Chapter 11

A Strategic Roadmap for Large-Scale Green Hydrogen Demonstration Projects: Case studies from China

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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

		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

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); 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.

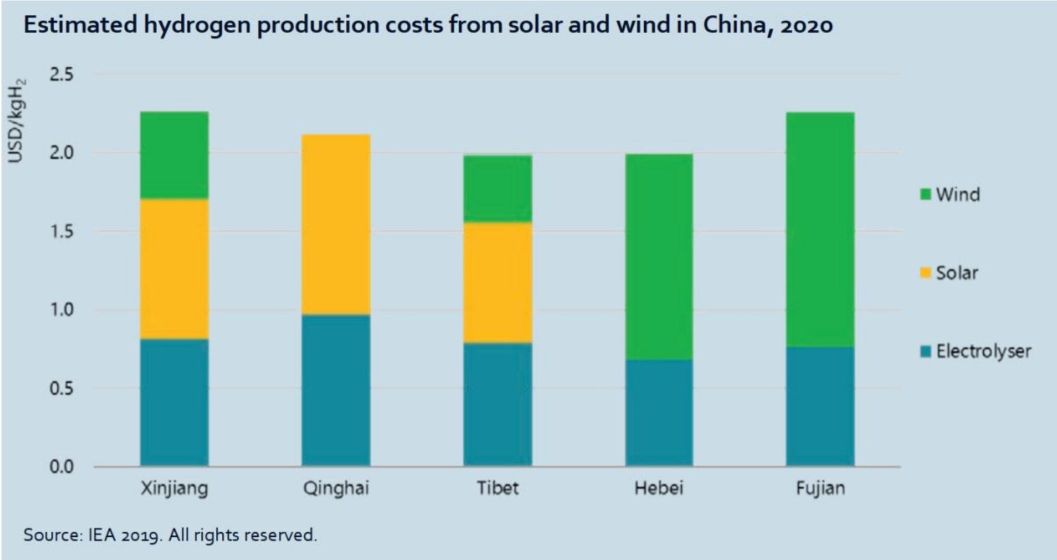
A brief elaboration of the literature and questionnaire survey results is presented in the SWOT framework below.

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).

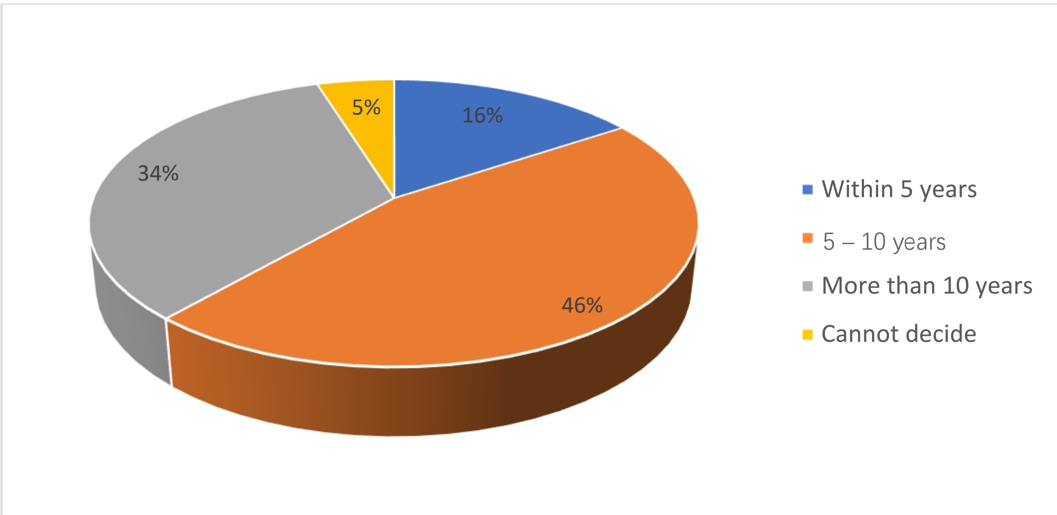
Figure 11.1: Estimated Hydrogen Production Costs from Solar and Wind in China, 2020



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).

