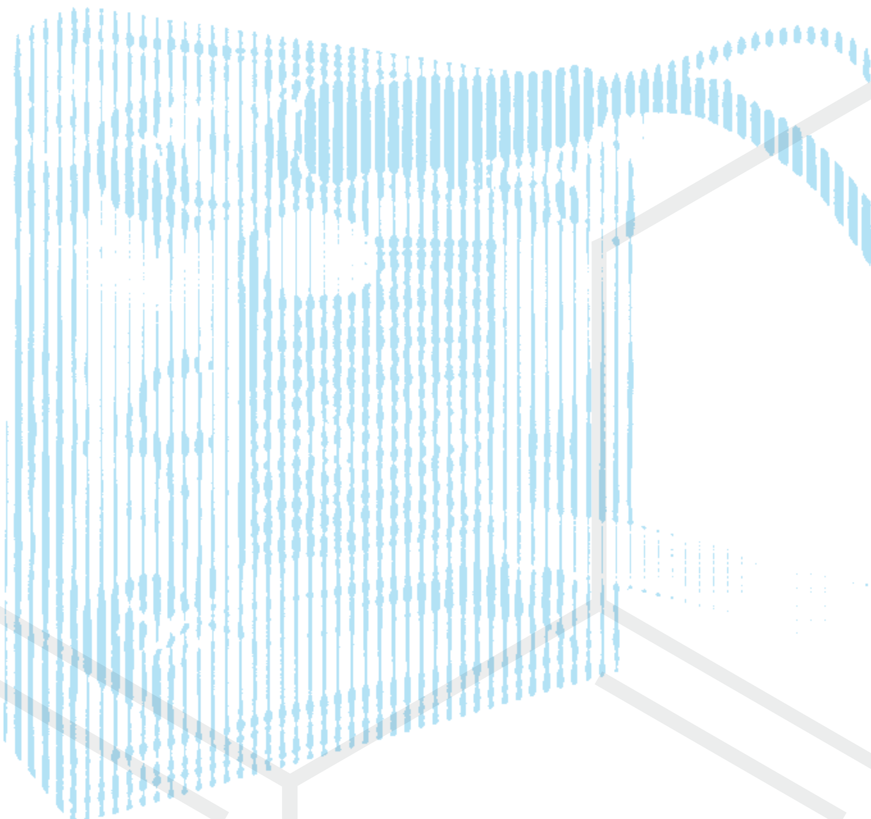
Global Challenges in Focus

Progress in hydrogen fuel cell technology development and deployment in China



Hongxing (Tonny) Xie*
Peter Oksen**
Xingxing Guo*
Xin He*
Yue Bian*

*Bluetech Clean Air Alliance, Beijing
**WIPO GREEN, Geneva

With contributions from
Wanyi Wang, United Nations Development Programme (UNDP) China Office, and
Ziyuan Wang, Foshan Institute of Environment and Energy Technology, China

BCAA
中关村创蓝清洁空气产业联盟
BLUETECH CLEAN AIR ALLIANCE

WIPO
WORLD
INTELLECTUAL PROPERTY
ORGANIZATION

Executive summary

Hydrogen has several potential advantages as an energy form and storage medium in relation to climate change and environmental impacts. However, current hydrogen use is based almost exclusively on fossil fuel, and this means it is not climate change neutral or beneficial. Major technological advances are being made towards producing "green hydrogen," but this remains more expensive than fossil-based hydrogen. Hydrogen-use technologies are also being developed, but few are ready to be scaled up, so hydrogen as a form of clean energy remains largely a technology of the future.

The potential is nevertheless so attractive that many governments worldwide have formulated development plans for hydrogen and, together with the private sector, they are investing significantly in research and development. In China, hydrogen and fuel cells are expected to play an important role in fulfilling the official pledge of national carbon neutrality by 2060 and are already embedded in numerous economic development plans and policies. More than 100 standards to regulate the production and use of hydrogen in China have been formulated, which is a prerequisite for scaling up the technology. Innovation in the field has increased dramatically in recent years, and this is reflected in the current global dominance of Chinese-based patent applications. Several Chinese provincial governments and industrial city clusters have embarked on ambitious programs to develop and promote hydrogen in transport – notably heavy-duty and long-haul transport – and industry.

