (SGD5 per tonne of $CO_2$). Table 10.7 presents various carbon prices used in the calculation of potential benefits of producing hydrogen from curtailed electricity via abating the emissions of carbon dioxide.

**Table 10.7: Carbon Prices**

(unit: US$/tonne-$CO_2$)

| | Carbon Price/Tax | Carbon Price/Tax (US$) | Remarks |
|---|---|---|---|
| RGGI (the highest) | 7.6 | 7.6 | |
| RGGI (the lowest) | 2.05 | 2.05 | |
| EUETS (the highest) | 49.88 | 60.15 | @1.2059 |
| EUETS (the lowest) | 2.59 | 3.40 | @1.3113 |
| Singapore | 5 | 3.77 | @0.755 |

EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.

Source: Authors' compilation of data from RGGI (2009, 2021), Investing.com (2021), National Environmental Agency (2021).

## 4. Results, Discussions, and Policy Implications

This study carries out a cost-benefit analysis of using curtailed electricity from renewables to produce hydrogen. The costs of this are compared to the possible monetised benefits accrued from the amount of the emissions of carbon dioxide abated due to reduced usage of fossil fuels in energy mix.

### 4.1. Results

#### 4.1.1. ASEAN

Table 10.8 shows the amount of hydrogen produced from curtailed electricity under 20% curtailed renewables by different scenarios in the second row and the amount of the emissions carbon dioxide abated by different scenarios in the third row. The fourth row presents the amount of carbon dioxide abated per the unit amount of hydrogen produced from curtailed electricity from variable renewables via electrolysis. This is considered environmental benefits and the benefits are monetised by multiplying by carbon prices. In sum, Table 10.8 presents the possible amount of carbon dioxide abated per hydrogen produced in 2050.

**Table 10.8: Possible Amounts of $CO_2$ Abated per $H_2$ Production in 2050**

(unit: million tonnes)

| | Scenario1$H_2$ | Scenario2$H_2$ | Scenario3$H_2$ |
|---|---|---|---|
| $H_2$ production in 2050 | 4.23 | 5.10 | 5.97 |
| $CO_2$ abated in 2050 | 648 | 710 | 734 |
| $CO_2$ abated per $H_2$ produced | 153.19 | 139.22 | 122.95 |

Source: Authors' compilation of data from Phoumin et al. (2021).

Using the carbon price (Table 10.7) and the possible amount of carbon dioxide abated per hydrogen produced (Table 10.8), the possible monetised benefits of unit of hydrogen produced from curtailed electricity from variable renewables via electrolysis is estimated. Table 10.9 shows the possible monetised benefits by different carbon prices expressed in US dollars per $kgH_2$, which accrue from hydrogen that replaces fossil fuels in the energy mix in ASEAN.

**Table 10.9: Possible Benefits of Hydrogen Produced from Curtailed Electricity**

(unit: US$/$kgH_2$)

| | **Scenario1$H_2$** | **Scenario2$H_2$** | **Scenario3$H_2$** |
|---|---|---|---|
| RGGI (the highest) | 1.16 | 1.06 | 0.93 |
| RGGI (the lowest) | 0.31 | 0.29 | 0.25 |
| EUETS (the highest) | 9.21 | 8.37 | 7.40 |
| EUETS (the lowest) | 0.52 | 0.47 | 0.42 |
| Singapore | 0.58 | 0.53 | 0.46 |

EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

**4.1.2. EAS**

Table 10.10 shows the amount of hydrogen produced from curtailed electricity under 20% curtailed renewables by different scenarios in the second row and the amount of the emissions carbon dioxide by different scenarios in the third row. The fourth row presents the amount of the carbon dioxide abated per the unit amount of hydrogen produced from curtailed electricity from variable renewables via electrolysis. In sum, Table 10.10 presents the possible amount of $CO_2$ abated per hydrogen produced in 2050 in EAS.

**Table 10.10: Possible Amounts of $CO_2$ Abated per $H_2$ Production in 2050**

(unit: million tonnes)

| | **Scenario1$H_2$** | **Scenario2$H_2$** | **Scenario3$H_2$** |
|---|---|---|---|
| $H_2$ production in 2050 | 72 | 76 | 80 |
| $CO_2$ abated in 2050 | 18,059 | 18,527 | 18,994 |
| $CO_2$ abated per $H_2$ produced | 250.82 | 243.78 | 237.43 |

Source: Authors' calculations.

Using the carbon price presented in Table 10.7 and the possible amount of $CO_2$ abated per hydrogen produced (Table 10.10), the possible monetised benefits per unit of hydrogen produced from curtailed electricity from variable renewables via electrolysis are estimated. Table 10.11 shows the possible monetised benefits by different carbon prices expressed in US$ per $kgH_2$, which accrue from hydrogen that replaces fossil fuels in energy mix in EAS.

**Table 10.11: Possible Benefits of Hydrogen Produced from Curtailed Electricity**

(unit: US$/kg$H_2$)

| | Scenario1$H_2$ | Scenario2$H_2$ | Scenario3$H_2$ |
|---|---|---|---|
| RGGI (the highest) | 1.91 | 1.85 | 1.80 |
| RGGI (the lowest) | 0.51 | 0.50 | 0.49 |
| EUETS (the highest) | 15.09 | 14.66 | 14.28 |
| EUETS (the lowest) | 0.85 | 0.83 | 0.81 |
| Singapore | 0.95 | 0.92 | 0.90 |

EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.

Source: Authors' calculations.

### 4.2. Discussions

As noted in section 3, the electrolyser load factor is the key determinant of the cost estimate of producing hydrogen from curtailed electricity. The production cost is about US$2/kg$H_2$ when the electrolyser load factor is 1,000 hours. Except the case of the highest carbon price in EUETS, the cost appears to be higher than the benefit for all other cases. With the higher electrolyser load factor of 1,500 hours, the cost-benefit ratio could be lower than 1 for the RGGI highest carbon price.

The cost-benefit ratio is calculated by the two cost estimates (Table 10.12) over the possible monetised benefits (Tables 10.9 and 10.11 for ASEAN and EAS, respectively). Table 10.12 presents cost-benefit ratios under the electrolyser load factor is 1,500 hours in ASEAN. Two scenarios of RGGI (the highest carbon price) and EUETS (the highest carbon price) show the cost-benefit ratio is lower than 1, which implies those options are cost-effective and plausible.

**Table 10.12: Cost-Benefit Ratios under the Electrolyser Load Factor (1,500 hours) in ASEAN**

| | Scenario1$H_2$ | Scenario2$H_2$ | Scenario3$H_2$ |
|---|---|---|---|
| RGGI (the highest) | 0.86 | 0.95 | 1.07 |
| RGGI (the lowest) | 3.18 | 3.50 | 3.97 |
| EUETS (the highest) | 0.11 | 0.12 | 0.14 |
| EUETS (the lowest) | 1.92 | 2.11 | 2.39 |
| Singapore | 1.73 | 1.90 | 2.15 |

ASEAN = Association of Southeast Asian Nations, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.

Source: Authors' calculations.

Table 10.13 presents cost-benefit ratios under the electrolyser load factor is 1,000 hours in ASEAN. Only EUETS (the highest carbon price) shows a cost-benefit ratio of lower than 1, which indicates the options are cost effective.

**Table 10.13: Cost-Benefit Ratios under the Electrolyser Load Factor (1,000 hours) in ASEAN**

| | Scenario1$H_2$ | Scenario2$H_2$ | Scenario3$H_2$ |
|---|---|---|---|
| RGGI (the highest) | 1.72 | 1.89 | 2.14 |
| RGGI (the lowest) | 6.37 | 7.01 | 7.94 |
| EUETS (the highest) | 0.22 | 0.24 | 0.27 |
| EUETS (the lowest) | 3.84 | 4.23 | 4.79 |
| Singapore | 3.46 | 3.81 | 4.31 |

ASEAN = Association of Southeast Asian Nations, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

Table 10.14 presents cost-benefit ratios under the electrolyser load factor being 1,500 hours in EAS. Two scenarios of RGGI (the highest carbon price) and EUETS (the highest carbon price) show the cost-benefit ratios are lower than 1, which implies those options are cost-effective and plausible.

**Table 10.14: Cost-Benefit Ratios under the Electrolyser Load Factor (1,500 hours) in EAS**

| | Scenario1$H_2$ | Scenario2$H_2$ | Scenario3$H_2$ |
|---|---|---|---|
| RGGI (the highest) | 0.52 | 0.54 | 0.55 |
| RGGI (the lowest) | 1.94 | 2.00 | 2.05 |
| EUETS (the highest) | 0.07 | 0.07 | 0.07 |
| EUETS (the lowest) | 1.17 | 1.21 | 1.24 |
| Singapore | 1.06 | 1.09 | 1.12 |

EAS = East Asian Summit, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

Table 10.15 presents cost-benefit ratios under the electrolyser load factor is 1,000 hours in EAS. Only EUETS (the highest carbon price) shows the cost-benefit ratio is lower than one, which indicates the options are cost effective.

**Table 10.15: Cost-Benefit Ratio under the Electrolyser Load Factor (1,000 hours) in EAS**

| | Scenario1$H_2$ | Scenario2$H_2$ | Scenario3$H_2$ |
|---|---|---|---|
| RGGI (the highest) | 1.05 | 1.08 | 1.11 |
| RGGI (the lowest) | 3.89 | 4.00 | 4.11 |
| EUETS (the highest) | 0.13 | 0.14 | 0.14 |
| EUETS (the lowest) | 2.35 | 2.42 | 2.48 |
| Singapore | 2.11 | 2.17 | 2.23 |

EAS = East Asian Summit, EUETS = European Union Emissions Trading System, RGGI = Regional Greenhouse Gas Initiative.
Source: Authors' calculations.

Unlike ASEAN, the cost-benefit analysis for EAS shows a ratio of close to 1 under the highest carbon price of RGGI. The larger production of hydrogen from curtailed electricity from variable renewables via electrolysis replaces larger amount of fossil fuels in energy mix in EAS. This leads to the larger amount of $CO_2$ emissions abated from which larger monetised benefits are accrued. Larger potential in hydrogen production in EAS appears to make the cost-benefit ratio close to 1 even under the domain of a low carbon price such as US$10 per ton of $CO_2$.

The current carbon prices in RGGI appear not to make producing hydrogen from curtailed electricity cost-effective or plausible. The carbon prices need to double the current price levels if the electrolyser load factor is about 1,000 hours. If the electrolyser load factor is about 1,500 hours or higher, then the current carbon prices seem to be cost-effective for producing hydrogen via electrolysis from curtailed electricity.

The carbon prices in EUETS have been above EUR20 per tonne of $CO_2$ since 2020. The current carbon prices in EUETS appear to make producing hydrogen from curtailed electricity cost-effective or plausible. If such trends in carbon prices in EUETS continue, then producing hydrogen via electrolysis from curtailed electricity seems to be cost effective or plausible in European nations.