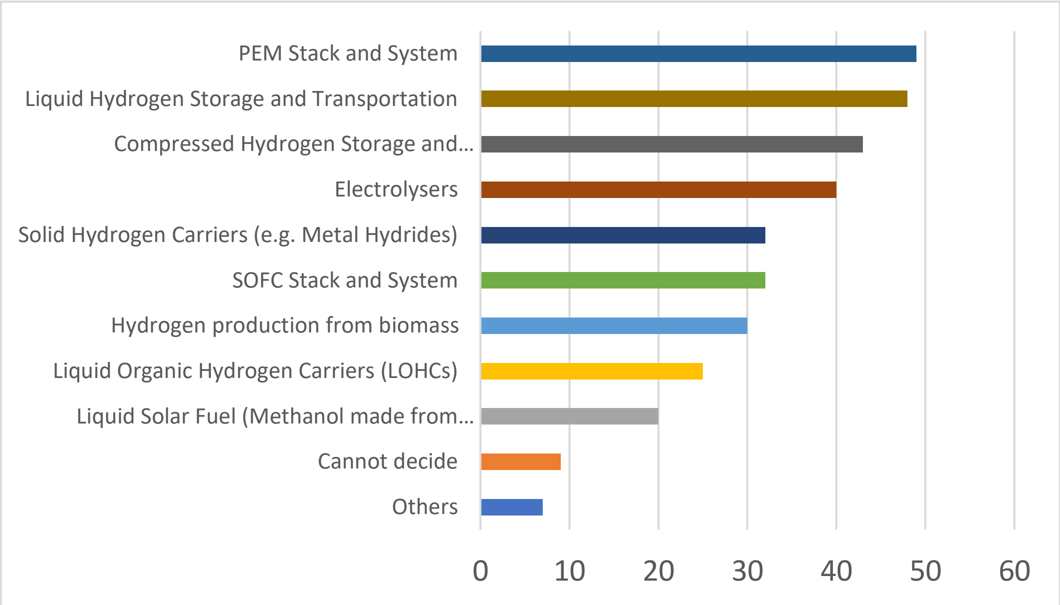
Figure 11.2. Timeline for Hydrogen Produced from Renewables to Become Massively Adopted for Commercial Applications in China



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).

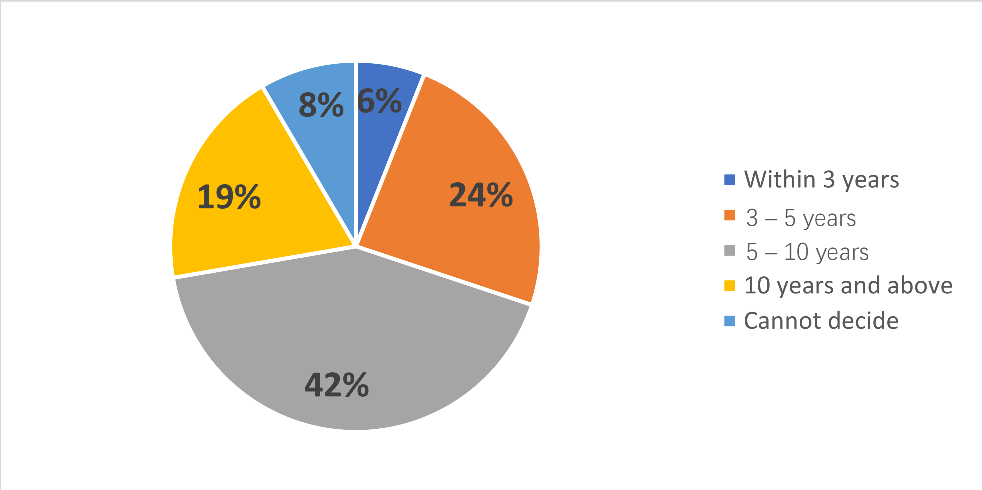
Table 11.5. Adequacy of the Current Policy Support Provided at Various Levels of the Chinese Government on Hydrogen and Fuel Cell Industries and Applications

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).