Despite the technological and economic obstacles associated with scaling up and mainstreaming hydrogen-based energy, there are strong indications that the political will and economic means are there to make it an important complement to other new and renewable energies.

Introduction

Hydrogen is high on the political and innovation agenda of many countries, research institutions and companies. It is a highly versatile energy storage medium with great potential for contributing to a transition towards carbon-neutral energy. However, hydrogen sources are dominated by fossil fuels, and the technical and economic challenges to scaling up the use of hydrogen remain considerable. This report provides an overview of current hydrogen and fuel cell technology trends internationally, and a focused review of China, the largest deployment market for hydrogen and fuel cell technologies. In recent years, China has actively promoted research and development (R&D), demonstration and commercial applications of hydrogen technologies. The report provides insights into current policy, planning, standards, patents, pilot projects and demonstration activities in hydrogen and fuel cell development in China.

Hydrogen and fuel cell technology – international trends and potential

The advantage of hydrogen as an energy storage medium

Hydrogen as an energy source is gaining international momentum, and is being strongly promoted in business and policies. Several technologies are available that can harness the advantages of hydrogen. To make it economically attractive, however, further development and scaling up is required (IEA, 2019). That makes any assessments of its future role as a source of energy and storage medium uncertain.

Hydrogen is a colorless and odorless gas, and is the most abundant element on Earth and in the universe. It is energy-dense and combustible with oxygen, producing thermal energy with water as residue, and is therefore a fuel with no carbon dioxide (CO_2) or other unwanted gas emissions in the end-use process. In the transport sector, for example, that can help to improve air quality in large cities. It is a potentially clean and unlimited energy source that is already used in many chemical and other industries. Unfortunately, it does not exist in nature in a pure form and must therefore be produced.[1]

Clean and dirty hydrogen: green, gray, brown and blue

More than 95 percent of the hydrogen produced today originates in fossil fuels, with natural gas being the dominant source. Around 6 percent of natural gas extracted globally and 2 percent of coal is used to produce hydrogen (IEA, 2019). Natural gas is the cheapest source of hydrogen, and steam methane reforming (SMR) is the most common production method. Hydrogen produced in this way is often referred to as gray hydrogen. The process takes place at temperatures of between 700°C and 1100°C, and is energy intensive. Moreover, by-products include CO_2 and other greenhouse gases. The production of 1 ton of hydrogen can result in the production of more than 9 tons of CO_2, which is close to the level of emissions resulting from the combustion of gasoline (1 kg of hydrogen is energy equivalent to 1 gallon of gasoline, which emits around 9 kg of CO_2) (Rapier, 2021). Gasification of coal is a widespread source of hydrogen in several countries, often referred to as brown hydrogen. With the application of water and heat the coal produces syngas, which is a mixture of CO_2, carbon monoxide, hydrogen, methane and ethylene. The process is highly polluting and has been in use for hundreds of years, producing what was often referred to as "town-gas" (Farmer, 2020).

1 Hydrogen is not a primary source of energy like oil, coal, wind or solar but is more comparable to an energy carrier or medium such as electricity. In this report, we do not dwell on that distinction, as it is of little practical consequence. We therefore refer to hydrogen both as a source of energy and as a storage medium.

Production of hydrogen creates CO_2 emissions equivalent to those of Indonesia and the United Kingdom put together (IEA, 2019). The use of hydrogen today is, therefore, not carbon neutral; it can be seen as a fossil fuel in the same family as oil, coal and, of course, natural gas.

However, producing carbon-neutral, or green, hydrogen is perfectly possible. This area of technology is developing rapidly, although it remains more expensive than natural gas. Rather than using natural gas as a raw material to produce hydrogen, water can be split into hydrogen and oxygen by electrolysis, whereby the anode produces oxygen and the cathode hydrogen. The process requires a lot of electricity, but if that electricity comes from renewable energy sources, the hydrogen will likely be carbon neutral. Regions with abundant renewable energy, such as the Middle East, northern Africa, South America and Australia (solar energy), could become hydrogen production regions. It is not unrealistic that green hydrogen could hit cost parity with gray hydrogen as early as 2030 (Hydrogen Council and McKinsey, 2021). The European Union is aiming to achieve 40 GW of electrolyzer capacity by 2030, which indicates strong political will to develop green hydrogen quickly. It is forecast that about 17 percent of all hydrogen produced in China will be green by 2030, and that the total amount of green hydrogen produced annually will exceed 18 million tons (China Hydrogen Alliance, 2019).