The current carbon price in Singapore will not make producing hydrogen via electrolysis from curtailed electricity plausible. Carbon prices should be twice higher than the current carbon tax for the electrolyser load factor of 1,500 hours and more than quadruple the current carbon tax for the electrolyser load factor of 1,000 hours.

Proost (2019) presents the cost could be higher than US$10/kg$H_2$ if the electrolyser load factor is 500 hours or lower. A low carbon price would make the monetised environmental benefits accrued from abated $CO_2$ emissions low, which in turn makes hydrogen production from curtailed electricity from variable renewables via electrolysis less attractive if not attractive at all.

In sum, producing hydrogen from curtailed electricity from variable renewables via electrolysis could be a plausible option even under low carbon price if the electrolyser load factor is higher than 1,500 hours. If carbon prices are sufficiently high such as higher than US$20/tonne of $CO_2$, then producing hydrogen from curtailed electricity from variable renewables via electrolysis could be cost effective even under the low level of the electrolyser load factor such as 1,000 hours. If the electrolyser load factor is very low such as 500 hours, then curtailed electricity from variable renewables could be a plausible option for producing hydrogen only if the carbon prices are significantly high, e.g. in the range of US$80 to US$100/tonne of $CO_2$.

### 4.3. Policy Implications

The cost-benefit analyses of producing hydrogen from curtailed electricity present the plausible range of carbon prices that make curtailed electricity a cost-effective source of producing hydrogen. This study derives the following policy implications.

First, it is good to grant the abated amount of $CO_2$ to get carbon credits so that they can be traded in the carbon market. A regional carbon market is expected to promote the utilisation of hydrogen production from curtailed electricity from variable renewables. The hydrogen produced works as an energy storage that would solve the intrinsic intermittency of variable renewables and excess supply of electricity from variable renewables.

Second, the cost of producing hydrogen via electrolysis varies by the electrolyser load factors. It is beneficial to make the electrolyser load factors 1,000 hours or above. With this, producing hydrogen from curtailed electricity from renewables is viable even low carbon prices.

## 5. Conclusions

This study examines if curtailed electricity can be a cost effective and plausible option for producing hydrogen in ASEAN and EAS region employing a cost-benefit analysis. The cost estimation is based on two scenarios of the electrolyser load factor, namely 1,000 hours and 1,500 hours. The electrolyser load factor appears to be the key determinant of the cost estimate of producing hydrogen from curtailed electricity from renewables via electrolysis. The production cost is about US$2/kg$H_2$ when the electrolyser load factor is 1,000 hours. The benefit of producing hydrogen from curtailed electricity from renewables via electrolysis is estimated by three stages. At a first stage, the amount of fossil fuels to be replaced by the amount of hydrogen produced from curtailed electricity is estimated. At a second stage, the amount of $CO_2$ emissions to be abated by the reduced usage of fossil fuels in energy mix is estimated. At a third and final stage, the amount of $CO_2$ emissions abated by the unit amount of hydrogen produced is estimated, which is monetised by multiplying a prevailing carbon price.

The cost of producing hydrogen from curtailed electricity from variable renewables via electrolysis appears to be higher than the benefit accrued from the abated amount of $CO_2$ emissions for all but the case of the highest carbon price of EUETS for ASEAN and EAS. With the higher electrolyser load factor of 1,500 hours, the cost-benefit ratio could be lower than one for the highest carbon price of RGGI for EAS.

The current carbon prices of RGGI or Singapore appear not to make producing hydrogen from curtailed electricity cost-effective or plausible. The carbon prices of EUETS, which are above EUR20 per tonne of $CO_2$, appear to make producing hydrogen from curtailed electricity from variable renewables via electrolysis cost effective or plausible. The current carbon price in Singapore appears not to make producing hydrogen from curtailed electricity from variable renewables via electrolysis plausible.

In sum, producing hydrogen from curtailed electricity from renewables via electrolysis could be a plausible option under two occasions, either high carbon prices or the electrolyser load factor is higher than 1,500 hours. If carbon prices are significantly high, such as higher than US$20/tonne of $CO_2$, then producing hydrogen from curtailed electricity from renewable via electrolysis could be cost effective even under the low level of the electrolyser load factor, such as 1,000 hours. If the electrolyser load factor is very low, such as 500 hours, then producing hydrogen from curtailed electricity from renewables could be a plausible option only if the carbon prices are significantly high, such as in the range of US$80 to US$100/tonne of $CO_2$.

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## Chapter 11

# A Strategic Roadmap for Large-Scale Green Hydrogen Demonstration Projects: Case studies from China[15]

Xunpeng Shi, Yanfei Li, and Han Phoumin

Hydrogen is gaining increasing attention from industries and policymakers in China. However, most of the current demonstration projects in the country have relied on conventional sources, including industrial by-product hydrogen and grey hydrogen produced from fossil fuels. Strategies and policy frameworks leading to a shift to green or low-carbon hydrogen have not been explored in depth nor been identified clearly in the context of China. This study aims at bridging such gaps. A survey method and roadmapping technique have been used to survey experts on hydrogen energy from government bodies, industries, and academia and achieve basic consensus on strategically enabling large-scale green hydrogen demonstrations followed by commercialisation in China. A strategic roadmap is thus derived based on these findings, with recommendations on policy principles and tools at each phase of the development of hydrogen energy in China.

Keywords: Green hydrogen; Strategy; China; Roadmap

## 1. Introduction

Hydrogen is enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. The declining cost of hydrogen supply from renewables, or green hydrogen, and the urgency of greenhouse gas emission mitigation are behind the increasing momentum (IRENA, 2018). While green hydrogen is projected to proliferate in the coming years, it has yet to achieve economic competitiveness (IEA, 2019). The supply chains of the equipment and component technologies of hydrogen production and fuel cell production are yet to be validated through real projects in terms of their technical efficiency, capacity factor, economies of scale, and benefits from the learning effect. Therefore, it is vital for policymakers and industry stakeholders to coordinate on the agenda to achieve large-scale demonstration projects of green energy, which remains largely a gap both internationally and in China. Further studies of roadmaps toward large-scale green hydrogen in China are timely for the energy policymakers to find ways to realise large-scale green hydrogen.

From a policy perspective, there are two noticeable gaps in China's hydrogen development. First, there is a lack of comprehensive and valid feasibility studies on the potential renewable or clean energy available to hydrogen projects, as well as their associated energy infrastructure network for transportation and distribution.

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Second, there is a lack of consensus among stakeholders regarding who should do what to resolve the standing institutional and regulatory barriers hindering these projects. For example, under current regulations, power grid companies have no capacity to transmit curtailed renewables as well as nuclear energy to hydrogen production facilities near demand markets; neither do they have the incentive to build dedicated new lines for such a purpose. Furthermore, the current power sector regulations do not allow onsite production of hydrogen at the renewable power stations using the curtailed electricity.

It is thus important to start large-scale green hydrogen demonstrations in China and conduct associated economic and policy assessments in order to serve the original purpose of developing hydrogen energy: as a key pillar towards the transition to low or even zero-emissions energy, as well as the deep coupling of renewable energy and the transport sector and the power sector.

An implementation plan study could improve the situation in this regard by providing a roadmap for all green hydrogen stakeholders. The practices will collect information and ideas from field experts from industry, government, and academia to comprehensively identify both economic and non-economic barriers, coming together with ideas and agreements on who should do what by what time to resolve these barriers as much as possible.

The existing studies on hydrogen policy and related subjects mainly focus on environmental benefits and economic costs and their policy suggestions are static without a timeline. For example, Ajanovic and Haas (2018) analysed the economic prospects of hydrogen in passenger car transport. Lin et al. (2021) proposed a sustainability prioritisation framework to assess hydrogen production pathways. Shi et al. (2020) provided an analytical framework to quantify the water footprint of hydrogen using Australia as a case study. Given the significance of hydrogen in decarbonising the transport sector, many policy-related studies focus on the transport sector. For example, Ajanovic and Haas (2021) investigated key barriers to increasing hydrogen and Fuel Cell Electricity Vehicles (FCEVs) with a focus on their economic performance. They conclude that a stable and long-term policy framework is the key condition to achieve full benefits of hydrogen and fuel cells in the transport sector. See Ajanovic and Haas (2021) for a recent review on policy studies of hydrogen use in the transport sector. There are also many studies on barriers to hydrogen development (Seymour, Murray, and Fernandes, 2008), the effectiveness of green hydrogen support policies (Talebian, Herrera, and Mérida, 2021), sociology of hydrogen technological expectations (Upham et al., 2020), and general hydrogen policy (Demirbas, 2017).

Roadmaps of hydrogen development have emerged in the policy arena, but there is a lack of comprehensive ones from an academic perspective. The International Energy Agency (IEA) has offered guidance on hydrogen's future development. It suggests scaling up low-carbon production and fostering innovation as near-term actions to overcome barriers further and reduce costs (IEA, 2019). However, among the seven recommendations for scaling up hydrogen demand, only one is about clean hydrogen, i.e. boosting commercial demand for clean hydrogen, but it did not discuss how green hydrogen may be promoted. While there are technical or country-specific roadmaps, there is nonetheless a lack of a comprehensive green hydrogen development roadmap. Ardo et al. (2018) explored pathways to electrochemical solar-hydrogen technologies. Murray et al. (2007) compared hydrogen technology development in Portugal with that of other countries and identified key areas of promise for hydrogen technologies. Havertz (2021) investigated the South Korean hydrogen policy against the concept of ecological modernisation and found that the overall environmental benefits of this program are poor in the medium-term but might lead to a significant emissions reduction in the long term.

To fill these gaps, this report aims to apply the roadmapping method to the development of green hydrogen technologies in China. The major contribution of this study is the application of the roadmapping technique to the hydrogen industry. The second contribution is to assess green hydrogen's development status and possible and desirable future in China. The third contribution of the study is that the results will have practical importance for China and global hydrogen development.

The remaining of chapter proceeds as follows. The next section introduces the background of this study, including a summary of China's hydrogen policies and roadmaps in China and other major countries. Section 3 presents the methodology for this report. Section 4 presents the survey results, followed by a brief elaboration of the strategic roadmap. The last section concludes the chapter.

## 2. Literature Review

### 2.1. Hydrogen Energy Development in China

The Chinese government at various levels has actively promoted hydrogen energy development. As of 2019, out of 34 Chinese provincial administrative regions, 17 (plus at least 22 municipal administrations) have published policies to develop hydrogen energy-related industries and infrastructure; this is complemented by more than 10 policy documents issued by the central government of China (CEBA, 2019). A review of China's recent government policies focusing on hydrogen and fuel cell development is provided by the following two tables, with Table 11.1 focusing on central government policies and Table 11.2 on local government policies.