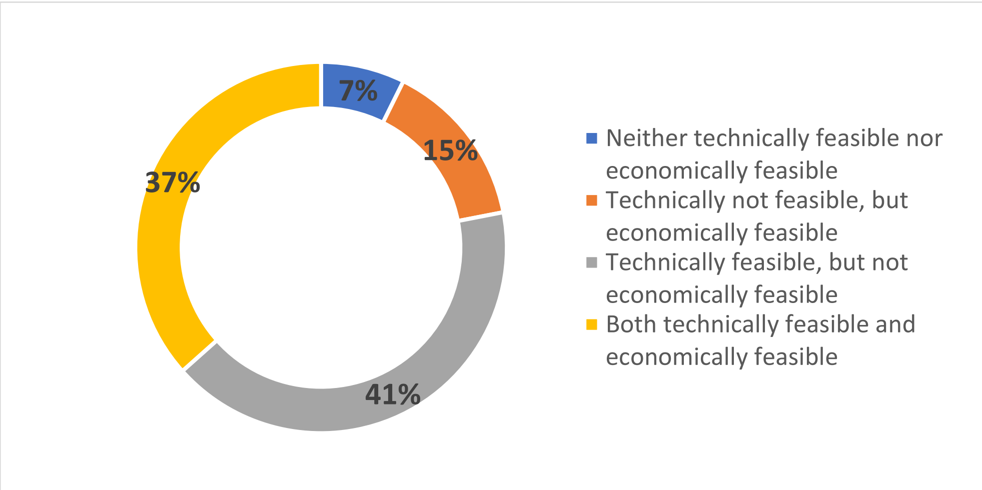
Table 11.7. The Ideal Share of Green Hydrogen in the Energy Consumption of China by 2050

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.

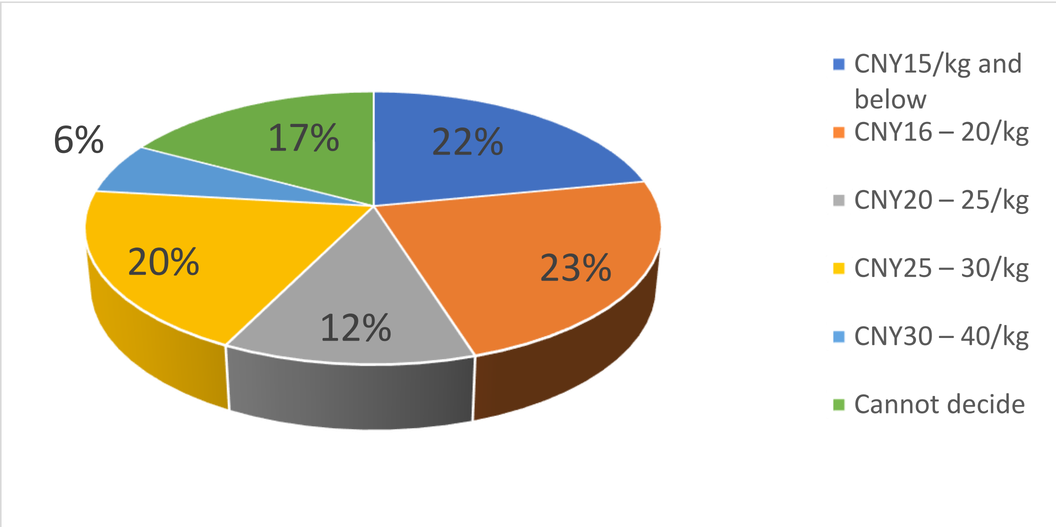
4.4. Threats

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.

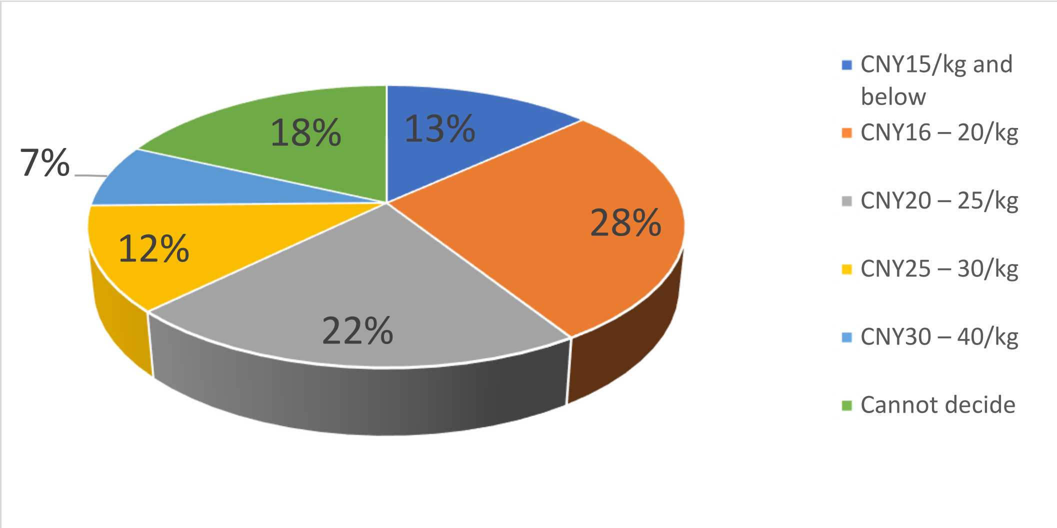
For fuel-cell commercial vehicles (e.g. buses and trucks) to become competitive and thus widely adopted, it would require the hydrogen supply cost (covering production, storage, transportation, and dispensing) to be in the range of CNY16–20/kg or lower (Figure 11.6). For fuel cell passenger vehicles, 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



