Chapter 7

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

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Chapter 7

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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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