**Table 11.1: Summary of Central Government Policies Relevant to Hydrogen Energy**

| Policy Document | Year | Government Department/Agency | Focal Areas |
|---|---|---|---|
| New energy vehicle industry development plan (2021–35） | 2020 | State Council | Pursue technological breakthrough in and achieve commercialisation of fuel cell vehicle; develop hydrogen energy supply chain and infrastructure |
| Notice on the demonstration application of fuel cell vehicles | 2020 | Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and | Replace subsidies on fuel cell electric vehicles with awards for demonstration cities, with a goal of establishing hydrogen and fuel cell supply chains and |

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|---|---|---|---|
| | | Technology, National Development and Reform Commission (NDRC), and National Energy Administration (NEA) | achieving a breakthrough in key technologies in 4 years |
| Directive directory of green industries | 2019 | NDRC | Encourage the development of hydrogen energy infrastructure, as well as the application of fuel cells in the transport sector |
| 2019 focus of work on standardisation of new energy vehicles | 2019 | Ministry of Industry and Information Technology | Standardisation of fuel cells and hydrogen refueling technologies |
| Notification on the adjustment and perfection of fiscal subsidies for new energy vehicles | 2018 | Ministry of Finance | Maintain fiscal subsidy levels for fuel cell electric vehicles |
| The 13th Five-Year Plan for scientific and technological innovation in transportation | 2017 | Ministry of Science and Technology | Deepen R&D in essential technologies of fuel cell electric vehicle and demonstration of hydrogen energy infrastructure |
| Medium- and long-term development plan for the automobile industry | 2017 | Ministry of Industry and Information Technology, NDRC, and Ministry of Science and Technology | Expand the scope of trials and demonstrations for fuel cell electric vehicles |
| Energy development in the 13th Five-year Plan | 2016 | NDRC and NEA | Hydrogen and fuel cells are listed as key technologies and called for innovations in them |
| Revolutionary Strategy for Energy Production and Consumption (2016–2030) | 2016 | NDRC and NEA | Technological innovations in hydrogen and fuel cells technologies as one of the key pillars |
| Made in China 2025 | 2015 | State Council | 1,000 fuel cell electric vehicles for demonstration by 2020, 120,000 units by 2025, and over 1 million units by 2030; readiness of hydrogen energy infrastructure for the demonstration and adoption |

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|---|---|---|---|
| Notification on Incentives for Construction of Charging Facilities for New Energy Vehicles | 2014 | Ministry of Industry and Information Technology | CNY4 million per refilling station with capacity higher than 200 kg per day |
| Notice on continuing to promote and apply new energy Vehicles | 2013 | Ministry of Industry and Information Technology | CNY200,000/unit for passenger fuel cell electric vehicles; CNY500,000/unit for commercial fuel cell electric vehicles |
| Energy conservation and new energy vehicle industry development plan (2012–20) | 2012 | State Council | Provision of fiscal subsidies to battery electric vehicles, plug-in hybrid vehicles, and fuel cell electric vehicles |

CNY = Chinese yuan.
Source: Authors' compilation from various sources.

**Table 11.2: Summary of Local Government Policies on Hydrogen Energy**

| Province/City | Year | Policy Document |
|---|---|---|
| Hebei province | 2020 | A 3-year action plan for the clustered development of hydrogen energy industry chain in Hebei Province |
| | 2019 | Suggestions on Promoting the Development of Hydrogen Energy Industry in Hebei Province |
| | 2019 | Hydrogen Zhangjiakou construction plan |
| Shandong province | 2020 | Medium- and long-term Development plan for Hydrogen industry in Shandong Province (2020–30) |
| Shanxi province | 2019 | Shanxi New Energy Automobile Industry 2019 Action Plan |
| Jiangsu province | 2019 | Action Plan for hydrogen Fuel cell Vehicle Industry development in Jiangsu Province |
| | 2019 | Development plan of Hydrogen fuel cell vehicle industry in Changshu city (2019–30);<br>Changshu Hydrogen fuel cell vehicle industry development action plan (2019–22) |
| | 2018 | A 3-year action plan for the development of hydrogen industry in Zhangjiagang (2018–20) |
| | 2018 | Guiding Opinions on the Development of Suzhou Hydrogen Energy Industry (Trial) |
| | 2018 | Opinions on the implementation of supporting hydrogen industry development in Rugao |
| Shanghai | 2017 | Shanghai fuel cell vehicle development plan |
| Hunan province | 2019 | Development plan of Zhuzhou Hydrogen Energy Industry 2019–25 |

| | | |
|---|---|---|
| Hubei province | 2018 | Wuhan Hydrogen Industry Development Plan |
| Zhejiang province | 2019 | Guiding Opinions on accelerating the Development of Hydrogen energy Industry in Zhejiang Province |
| | 2019 | Suggestions on accelerating the development of hydrogen industry in Ningbo |
| | 2019 | Implementation Plan for Promoting the Development and Demonstration Application of Hydrogen Energy Industry in Jiashan County (2019–22) |
| Guangdong province | 2020 | Hydrogen Energy Industry Development Plan of Nanhai District, Foshan city (2020–35) |
| | 2020 | Guangzhou Hydrogen Industry Development Plan (2019–30) |
| | 2019 | Measures of Nanhai District of Foshan City to promote the construction and operation of hydrogen refueling station and the operation support of hydrogen energy vehicles |
| | 2018 | Hydrogen Energy Industry Development Plan of Foshan city (2018–30) |
| | 2018 | Foshan New Energy Automobile Industry Development Plan (2018–30) |
| | 2018 | Support measures for hydrogen energy distribution freight vehicles in Foshan City |
| Sichuan province | 2019 | Chengdu Hydrogen Energy Industry Development Plan (2019–23) |
| Inner Mongolia | 2020 | Inner Mongolia Wuhai Hydrogen industry development plan |
| Jilin province | 2019 | Baicheng New energy and hydrogen industry development planning |

CNY = Chinese yuan.

Source: Authors' compilation from various sources.

Small- to medium-scale demonstrations can be found in several cities and provinces in China. There are currently over 2,000 FCEVs operating in China, mostly supported by demonstration projects, together with 26 hydrogen refueling stations (HRSs) (CBEA, 2019). However, most of these demonstrations are relying on hydrogen supplied from petroleum industries as a byproduct – the so-called grey hydrogen.

Green hydrogen demonstration projects are on the way. Zhangjiakou is the first city in China that has developed medium-scale renewable energy-to-hydrogen capacity, currently at 6,000 tonnes of hydrogen per year using wind power (Energy Development, 2020). However, Zhangjiakou applied a virtual wind electricity design, which means that the wind electricity is first injected into the power grid, and the electrolysis plant gets electricity from the grid at a tariff that is negotiated and thus close to the cost of wind electricity. Lanzhou city of Gansu province invested in a small-scale power-to-liquid demonstration project, converting the solar energy from a 10-MW PV station into hydrogen and then subsequently into methanol (Lanzhou Bureau of Science, 2019). Another 300 MW solar energy-to-hydrogen project will be implemented in Gansu province from 2021 (Gansu Provincial Government, 2021). Chapter 4 to Chapter 6 of this ERIA research report provide support on the feasibility of larger-scale green hydrogen demonstration projects in Guangdong province and Jiangxi province of China, considering using both solar and wind energy. Chapter 7 also explores the possibility of small-scale hydrogen energy applications for integration with solar energy in a microgrid system to improve the technical and economic efficiency of the system. Thus, at all scales, green hydrogen seems to have the potential of achieving economic feasibility in China.

Apart from the demonstration project, subsidies are also commonly used in China. The following tables summarise the subsidy policies in China at both the central and local level (Guangdong as an example of local level), before and after the announcement of the 'Notice on the demonstration application of fuel cell vehicles' in September 2020 (Table 11.3 and Table 11.4).

**Table 11.3: Subsidies Provided to FCEV in China at both Central and Local Government Levels before 2020**

| | Central Government | Guangdong Province |
|---|---|---|
| FC passenger vehicle | CNY6,000/kW (up to CNY200,000 per vehicle) | CNY200,000 per vehicle |
| FC light truck/bus | CNY300,000 per vehicle | CNY300,000 per vehicle |
| FC heavy truck/bus | CNY500,000 per vehicle | CNY500,000 per vehicle |
| HRS | | Up to CNY5 million/station |

CNY = Chinese yuan, FC = fuel cell, FCEV = fuel cell electric vehicle, HRS = hydrogen refueling station.
Source: Ministry of Finance (MOF) (2018) and (Guangdong Pronvincial Development and Reform Commission 2020).

**Table 11.4: Subsidies Provided to FCEVs in China at Central Government Level after September 2020**

| | Category | Award |
|---|---|---|
| FCEV | Passenger and Medium-size Vehicles | CNY130,000–250,000 per vehicle |
| | Heavy-duty vehicles | CNY270,000–540,000 per vehicle |
| Hydrogen Supply | Hydrogen consumption on vehicles | CNY7/kg in 2020, reducing to CNY3/kg by 2023 |
| | Hydrogen Supply Cost at HRS lower than CNY35/kg | CNY1/kg |
| | Low-carbon hydrogen | CNY3/kg |
| | Distance of hydrogen transportation and delivery lower than 200 km | CNY1/kg |

CNY = Chinese yuan, FC = fuel cell, FCEV = fuel cell electric vehicle, HRS = hydrogen refueling station.
Source: Ministry of Finance et al. (2020).

## 2.2. Development of Hydrogen Roadmaps in Selected Countries

Many countries have set up their hydrogen strategies that incorporate a roadmap. Australia's hydrogen roadmap recognises hydrogen as a future low-emissions energy product for exports due to its resource and technological advantages, export capabilities, and close relationships with key international energy markets (Bruce et al., 2018). Australia's National Hydrogen Strategy (COAG Energy Council, 2019) further elaborates pathways towards the vision of a clean, innovative, safe, and competitive hydrogen industry that benefits all Australians, with Australia being a major global player by 2030.

In 2020, the US DOE (2020) published an updated hydrogen roadmap for a world-leading hydrogen economy. It estimates that hydrogen will meet 14% of the US final energy demand by 2050. The US roadmap sets four benchmarks: Immediate next steps (2020–22), Early scale-up (2023–25), Diversification (2026–30), and Broad rollout (2031 and beyond). The European Hydrogen Roadmap (2019) launched in 2019 envisions a more ambitious future, accounting for 24% of final energy demand and 5.4 million jobs by 2050. The European Hydrogen Roadmap proposes milestones for transport, building, industry, and power systems up to 2030. The German Hydrogen Roadmap provides detailed milestones for R&D, market, technology, and policy for three stages (the 2020s, 2030s, and long term) (Federal Ministry for Economic Affairs and Energy, 2020).

The Korean Hydrogen Economy Roadmap was announced in January 2019 and outlines the goal of FCEV production, FCEV buses, refueling stations, and fuel cells for power generation by 2040. Action plans include building a Hydrogen Industry Cluster to foster R&D cooperation from 2021 and three cities as a national H2 testbed city (IEA/IRENA, 2020).