Nonetheless, green hydrogen needs to be scaled up significantly to compete with gray and brown hydrogen. Optimistic calculations of break-even points between green and gray hydrogen include provision for policy support initiatives such as carbon taxes (Hydrogen Council and McKinsey, 2021).

Another option is to replace natural gas with biogas in the hydrogen production process. Biogas is most commonly produced through anaerobic digestion of waste biomass, gasification, or extraction of landfill gas, but it must be upgraded to biomethane with the same high (more than 90 percent) level of methane content that characterizes natural gas. That process also requires energy, but it can be quite efficient, with up to 87 percent of the methane contained in the biogas separated. Pure hydrogen can then be produced from the biomethane using the SMR process in a similar fashion to the process using natural gas (Saur and Milbrandt, 2014).

Converting biogas directly to hydrogen is also possible. A pilot plant financed by the European Union is in operation in Italy. It uses a palladium-based membrane reactor technology (combined chemical conversion and membrane separation process), which can produce hydrogen with a 70 percent conversion efficiency at a relatively low temperature of around 500°C (CORDIS, 2020).

By using carbon capture and storage (CCS) technology in the natural gas extraction process, low-carbon hydrogen can be produced. CCS technology removes by-products that are harmful to the climate. It still requires considerable development but, by some estimates, it could be commercially competitive with gray hydrogen by 2030 (Hydrogen Council and McKinsey, 2021). Others, however, are much less optimistic (Barnard, 2021). Hydrogen produced from fossil fuels using CCS technology is commonly known as blue hydrogen.

Supply-side considerations are not addressed to a large extent in this report, the focus of which is on current hydrogen use technologies and those under development, rather than the hydrogen production process. Remember, though, that the technologies discussed are no greener or more carbon neutral than the hydrogen that feeds them. A hydrogen-based technology on its own is not necessarily green at all.

Hydrogen technology

Hydrogen has great potential in several economic sectors. Generally, it enters the energy system as a storage medium or fuel. The energy can be extracted through direct combustion or electro-chemical conversion in fuel cells. It can be transported as a gas or in liquid form, similar to liquefied natural gas. Paste-based forms of hydrogen are also being developed, which may extend the application of hydrogen in transport (Burgess, 2021). Here the hydrogen is chemically bound in stable solid magnesium hydride and can be released by adding water in a controlled process. Hydrogen offers potentially superior refueling times and driving ranges for heavy and long-haul transport and personal vehicles compared with current battery-based electric vehicles (EVs). Hydrogen also has considerable potential for storage of excess renewable energy from hard-to-control sources such as wind or solar. The excess energy can feed into a water-electrolysis process, whereby hydrogen is produced for storage, transport and consumption.

Direct fuel

Hydrogen can be used as fuel in several sectors. It can be used in gas turbines to generate power. In buildings it can be mixed with natural gas in existing gas networks for domestic use. It can also be used as fuel in internal combustion engines, which is especially relevant for heavy vehicles such as trucks, but it is also increasingly being viewed as an alternative low-carbon fuel for aviation and shipping (IEA, 2019). Shipping accounts for 2 percent of global greenhouse gas emissions, 80 percent of which are generated by long-distance vessels. Currently, the most economic path toward zero emissions in shipping is to use ammonia as fuel in internal combustion engines. Ammonia can be produced from hydrogen by adding nitrogen from air in the Haber-Bosch process. Liquid ammonia, unlike liquid hydrogen, does not require refrigeration to extreme temperatures. It also has higher energy density and is therefore efficient to transport. However, fueling all long-distance shipping with ammonia would require a three- to four-fold increase in current global ammonia production (Hydrogen Council and McKinsey, 2021; Yara, 2021).

Fuel cells

Fuel cells employ an electro-chemical process that produces electricity from hydrogen and oxygen without any intermediate storage or combustion. The process is reportedly twice as efficient as internal combustion engines and turbines (Nahar *et al.*, 2017) and the waste product is water and, in the case of some fuel cell types, CO_2.

Fuel cells are similar to batteries in their function but require a constant supply of fuel in the form of hydrogen and oxygen (air). Fuel cells are scalable and can be used as small, low-wattage power supply units (such as for domestic or vehicle use), or as large industrial energy storage or megawatt power plants. The technology has been in use since the 1960s and is thus relatively mature. It was famously used in the NASA Space Shuttle program to provide onboard electricity and drinking water.