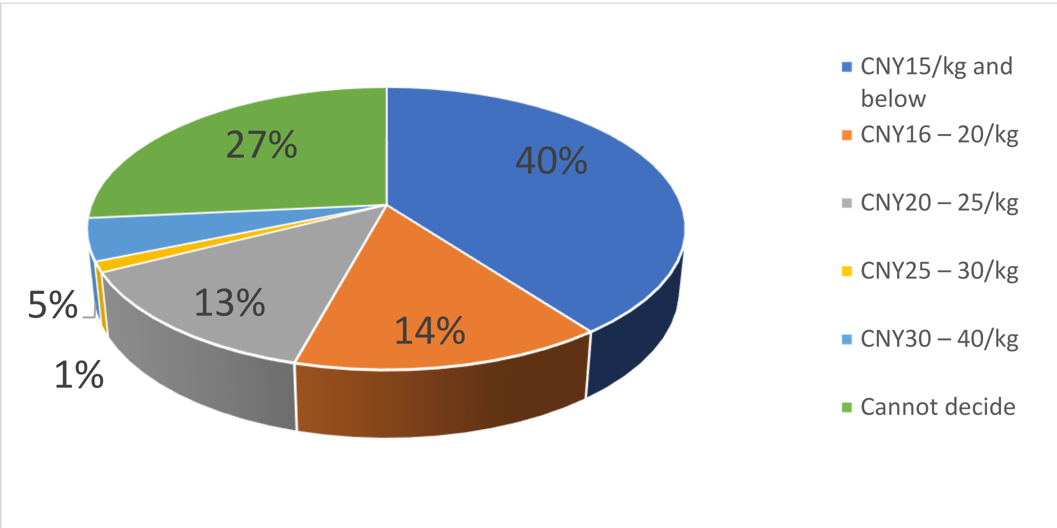
Source: Authors' survey.

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

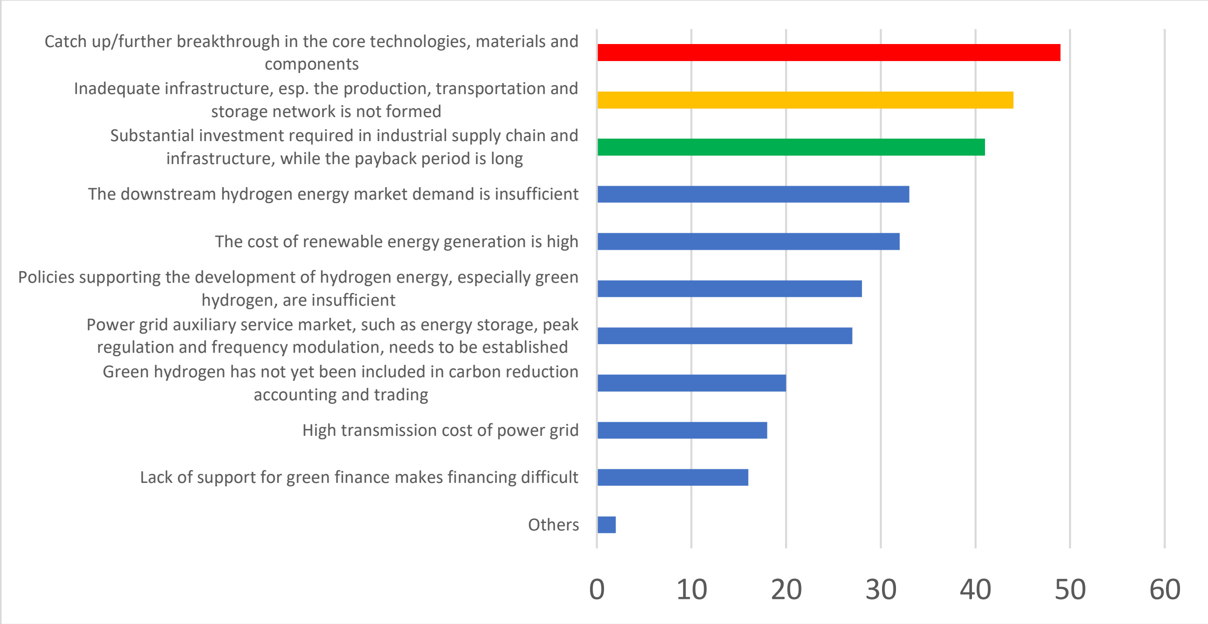
Item\Option	Near-term (in 5 years)	Mid-term (5-10 years)	Long-term (10 years and above)	Cannot decide
Fossil fuel to hydrogen (coal, natural gas, petroleum)	50(61.7%)	15(18.5%)	8(9.9%)	8(9.9%)
Industrial byproduct hydrogen	50(62.5%)	20(25.0%)	6(7.5%)	4(5.0%)
Fossil fuel to hydrogen with CCS	33(42.3%)	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.