In March 2019, Japan's third Strategic Roadmap for Hydrogen and Fuel Cells was released in March 2019, which aims to achieve four goals: increase energy self-sufficiency; decarbonise the economy; increase industrial competitiveness; and position Japan as a fuel cell technology exporter. The Japanese roadmap prioritises the hydrogen production cost and thus considers blue hydrogen currently and seeks opportunities to establish a global hydrogen supply chain (Government of Japan, 2019).

## 2.3. Chinese Roadmapping Studies on Hydrogen and Fuel Cells

Although China has not set up its official hydrogen roadmap, several semi-official Chinese industrial associations and research institutes have done relevant studies. The China National Institute of Standardization (CNIS) and National Standardization Technical Committee for Hydrogen Energy (SAT/TC 309), (2016) published China's first roadmap on the development of hydrogen energy infrastructure and its related technologies.

More recently, the China Hydrogen Alliance (2019) proposed both a technological roadmap and a corresponding policy framework. Regarding the supply of hydrogen, the technological roadmap features the following: industrial byproduct hydrogen will be the main source of supply in the earlier stage (2020–25), accompanied by the technological demonstration of renewable electricity electrolysis pathway and biomass-based pathways; in the midterm (2026–35), hydrogen from both renewables-based electrolysis and coal will be the mainstream; and, in the long term (2036–50), hydrogen from both renewables-based electrolysis and coal gasification with carbon capture sequestration (CCS) will constitute the main sources of supply, complemented by biomass-based, biochemical, and photocatalytic pathways. The storage and transportation will gradually deploy more advanced technologies, from low-pressure to high-pressure, and then to liquid and solid materials, and eventually towards the establishment of a large-scale pipeline network. In the corresponding policy roadmap, the China Hydrogen Alliance (2019) suggested that standards, laws, and regulations be established according to the above-mentioned three stages of development. At the same time, the demonstration of hydrogen energy should start with city-level pilots, moving to provincial-level demonstration zone and eventually to nationwide and full-scale rolling out.

Largely in line with the China Hydrogen Alliance (2019), the roadmap proposed by China EV100 (2020) estimated the target supply cost of hydrogen as CNY40/kg by 2025, CNY30/kg by 2035, and eventually CNY20/kg by 2050. Especially, it suggested that power generation capacity by renewables could reach a level of 1,000 GW by 2025 and 4,000 GW by 2050 in China, and therefore hydrogen infrastructure as energy storage should be deployed, especially for the provision of trans-seasonal storage.

The technological roadmap by China SAE (2020) proposed developing medium-sized to large fuel cell commercial vehicles in areas where there is ample supply of hydrogen from either renewable energy or industrial byproduct in the early stage. At a later stage, fuel cell applications should be extended to heavy-duty and long-distance vehicles, such as heavy trucks, tractors, and trailers. Such a development is part of the plan to electrify the road transport sector in China and it is complementary to developing battery electric vehicles serving urban and short-distance road transportation.

Ren and Guan (2020) projected that the fuel cell vehicle industry in China would go through three phases starting from 2020:

1. Demonstration phase (2020–24): Aiming at improving the technology and driving by policy support, in major cities, several thousands of fuel cell vehicles will be deployed for demonstration;
2. Agglomeration and fast development period (2025–30): Fuel cell vehicle applications further penetrate, especially in regions with developed and agglomerated supply chains or rich hydrogen energy resources. With policy support, hydrogen and fuel cells reach cost competitiveness in 80% of identified application scenarios; and
3. Full-scale deployment of fuel cell vehicles (post-2030): fuel cell vehicles to reach cost parity with internal combustion engine vehicles, without policy support. By then, the growth of the industry will be mainly driven by market forces.

Throughout the three phases, the priority and focus will be put on commercial vehicles first. Later, as the technology matures, infrastructure gets ready, and supply chains continuously bring down the costs, and passenger vehicle applications will be gradually developed.

GEIDCO (2021), an international organisation supported by the State Grid of China, produced a roadmap to achieve carbon neutrality in 2060, from the perspective of the power sector. This roadmap also foresees the coupling of electricity and hydrogen as an essential method to deepen decarbonisation, especially in the power sector, transport, and industry. By 2030, the economy of hydrogen production from clean electricity will surpass that of fossil energy, and the production of hydrogen from water electrolysis will reach 4 million tonnes. In 2060, the production of hydrogen in China will reach 60 million tonnes, and the cost of hydrogen, ammonia, and methane produced by electrochemical methods will drop significantly. Moreover, GEIDCO expects hydrogen and fuel cell power generation to play a key role in the power sector of China as peak load generating units, with installed capacity increasing to 100 GW by 2050 and 200 GW by 2060.

It can thus be observed from the above that the existing roadmap studies focus more on technological issues. Policy issues and market issues are not elaborated in detail with dedicated studies. This report will contribute by paying more attention to these two dimensions, while keeping in mind that they are closely related to progress in meeting technological targets listed in the above-mentioned roadmaps.

## 3. Methodology

Building on findings from others, this chapter serves to identify vision, goals/milestones, key requirements/common needs, barriers/constraints, and risks faced by the stakeholders of potential large-scale green hydrogen demonstration projects in China.

Besides systemically reviewing and summarising the findings from the previous chapters, this study will develop a questionnaire based on the SWOT framework and conduct expert interviews. The review results will be presented in the SWOT framework.

The SWOT method has been frequently applied to energy research including regional energy policy planning (Cayir Ervural et al., 2018), future scenarios (Shi, 2016), and renewable energy development (Kamran, Fazal, and Mudassar, 2020).

This study also applies the concept of roadmapping, defined initially as 'an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field' (Galvin, 1998). Roadmapping technique as a management tool has been popular for promoting innovation, strategy, and policy, at the organisational, sectoral, and national levels (Chutivongse and Gerdsri, 2020). The roadmapping also draws foresight approaches, including scenarios, Delphi surveys, and quantitative forecasts (McDowall, 2012). The roadmapping techniques have also been applied to various aggregated levels, such as for the creative industries (Abbasi, Vassilopoulou, and Stergioulas. 2017), building materials industry (Shim, Kim, and Choi, 2019), and smart cities (Park, del Pobil, and Kwon, 2018).

Roadmapping can be conducted at strategic, policy, or technology levels. Strategic roadmapping is a common planning tool that defines where a business is, where it wants to go, and how to get it there (Abdel-Fattah, Helmy, and Hassan, 2019). Policy roadmapping links the work done at each policy to the overall goals and has been widely applied, such as with renewable energy policy roadmaps (Edkins, Marquard, and Winkler, 2010). Similarly, a technology roadmapping method is a tool for decision-makers to identify, assess, and choose the strategic options that can deliver the best technological objectives (Dastranj, Ghazinoory, and Gholami, 2018). It became popular after a seminal comment on its successful use by Motorola and in the semiconductor industry (Galvin, 1998). Technology roadmaps have been frequently applied at the firm level to integrate technology developments with business planning (McDowall, 2012).

Although roadmapping may be different between strategic and technological roadmapping, and the approaches to develop technology roadmaps vary among scholars, such as (Vinet and Zhedanov, 2011) and (Phaal, 2004), there are some common core steps. According to the review by McDowall (2012), roadmaps address three different perspectives of the future: expectations (possible), desires (hope) and promises (plan). As a *tool* in the ongoing management of innovation, a roadmap includes at least the three core steps as below: 1) formulating a consensus view, at least of those who have participated in the process, of the current 'state of the debate', including the status and possible development of a technology, barriers and opportunities; 2) *realistically and pragmatically* projecting feasible and desirable future scenarios; and 3) prescribing the key areas of further progress, including the barriers and the opportunities, to guide innovations.

Based on the core steps in the roadmapping technique, we propose the following framework for our strategic/policy roadmap of green hydrogen development in China. Such a framework can also be applied to green hydrogen in other countries or development in other technologies.

Applying the roadmapping method, we carry out the study in three core steps:

**Step 1:** For the first step, we survey Chinese experts. The interviews are designed to collect first-hand, real experience on the hydrogen industry and identify the key factors that affect green hydrogen development. The interviews target senior experts and executives from hydrogen and related industries through both online and face-to-face interviews. Interviewed representatives cover all parts of the hydrogen supply chain.

Thus, besides systematically reviewing and summarising the findings from the previous chapters, this study will develop a questionnaire and conduct expert interviews. Three broader questions are raised: (a) Where is the green hydrogen now? i.e. the present state of technology, products, markets, barriers and opportunities, etc.; (b) Where is green hydrogen going? i.e. what is its vision, mission, objectives, goals, and targets, especially regarding zero-emission green hydrogen from renewables; and (c) How can we get to the desirable future? i.e. policy measures, action plans, research and development programs, long-term and short-term strategies. etc. A sample of questions is listed in the appendix.

**Step 2:** Based on the survey and the focused group discussion, we project a feasible and desirable future of green hydrogen in China.

**Step 3:** In the last step, a set of policy guidelines and an implementation plan to achieve such desirable futures is derived.

The paper adopts the International Renewable Energy Agency (IRENA) stages of green hydrogen policy support and divides the development for green hydrogen into technological readiness, market penetration, and market growth (IRENA 2020). At each stage, we elaborate the roadmap from five aspects: technological development, infrastructure, applications, laws and regulations, and policy.

## 4. Survey of Hydrogen Development in China

Applying a SWOT analytical framework to the information collection through literature survey and expert interviews, this section analyses the internal and external opportunities and challenges that China's green hydrogen development faces.

The survey was conducted between February to March 2021 among Chinese experts on hydrogen energy from various backgrounds, including government, industry, academia, research institutes, and international organisations. The working language of the survey was Chinese Mandarin. A total of 95 responses were received, of which 83 were considered valid responses.

Overall, the survey experts believed that green hydrogen will be developed on a large scale in the mid-term. However, it is necessary to take action in a large-scale demonstration in the near term in order to build up the capacity of relevant supply chains domestically and get up to speed in relevant technologies. Experts also suggest that China should set priorities in the process of developing hydrogen energy; this is true from technological, commercial (infrastructure and market readiness), and policy perspectives. Thus, an official national hydrogen energy roadmap is to be developed and issued in order to coordinate actions and investments across the upstream and downstream of the supply chains, while putting necessary policies in place through different phases of the development of hydrogen energy.