Like a battery, a fuel cell is composed of an anode, a cathode and an electrolyte. Fuel cells exist in several forms, depending on the materials used. In some cases, the electrodes (anode and cathode) are made of noble metals like platinum, making them expensive. The electrolyte may be solid or liquid. The electro-chemical process generates heat, with some systems operating at high temperatures (700–1000°C) and others functioning at temperatures well below 100°C. Energy conversion efficiency varies from 60 percent to 70 percent but can be increased to more than 80 percent if the heat generated is utilized productively in co-generation systems (Hydrogen Europe, 2021). The most common types of fuel cells, each with distinct efficiency, cost and maintenance characteristics, are proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), alkaline fuel cells (AFCs), molten carbonate fuel cells (MCFCs) and phosphoric acid fuel cells (PAFCs).

The PEMFC is the most commonly used fuel cell in vehicles. It deploys a polymeric membrane as the electrolyte and carbon electrodes containing platinum. The latter makes such cells relatively expensive, but the platinum can be recycled, and research is being done on alternatives that may reduce costs.

Figure 1. Principles of PEMFCs (Hydrogen Europe, 2021).

PEMFC – Proton Exchange Membrane Fuel Cells

- Electrolyte: water-based, acidic polymer membrane
- Also called polymer electrolyte membrane fuel cells
- Use a platinum-based catalyst on both electrodes
- Generally hydrogen fuelled
- Operate at relatively low temperatures (below 100° C)
- High-temperature variants use a mineral acid-based electrolyte and can operate up to 200° C
- Electrical output can be varied, ideal for vehicles

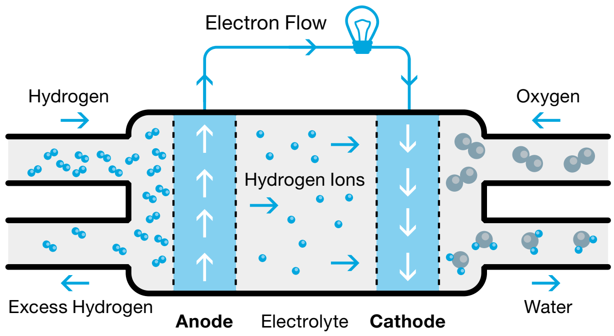
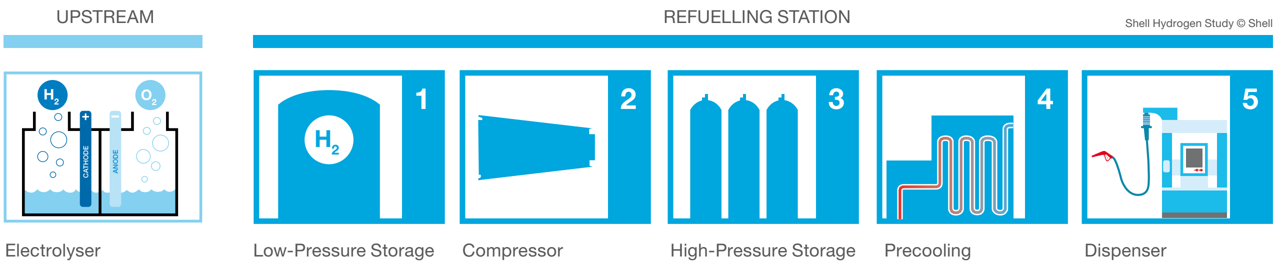


Figure 2. Hydrogen refueling process (Hydrogen Europe, 2021).



The cells require only oxygen and pure hydrogen as fuel, and produce only water as residue. They operate at a low temperature of around 80°C and can accommodate the requirement of vehicles for initial high demand of high-density power (figure 1). In fuel cell electric vehicles (FCEVs) using pure hydrogen to drive electric motors, there are no tailpipe emissions other than water.

For hydrogen to be adopted broadly, expensive refueling infrastructure must be put in place. Refueling with hydrogen is not as simple as with gasoline. In principle, hydrogen can be produced on site by adding an electrolyzer (a unit hosting the water electrolysis process) and a power and water source (figure 2). That eliminates the need for liquefaction and transport to the refueling station. However, the hydrogen produced must be compressed before it is dispensed to the vehicle, and the compression process generates heat that must subsequently be removed through a cooling process. Liquefaction is not strictly necessary for transport but may improve efficiency. The liquefaction process involves compression and cooling to less than –240°C, which demands a significant amount of energy. All the components of a refueling system require energy and equipment, making refueling relatively complex and expensive.