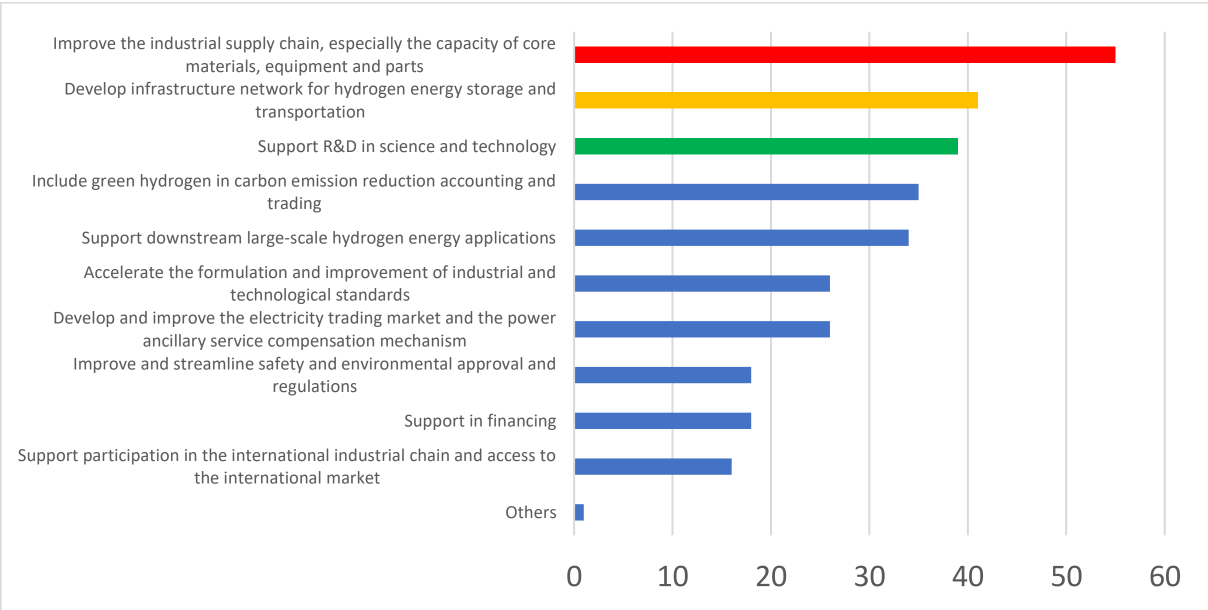
Technological catching up is the most highlighted challenge, followed by infrastructure development and the financing of such investments. On the policy front, developing the domestic supply chain capacity, formation of a hydrogen energy infrastructure network, and supporting research and development 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; Increasing the size of electrolyser; 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; Upgrade gas pipeline networks for blended hydrogen; Global trading facilities	Gas pipeline systems repurposed for pure hydrogen transportation; National wide refueling infrastructure.
Applications	Sector coupling; 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; More popular use of FCEVs; Extended to aviation and shipping, steelmaking, refineries and chemical industries.	Import/export of green hydrogen; Power system decarbonised; Extended to heating and power generation.
Regulations and standards	Safety first, with adaptive regulations.	Flexible regulations; Green hydrogen standards; Risk mitigation.	Clear regulatory frameworks; Synergies and combined systems; Standards for global trading.	Prevention of carbon leakage for a fair global trading.
Policy	Carbon pricing; Green hydrogen certificate; Electricity market (Power and Auxiliary services); International collaboration.	**Strategic investment/** RD&D funding (Program); Decarbonisation targets; Creation of downstream market demand for hydrogen energy through incentivising applications.	Supporting policy exit; Public-private partnerships; Establishment of power market mechanisms to reflect the value of hydrogen as energy storage and peak generating capacity; 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)?