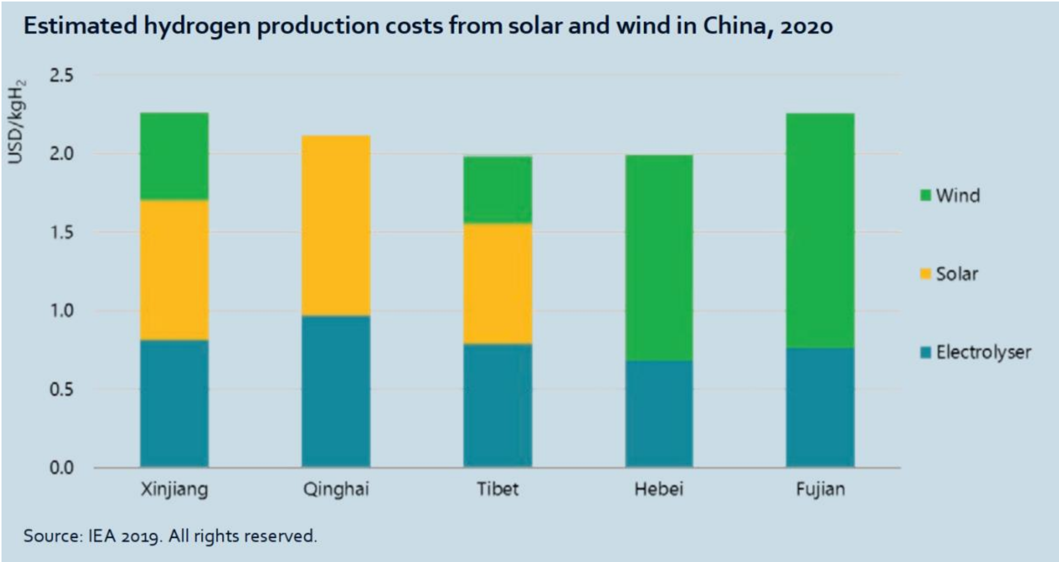
A brief elaboration of the literature and questionnaire survey results is presented in the SWOT framework below.

### 4.1. Strengths

The strengths of China's green hydrogen lie in its comprehensive supply chain and market prosperity. China is projected to become a major market for hydrogen energy by 2040 (ERIA, 2019). The China Hydrogen Energy Alliance predicts that, by 2050, hydrogen energy will account for about 10% of China's total final energy demand. The demand for hydrogen will be close to 60 million tonnes and 70% will be produced by renewable energy (China Hydrogen Energy Alliance, 2019). In this ERIA project report, Chapter 2 projects that, on the one hand, the total hydrogen energy demand in China could reach 29 Mtoe by 2030 and 58 Mtoe by 2040. On the other hand, the total green hydrogen supply in China could reach as high as 133 Mtoe by 2030 and 149 Mtoe by 2040, using curtailed electricity from renewables. Therefore, green hydrogen in China could meet not only the demand for hydrogen for energy uses but also that for industrial uses, such as in steel production, petrochemical industries, and fertiliser production.

The cost of green hydrogen is site-specific and thus some parts of China can produce low-cost green hydrogen. For regions with good renewable energy sources, such as Western China, green hydrogen could achieve cost-competitiveness at earlier stages than other regions. According to IEA (2019), some provinces in China can produce green hydrogen at the cost of US$2–2.3/kg$H_2$, which is already cost-competitive (Figure 11.1).

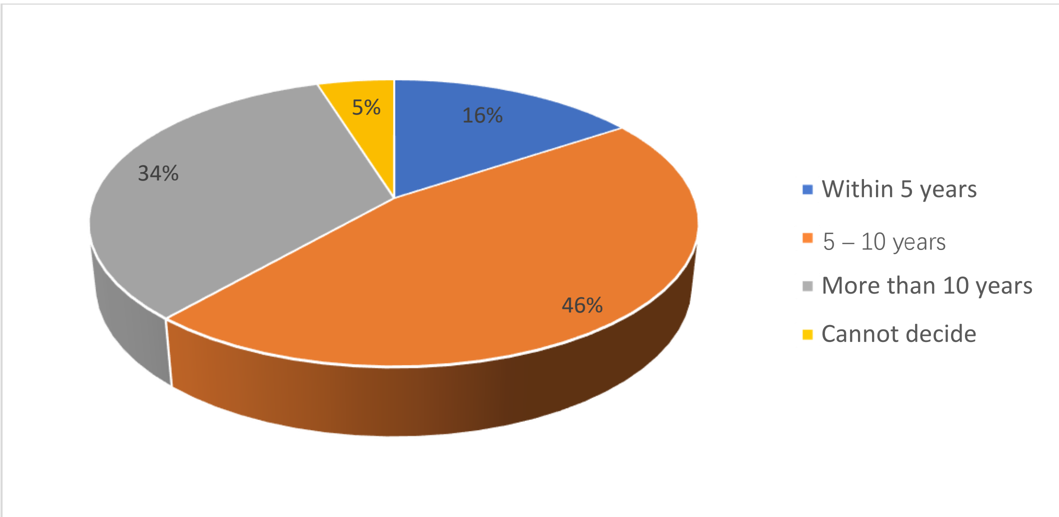
**Figure 11.1: Estimated Hydrogen Production Costs from Solar and Wind in China, 2020**




Source: IEA (2019): 63.

Due to this resource advantage, most experts expect that hydrogen produced from renewables will become massively adopted for commercial applications in China in 5–10 years (Figure 11.2).

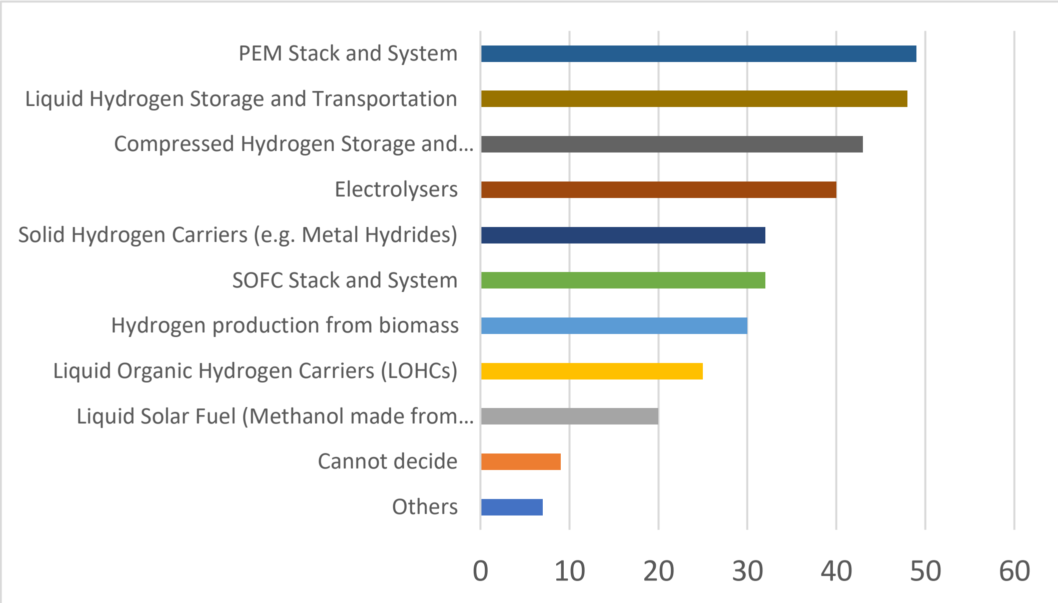
**Figure 11.2. Timeline for Hydrogen Produced from Renewables to Become Massively Adopted for Commercial Applications in China**




Source: Authors' survey.

The technologies that are critical to the economic feasibility of hydrogen energy in China and have the potential of significant decreases in costs or major breakthroughs are ranked by experts and presented in Figure 11.3. Polymer electrolyte membrane (PEM) fuel cells, liquid hydrogen transportation, and compressed hydrogen transportation received the most attention. The ranking should not be interpreted as saying that other technologies are less important or have less potential. Rather, it reflects the fact that industries and policymakers are putting more emphasis on achieving a breakthrough in those highly ranked technologies either through catching-up or original innovations in order to enable large-scale commercialisation of hydrogen energy and fuel cell applications in China.

**Figure 11.3. Critical Technologies with the Potential for a Major Breakthrough in Future**




PEM = Polymer electrolyte membrane, SOFC = solid oxide fuel cell.
Source: Authors' survey.

### 4.2. Weakness

China's green hydrogen development has weakness in standards and regulations, as well as technology development and investment. While China has paid a great amount of attention to hydrogen on the policy end, more attention needs to be paid to two important dimensions, i.e. the promotion of low-carbon or even green hydrogen, and establishing a comprehensive and updated system of standards, regulations, and legislation for hydrogen energy. A majority of the surveyed experts do not think that the current policy support given to hydrogen energy and fuel cell applications is sufficient (Table 11.5).

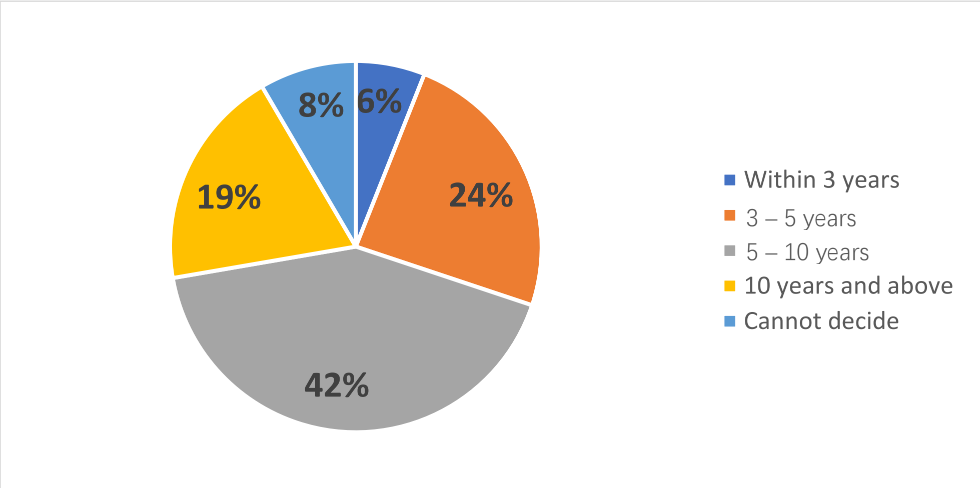
**Table 11.5. Adequacy of the Current Policy Support Provided at Various Levels of the Chinese Government on Hydrogen and Fuel Cell Industries and Applications**

| Options | Counts | Ratio |
|---|---|---|
| Very inadequate | 10 | 12.05% |
| Inadequate | 41 | 49.4% |
| Appropriate | 21 | 25.3% |
| Excessive | 10 | 12.05% |
| Very excessive | 1 | 1.2% |
| Valid responses | 83 | |

Source: Authors' survey.

On the front of China's technological catching up in hydrogen and fuel cells, a majority of the experts expect that, at most, it will take some 5–10 years (Figure 11.4).

**Figure 11.4. Timeline for Chinese Companies to Catch Up on Internationally Advanced Technologies in Hydrogen and Fuel Cells**




Source: Authors' survey.

The next question is on how to enable catching up in the above-mentioned technologies. The most important factors identified include: technical standards (including safety standards); talents; policies, laws, and regulations; and collaborations along the international supply chain and access to essential materials and parts. The surveyed experts have put high emphasis on the controllable supply chain in hydrogen and fuel cell technologies. Our results show that the desirable level of localisation of the supply chain for hydrogen and fuel cell technologies should be at least 70%–80%. Such may have reflected the mindset that the Chinese society developed after experiencing the US cutting off international supply chains for exporting essential high-tech intermediary inputs to China in recent years.