Current trends and international potential

Hydrogen is gaining ground despite the economic and technical challenges. Owing to its many uses and versatility, not least as a potentially clean, unlimited and climate change-neutral energy source, intensive R&D is taking place in many countries in the private and public sectors. Finding alternative and cheaper ways of producing green hydrogen has become a high priority, as green hydrogen will be a major selling point for scaling up hydrogen technologies. Governments are increasingly adopting hydrogen policies and, by early 2021, more than 30 countries had produced hydrogen roadmaps. Worldwide, governments have committed more than USD 70 billion in public funding to hydrogen development (Hydrogen Council and McKinsey, 2021). Industry is starting to see its potential, and several hydrogen industry companies have experienced soaring stock market prices, raising concerns over a financial "hydrogen bubble." The entry of big industry players into the field is, however, a sign that there is real potential and expectations of market gains in the near future.

China, the Republic of Korea, Japan and Germany are often cited as leading the way in developing hydrogen solutions, but Australia, France, the United States, the United Kingdom and Canada are also active (Bloomberg, 2021). Europe has the highest number of projects, especially on a large industrial scale (Hydrogen Council and McKinsey, 2021). In 2020, the European Commission published a hydrogen strategy and roadmap up to 2050, in which ambitious plans for the production and use of green hydrogen are outlined.

International Developments

Japan has for years been working to make the transition to a hydrogen economy. The Toyota Mirai, the first mass-produced hydrogen FCEV, has been on the market since 2014 (WEF, 2018). This mid-sized car has a range of 500 km on a tank, and its biggest market has been the United States. Japan also hosts the world's largest operational hydrolysis plant, which has a capacity of 10 MW and is fed from a nearby 20 MW photovoltaic plant (Godske, 2021b).

In 2020, the Republic of Korea issued its hydrogen economy roadmap, envisaging the production of 6.2 million hydrogen and fuel cell-based vehicles and the construction of 1,200 refueling stations by 2040 (Engie, 2020; Bloomberg, 2021).

In India, a public auction for green hydrogen production is planned for 2021 with the purpose of producing green ammonia, possibly as part of mandatory minimum green hydrogen purchases for some industries. With the cost of solar power falling, as seen in recent tender bids in India, the electrolysis of green hydrogen is becoming more economically viable. Public auctions could help to lower prices, as happened in the case of wind and solar power (Saurabh, 2021).

Chile has already launched its first national tender for green hydrogen, with 10 companies bidding by September 2021. The winner(s) will receive government project financing of up to USD 30 million. Chile, with its enormous solar energy potential, is developing a strategy to "export sunshine" in the form of hydrogen via sea tankers. That could in turn bring down the price of green hydrogen globally (Global Energy Prize, 2021).

In Germany, more than 30 power-to-gas demonstration projects are under way. Hydrogen is considered a key future sustainability technology, and the German Government has allocated 7 billion euro up to 2030 to support the development of hydrogen (Godske, 2021a). In early 2021, the Federal Ministry of Education and Research had already allocated 700 million euro to support three major projects for the serial production of electrolysis units, hydrogen production directly off-grid from offshore windmills, and the development of high-pressure tanks and pipes to store hydrogen (BMBF, 2021).

The world's largest electrolysis plant thus far is being built near Leipzig. With planned capacity of 24 MW, it will primarily supply local industry with hydrogen through pipelines. In Hamburg, an even larger plant of 100 MW is due for completion in 2025 (Godske, 2021b). In northern Germany, a train powered by a hydrogen fuel cell runs on a 100 km stretch of track. The train, built by Alstom, a French rail transport manufacturer, can run for 1,000 km on a tank of hydrogen, and energy not used directly is stored in batteries (WEF, 2018). In 2020, a similar train was tested successfully in Groeningen, the Netherlands, showing that it could be a fully sustainable alternative to diesel trains running on the same network (Alstom, 2021). In Austria a 6 MW hydrolysis plant opened in 2019 (Godske, 2021b). In Paris, a fleet of 600 taxis operate on fuel cells. Denmark is home to the world's first countrywide hydrogen refueling station network, and half the population now lives within 15 km of a station (Bloomberg, 2021). Ørsted, a major Danish energy company, is leading a consortium that plans to install hydrogen production capacity of 1.3 GW in Copenhagen by 2030 (Godske, 2021b). Haldor Topsøe, a major Danish petrochemical company, plans to build a new factory to produce electrolysis units. The plant will produce units with 500 MW capacity per year. The decision by the European Union to support at least 6 GW of electrolysis capacity until 2024 and at least 40 GW until 2030 is one of the incentives behind developments in Denmark (Andersen, 2021). However, the country is yet to produce a comprehensive hydrogen policy and roadmap.