### 4.3. Opportunities

Green hydrogen development in China has policy support and could be further boosted by the continuous evolution of power markets.

To achieve carbon neutrality, strengthen energy security, and enhance the integration of renewable energy, China needs to develop hydrogen energy, especially green hydrogen. The key central government energy policies, such as the 'Made in China 2025' by the State Council in 2015, 'Energy development in the 13th Five-year Plan' by National Development and Reform Commission (NDRC) and National Energy Administration (NEA) in 2016, and 'Revolutionary Strategy for Energy Production and Consumption (2016-2030)' by NDRC and NEA in 2016, concern the role of hydrogen and fuel cells in the overall future energy mix, as well as the progress in technologies. In the meantime, many local government policies focus on developing demonstrations, hydrogen, and fuel cell supply chains, as well as developing relevant industrial clusters in their own administrative area.

Table 11.6 presents the motivations for developing hydrogen energy in China. Meeting the carbon neutrality target is ranked the highest, followed by relieving energy security and improving the integration of renewable energy.

**Table 11.6. Main Purposes of Developing Hydrogen Energy in China**

| Items | Average Score |
|---|---|
| Carbon emissions reduction and the carbon neutrality target | 3.66 |
| Improving energy security (e.g. reducing reliance on imports, diversification of energy supply, diversification of energy infrastructure, etc.) | 3.58 |
| Integration and absorption of renewable energy | 2.55 |
| Reduce the cost of energy | 2.07 |
| Electrify commercial vehicles, as a complementary option to battery electric vehicles | 2.01 |

Source: Authors' survey.

These identified most important motivations are consistent with the highest number of votes on the ideal share of green hydrogen in the energy consumption of China by 2050 as '30% or higher' (Table 11.7).

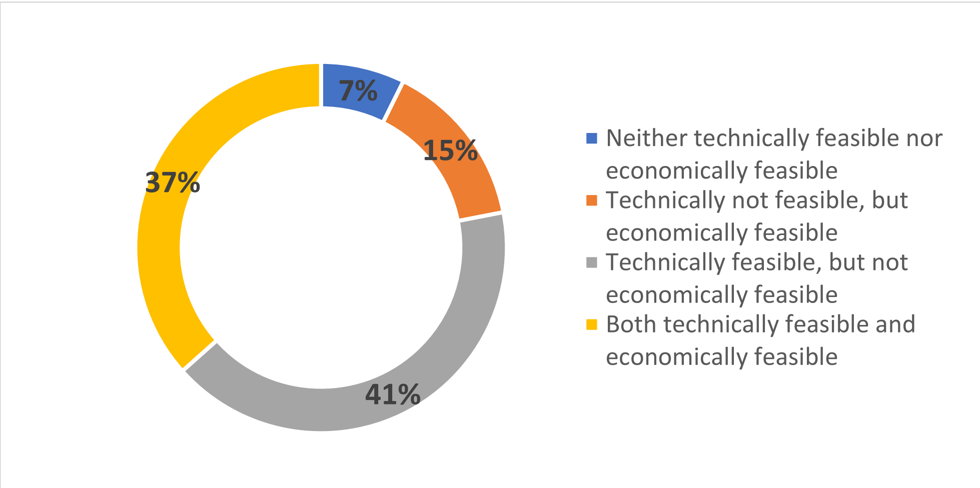
**Table 11.7. The Ideal Share of Green Hydrogen in the Energy Consumption of China by 2050**

| Options | Counts | Ratio |
|---|---|---|
| 10% or below | 7 | 8.43% |
| 10 – 15% | 20 | 24.1% |
| 15 – 20% | 15 | 18.07% |
| 20 – 25% | 11 | 13.25% |
| 25 – 30% | 6 | 7.23% |
| 30% or above | 24 | 28.92% |
| Valid Responses | 83 | |

Source: Authors' survey.

When it comes to the feasibility of supplying green hydrogen produced in Western China, where the renewable resources are rich, to Eastern China, where the demand for green hydrogen would be, over 70% of the experts think that such is technically feasible, but only 37% of them think it is economically feasible (Figure 11.5).

**Figure 11.5. The Feasibility of Supplying Green Hydrogen Produced in Western China to Eastern China**




Source: Authors' survey.

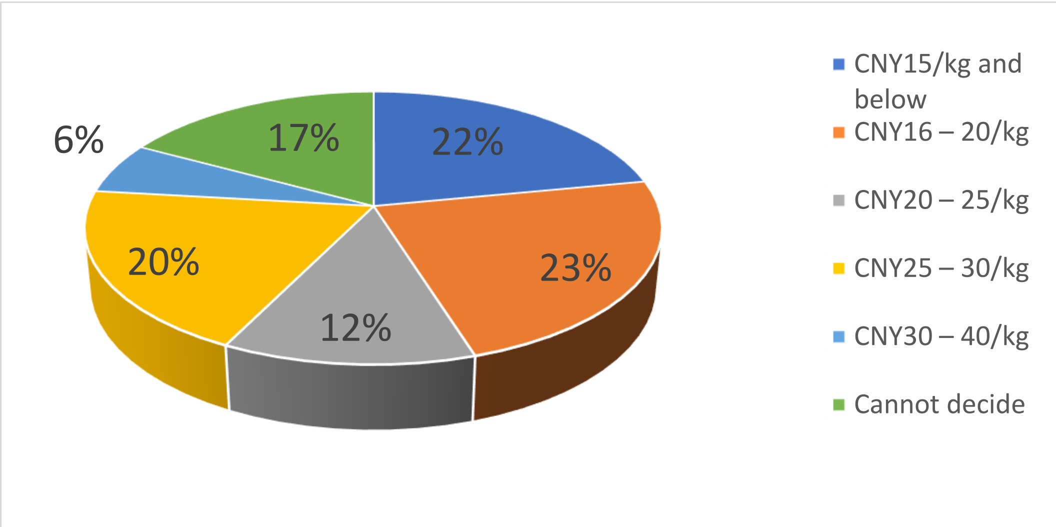
### 4.4. Threats

The major threat for green hydrogen development in China is the lower cost of fossil fuel hydrogen.

Green hydrogen is still expensive to produce today. IEA (2019) estimated that the cost of green hydrogen in China at US$3 to US$7.50/kg, compared to US$0.90 to US$3.20/kg for production using steam methane reformation. As a result, it is surprising to find that most of these demonstration projects currently source hydrogen from conventional petroleum by-products. Further, all HRSs in China currently use compressed hydrogen ($CH_2$) trucks to transport hydrogen at 35 MPa (350 bar). For these reasons, hydrogen energy in China is currently neither competitive in prices (around CNY85/kg for refueling at the HRS) nor green.

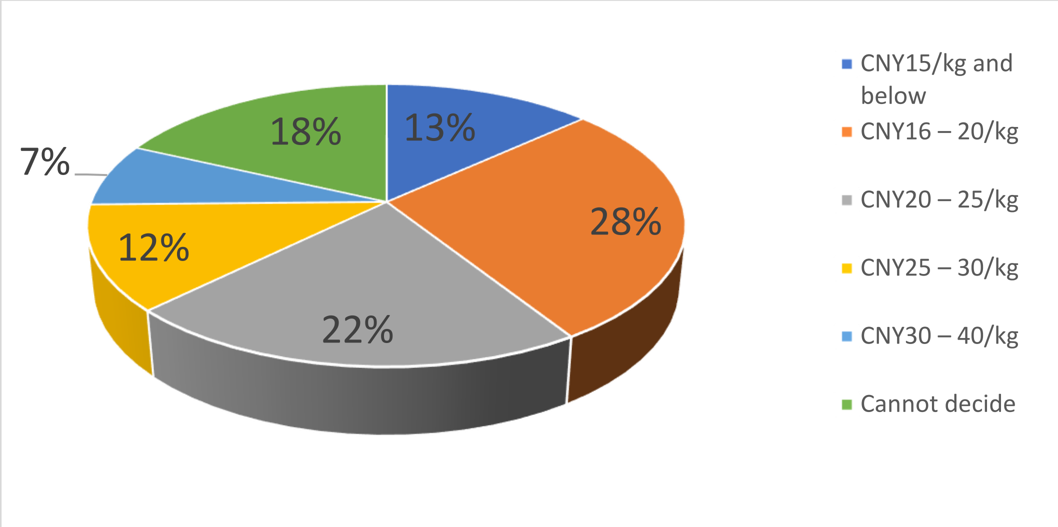
For fuel-cell commercial vehicles (e.g. buses and trucks) to become competitive and thus widely adopted, it would require the hydrogen supply cost (covering production, storage, transportation, and dispensing) to be in the range of CNY16–20/kg or lower (Figure 11.6). For fuel cell passenger vehicles, the implied competitive cost of hydrogen supply is slightly higher and the range seems wider, with the majority of the experts' opinions falling between CNY16–25/kg (Figure 11.7). For hydrogen and fuel cell-based energy storage (e.g. storage of electricity from renewables) to become competitive, the cost of hydrogen supplied must be CNY15/kg or lower (Figure 11.8).

**Figure 11.6. Hydrogen Supply Cost (Covering Production, Storage, Transportation, and Dispensing) that Makes Fuel Cell-Based Commercial Vehicles Competitive**



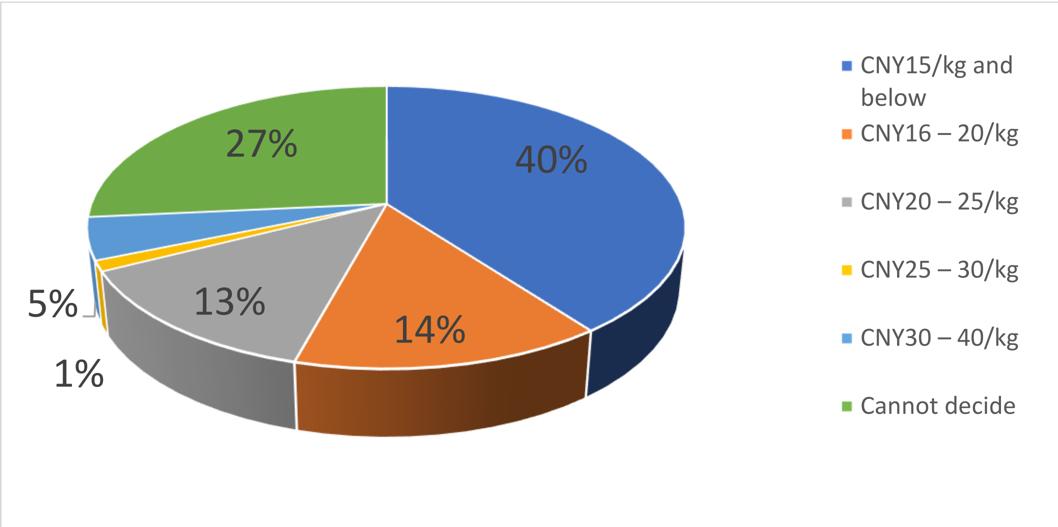

Source: Authors' survey.

**Figure 11.7. Hydrogen Supply Cost (Covering Production, Storage, Transportation, and Dispensing) that Makes Fuel Cell-Based Passenger Vehicles Competitive**




Source: Authors' survey.

**Figure 11.8. Hydrogen Supply Cost (Covering Production, Storage, Transportation, and Dispensing) that Makes Hydrogen and Fuel Cells Competitive in Energy Storage Applications**




Source: Authors' survey.

The competitive levels of the cost of fuel cell stacks follow a similar pattern in the above-mentioned three blocks of end-use applications. For fuel cell vehicles, the stack costs must be in the range of CNY500–1,000/kW or lower. For energy storage uses, the stack costs must be lower than CNY500/kW.

Other questions related to the economics of hydrogen and fuel cells are on the market side, especially the economic benefits other than the revenue from supplying hydrogen. When asked about the desirable prices of carbon emissions, the majority of the experts indicated that prices at CNY100–200/tonnes of $CO_2$ would make hydrogen and fuel cells competitive.

Currently, carbon markets around China generate prices lower than CNY100/tonne, with Shanghai, Guangdong, and Fujian prices between CNY17–40/tonne (Tanjiaoyi, 2020). Experts also indicate that, by providing energy storage, peak shaving, and frequency modulation, the remuneration to such grid services should consist of 10%–20% of the income of grid-connected hydrogen and fuel cell applications.

## 5. A Strategic Roadmap for Developing Large Green Hydrogen Projects in China

### 5.1. Experts' projections

The experts stated an integrated policy framework is called for in view of the complexity of challenges in realising the green hydrogen vision. On the one hand, policy tools to support research, development of supply chains, investment in the infrastructure network, and creation of downstream market demand are called for as direct support. On the other hand, general policy issues such as the development of standards and regulation systems, preparation of required human resources, integrating green hydrogen into carbon emissions trading, and establishing pricing and remuneration mechanisms for integrating hydrogen energy storage into the electricity market and auxiliary service market are called for as indirect support.

Table 11.8 and Table 11.9 present the projections by surveyed experts on the time sequence or priority of developing hydrogen energy applications, as well as the corresponding infrastructure in China. On the application side, commercial vehicles, light trucks, and municipal service vehicles based on fuel cell technologies are prioritised for deployment within 5 years. On the supply infrastructure side, grey hydrogen from fossil fuel and industrial by-products, blue hydrogen from fossil fuels with CCS, and compressed hydrogen transportation and storage will be prioritised for development within 5 years.

The results suggest that hydrogen as energy storage for renewables may also see developments in the near-term (5 years) and perhaps at large scale only in the mid-term (10 years), according to the two tables. Other applications and infrastructures will mostly be developed in the mid-term.

**Table 11.8. Projections on the Timeline of Developing Hydrogen Energy Applications in China**

| Item\Option | Near-term (in 5 years) | Mid-term (5-10 years) | Long-term (10 years and above) | Cannot decide |
|---|---|---|---|---|
| Fuel cell commercial vehicles | 45(54.9%) | 26(31.7%) | 7(8.5%) | 4(4.9%) |
| Fuel cell light trucks/municiple service fleet | 48(60.0%) | 20(25.0%) | 7(8.8%) | 5(6.3%) |
| Hydrogen energy storage/power gen/heating | 26(31.7%) | 28(34.1%) | 24(29.3%) | 4(4.9%) |
| Fuel cell passenger vehicles | 22(27.2%) | 37(45.7%) | 17(21.0%) | 5(6.2%) |
| Fuel cell railway | 18(21.7%) | 29(34.9%) | 28(33.7%) | 8(9.6%) |
| Fuel cell drone/aircraft | 21(25.9%) | 31(38.3%) | 20(24.7%) | 9(11.1%) |
| Fuel cell ships | 15(18.5%) | 30(37.0%) | 26(32.1%) | 10(12.3%) |

Source: Authors' survey.

**Table 11.9: Projections on the Timeline of Developing the Relevant Hydrogen Energy Infrastructure in China**

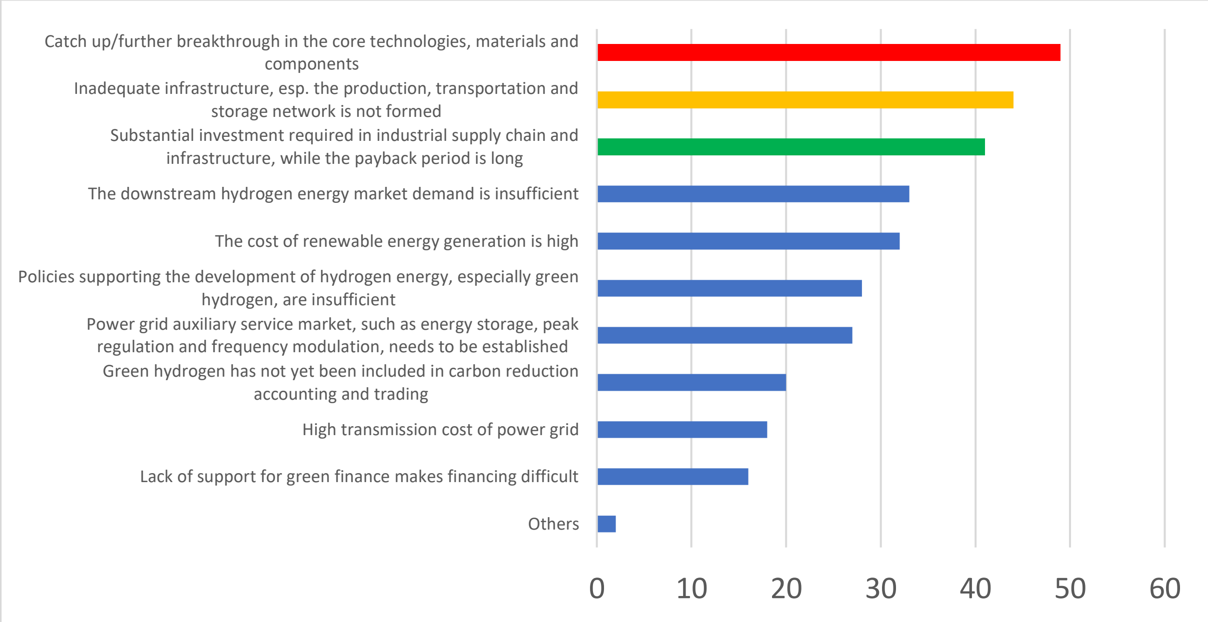
| Item\Option | Near-term (in 5 years) | Mid-term (5-10 years) | Long-term (10 years and above) | Cannot decide |
|---|---|---|---|---|
| Fossil fuel to hydrogen (coal, natural gas, petroleum) | 50(61.7%) | 15(18.5%) | 8(9.9%) | 8(9.9%) |
| Industrial byproduct hydrogen | 50(62.5%) | 20(25.0%) | 6(7.5%) | 4(5.0%) |
| Fossil fuel to hydrogen with CCS | 33(42.3%) | 26(33.3%) | 11(14.1%) | 8(10.3%) |
| Renewables to hydrogen | 31(38.3%) | 33(40.7%) | 12(14.8%) | 5(6.2%) |
| Compressed hydrogen transport and storage | 53(63.9%) | 20(24.1%) | 6(7.2%) | 4(4.8%) |
| Liquid hydrogen transport and storage | 26(32.1%) | 40(49.4%) | 11(13.6%) | 4(4.9%) |
| Hydrogen pipeline | 13(15.9%) | 35(42. 7%) | 29(35.4%) | 5(6.1%) |
| Liquid organic hydrogen carriers (LOHCs) | 13(15.9%) | 32(39.0%) | 23(28.0%) | 14(17.1%) |
| Liquid ammonia for hydrogen transportation | 16(19.5%) | 32(39.0%) | 25(30.5%) | 9(11.0%) |
| Liquid solar fuel (methanol) for hydrogen transportation | 19(23.5%) | 29(35.8%) | 23(28.4%) | 10(12.3%) |
| Solid hydrogen carriers | 15(18.5%) | 22(27.2%) | 31(38.3%) | 13(16.0%) |

CCS = carbon capture sequestration.
Source: Authors' survey.

Next, this round of questionnaires briefly touched on how to realise such visions. In this regard, Figure 11.9 evaluates the most important challenges faced by China in developing green hydrogen. Figure 11.10 ranks the issues that policies should focus on in order to support the development of green hydrogen in China.

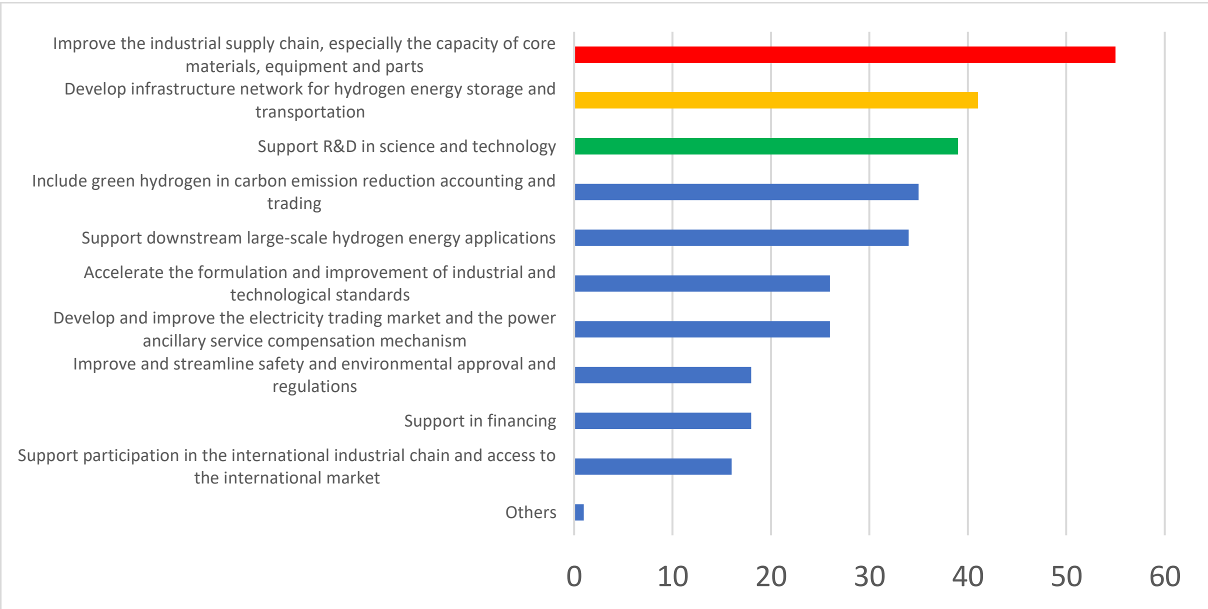
Technological catching up is the most highlighted challenge, followed by infrastructure development and the financing of such investments. On the policy front, developing the domestic supply chain capacity, formation of a hydrogen energy infrastructure network, and supporting research and development are the most highly ranked policy issues.

**Figure 11.9: The Major Challenges Faced by China in Developing Green Hydrogen**




Source: Authors' survey.

**Figure 11.10: The Issues that Policies Should Focus on in Order to Support the Development of Green Hydrogen in China**




Source: Authors' survey.

## 5.2. A strategic roadmap

Based on the survey results and the analytical framework presented in Section 3, this section briefly presents the roadmap according to the three stages and across five areas (Table 11.10).

The surveyed experts believe that developing large-scale green hydrogen needs a systematic view. The design of the whole hydrogen-based supply chain on the specific geographical location, the choice of transport and storage technologies, and the size of the system would all matter significantly in the total cost of hydrogen supplied at the user end, such as a fuel cell power plant or an HRS.

On the policy front, the development of hydrogen needs an enabling environment that recognises and rewards its value. Across the supply chain and different stages, such an enabling environment could be created through the integration of the power and gas sectors; sector coupling; integrating buildings, transport, and industry with the power generation sector; and decarburisation targets at sectoral and regional levels. Carbon pricing and certification, or a guarantee of origin system, is also essential to make green hydrogen cost-competitive with fossil fuel hydrogen.

The first column of Table 11.10 records the overall strategies across all stages. For the technological part, the key strategy is to promote R&D to continuously bring down the production cost. For infrastructure, the time-invariant strategy is applying hydrogen as energy storage to increase the penetration of VREs. On the application part, the common strategy over time is sector coupling that can maximise the value of hydrogen. On the law and regulation aspect, the key strategy is to have appropriate regulations and safety standards. From the policy perspective, the overarching strategies are carbon prices, green certification, and power markets and other market mechanisms that reward the value of hydrogen as energy storage and peak generating capacity and green hydrogen as low-carbon energy.

At the current **Technology Readiness** stage (the second column of Table 11.10), the technological priorities are demonstration projects for green hydrogen production and hydrogen applications, such as FCEVs. Applications should focus on early commercially viable applications, like the expansion of FCEVs for heavy-duty vehicles and buses. Grey hydrogen from fossil fuel and industrial by-product, blue hydrogen from fossil fuels with CCS, and compressed hydrogen transportation and storage will be prioritised for development within 5 years. Such transport adoptions will also need the support of refueling infrastructure. At this stage, laws and regulations should be flexible to allow new technologies and ideas being tested. Policy support needs to prioritise the creation of downstream market demand for hydrogen energy. State fundings in R&D and demonstration projects will leverage the technological development and applications. Since hydrogen development is a common challenge to decarbonise the economy, global cooperation is desirable.

For the next **Market Penetration** stage (Table 11.10, column 3), the key feature of the strategy will be promoting scaling up. The production of green hydrogen will see the size of electrolysers becoming larger and more cost competitive. The falling production and equipment costs will enable new applications. Hybrid systems, such as CCHP-Hydrogen-Solar Energy, can increase the commercial viability of green hydrogen. Infrastructure that links green hydrogen supply and demand centres will be developed, including facilities that support international trade of hydrogen. Pure hydrogen pipelines may be developed between major VREs sites and demand centres. In addition to the increasing use of storage for VREs, hydrogen applications will be extended to other sectors, such as shipping, steelmaking, refineries, and chemical industries. Regulatory frameworks need to be clearer for market participants to attract investment. Policy incentives will gradually exit and transition from direct support to scalable market-based mechanisms. For example, the public-private partnership can be promoted to leverage private investment to scale up hydrogen on the full supply chain.

In the final **Market Growth** stage (Table 11.10, column 3), policy support will be gradually phased out and the private sector will lead the investment to escalate hydrogen development. Since green hydrogen will become cost-competitive in this stage, the scope of hydrogen and fuel cell applications has been maximised in the transport sector, and commercial application of hydrogen for heating and power generation emerges. For example, hydrogen may be blended into gas networks for heating and power generation. With the shrink in gas demand, some gas networks may be repurposed to translate pure hydrogen. Regulation will need to be clear to provide a stable environment for the investors. However, with the development of international trade, green hydrogen needs to be distinguished from fossil fuel-based hydrogen in order to maintain its momentum. A functional institution should be in place to prevent grey hydrogen production relocation to other places (so-called 'carbon leakage') and maintain a fair playing field for green hydrogen.

**Table 11.10: A Strategic Roadmap of Chinese Green Hydrogen**

| | Across stage | Technology Readiness (Current) | Market penetration | Market growth |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Technology | Research Development and Demonstration (RD&D) | Green hydrogen demonstration project in regions with abundant Variable Renewable Energies (VREs). | Breakthrough in Polymer Electrolyte Membrane (PEM) fuel cell and hydrogen transportation;<br>Increasing the size of electrolyser;<br>Scaling up production. | Cost competitive electrolysis. |
| Infrastructure (Storage and Transport) | Developing hydrogen infrastructure as energy storage for VREs. | Financing refuelling station and other infrastructure. | Pure hydrogen connections developed between VREs and demand centres;<br>Upgrade gas pipeline networks for blended hydrogen;<br>Global trading facilities | Gas pipeline systems repurposed for pure hydrogen transportation;<br>National wide refueling infrastructure. |
| Applications | Sector coupling;<br>Identification of the highest-value applications. | Pilot hydrogen use across applications, such as Fuel Cell Electricity Vehicles (FCEVs) for heavy-duty vehicles and buses. | Hybrid systems;<br>More popular use of FCEVs;<br>Extended to aviation and shipping, steelmaking, refineries and chemical industries. | Import/export of green hydrogen;<br>Power system decarbonised;<br>Extended to heating and power generation. |
| Regulations and standards | Safety first, with adaptive regulations. | Flexible regulations;<br>Green hydrogen standards;<br>Risk mitigation. | Clear regulatory frameworks;<br>Synergies and combined systems;<br>Standards for global trading. | Prevention of carbon leakage for a fair global trading. |
| Policy | Carbon pricing;<br>Green hydrogen certificate;<br>Electricity market (Power and Auxiliary services);<br>International collaboration. | **Strategic investment/** RD&D funding (Program);<br>Decarbonisation targets;<br>Creation of downstream market demand for hydrogen energy through incentivising applications. | Supporting policy exit;<br>Public-private partnerships;<br>Establishment of power market mechanisms to reflect the value of hydrogen as energy storage and peak generating capacity;<br>Extending carbon emissions trading to the green hydrogen supply chain. | Private sector driving without financial support; foster international trading hubs for low-carbon hydrogen. |

Source: Authors' deliberation.

## 6. Conclusions

Although hydrogen has enjoyed unprecedented political and business momentum, large-scale green hydrogen development has yet to be realised, especially in China. While the technological roadmap has been charted out officially in government policy documents, policy suggestions from the literature are abundant but static, without a timeline for implementation. Thus, there is no consensus regarding who should do what at different stages of hydrogen energy development in China to accelerate the development and commercialisation of green hydrogen. The further investigation of large-scale green hydrogen development in China can inform the academic literature and policy debates.

This report applies the roadmapping method to structure the presentation of implications on the development of green hydrogen technologies in China. The implications were collected from an expert survey and validated from results in other chapters.

The survey of green hydrogen development suggests that it is not cost-competitive within the next 5 years. However, given the need to decarbonise the Chinese economy and the transport sector, large-scale hydrogen applications are required. These will need a technological breakthrough throughout the supply chains, from production and transportation to applications. Flexible regulations with appropriate standards are also required. While policy support in the current stage is needed, in the final Market Growth stage, green hydrogen should be competitive without support. The private sector, while needing leverage from governments in the current stage, will be the key players in the future.

In the current Technology Readiness stage, the following policies implications are suggested:

1. The R&D and green hydrogen demonstration projects in VRE resource-rich regions should be promoted. The pioneering large-scale green hydrogen project in Zhangjiakou city should provide useful lessons and implications for others. Other planned large-scale green hydrogen projects need to proceed for diverse experiences. The next stage will depend on breakthroughs in production and storage technologies.
2. The current stage needs to further promote research and pilot infrastructure for storage and transport. This infrastructure development will test the two applications of hydrogen. Hydrogen at this stage does not necessarily to be green. Further development of hydrogen will focus on the transportation of hydrogen and blending gas. Ultimately, the existing gas infrastructure should be repurposed for pure hydrogen transportation while new facilities are ready to support international trading of hydrogen.
3. Regarding applications, the current priority is to explore hydrogen’s coupling role and apply it in the highest value applications, mainly in public transport. The second stage will see the extension of hydrogen to aviation and shipping, steelmaking,

refineries, and chemical industries. The final extension of hydrogen will be to power generation and heating.

4. On the premise of safety, the regulation should be adaptive so that the early development of hydrogen will not be unnecessarily limited. Further development of regulations will be stable and predictable so that investors will have confidence. In the final stage, the priority of regulations will be how to prevent carbon leakage.

5. The key policy principle is to reward hydrogen for its versatility for coupling and emerging backup and the low-carbon nature of green hydrogen. At the current stage, strategic governmental R&D and seed investment are productive tools. Decarbonisation targets and incentives for hydrogen applications could provide a long-term and short-run boost to hydrogen development, respectively. However, over time, government support needs to be gradually phased out and the private sector will drive the development without financial support in the final stage.

A key feature of this roadmap, and roadmapping in general, is dynamics and flexibility. Therefore, regular review and update of the roadmap is essential.

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**Appendix**

The questionnaire covers mainly the following questions:

1. What is the progress of the current renewable-to-gas projects (project size, capacity, location), if any? What is the next step? What are the technical, economic, institutional barriers/challenges?
2. What are the top three challenges that prevent the scale-up of green hydrogen production?
3. What are the top three factors to facilitate the scale-up of green hydrogen production?
4. Could you give your reflections on the effectiveness of the current promotive policies on hydrogen energy and fuel cell in your province/city as well as the country as a whole?
5. Which of these policies work well and which do not? What are the key mechanisms that render these policies working or not working?
6. SWOT: What are the strengths that your province/city has in the near future in developing hydrogen and fuel cell industries, infrastructure, and downstream applications (transport sector or power sector)?
7. SWOT: What are the weaknesses that your province/city has in the near future in developing hydrogen and fuel cell industries, infrastructure, and downstream applications (transport sector or power sector)?
8. SWOT: What are the opportunities that your province/city are facing in the near future in developing hydrogen and fuel cell industries, infrastructure, and downstream applications (transport sector or power sector)?
9. SWOT: What are the challenges that your province/city are facing in the near future in developing hydrogen and fuel cell industries, infrastructure, and downstream applications (transport sector or power sector)?
10. At the national level, what policies would become key accelerators (are needed) in the development of hydrogen and fuel cell industries, infrastructure, and downstream applications (transport sector or power sector)?
11. At the provincial/municipal level, what policies would become key accelerators in the development of hydrogen and fuel cell industries, infrastructure, and downstream applications (transport sector or power sector)?