In Norway, Yara, a major fertilizer company, is joining forces with Statkraft, a Norwegian utility company, to use hydropower for a large-scale commercial ammonia plant in Porsgrunn. The plan is to use hydrogen electrolysis to produce emissions-free ammonia for use as fuel in ships, as fertilizer and for industrial applications. By repurposing an existing ammonia plant, the capital investment was drastically reduced, and the project could pave the way for commercially competitive green ammonia. Besides producing an important export article, the plant may also help give the country's maritime industry an early competitive advantage (Casey, 2021; Yara, 2021).

Vehicle hydrogen fueling station in Esbjerg, Denmark, March 2021 (photo: Peter Oksen).

Hydrogen and fuel cells: a high priority for China

In China the Government and business and research institutions are taking a keen interest in the use of hydrogen and fuel cells. As the world's largest market for EVs, accounting for almost half of the global stock in 2020 (IEA, 2021), China also views hydrogen and fuel cells as key to strategic energy innovation. The commitment of China to low-carbon development and clean air schemes has provided a catalyst for hydrogen and fuel cell development. R&D activities in the field are expanding rapidly. In 2018, nearly 4,000 fuel cell patents were filed by Chinese applicants, surpassing Japan, which previously led the way on such patents.

Carbon peak and neutrality as policy drivers

In September 2020, Chinese president Xi Jinping told the United Nations General Assembly that carbon emissions in China would peak by 2030, and that the country would achieve carbon neutrality by 2060. By 2019, however, clean energy only accounted for around a quarter of total primary energy production in China (NBSC, 2020). There is a need to reduce reliance on fossil fuels and increase clean energy. As a new energy medium with high energy density and zero emissions, hydrogen – and in particular its use in fuel cells – has attracted attention at all levels of government. In addition, hydrogen can also play an important role for deep decarbonization in some sectors, such as iron and steel, chemical raw materials and high-grade heat production, where renewable-based electrification is not a feasible alternative to fossil fuels. In the future, when a large proportion of intermittent renewable energy power is connected to the grid in China, the safe and stable operation of the grid will require large-scale energy storage, smart-grid technology and distributed renewable energy network technology. This is why hydrogen is attractive as a renewable energy storage medium across seasons and regions. According to some forecasts, hydrogen may account for more than 10 percent of the country's energy structure in 2050 (China EV100, 2020).

Transport

Replacing fossil fuels with electricity and hydrogen in transport is essential for meaningful decarbonization. In 2020, the China Society of Automotive Engineers released its Energy Saving and New Energy Vehicle Technology Roadmap 2.0, in which it proposed to have 100,000 FCEVs on the road by 2025 and 1 million by 2035. The current fuel cell system and stack technology is capable of meeting technical vehicle application requirements and, in China, FCEVs have also passed the threshold requirements for commercial application, with several hundred types approved by the Ministry of Industry and Information Technology by 2020. Buses and trucks using fuel cells have entered the operational demonstration stage. As the technology matures and costs fall, hydrogen FCEVs will play an important part in transport in China.

Industry

The use of hydrogen in industry could contribute greatly to decarbonization. Hydrogen can be used as a clean raw material or a clean fuel in many industries, particularly iron and steel. In 2019, China accounted for more than half of global crude steel production (World Steel Association, 2020). Replacing traditional coke with direct reduction technology based on hydrogen to produce pig iron and crude steel could be revolutionary in terms of decarbonization.

Construction

In 2018, the production of key construction materials (including iron and steel, and cement and glass), construction itself and operational energy consumption in buildings accounted for almost 46.5 percent of national energy consumption in China and about 51 percent of the total national CO_2 emissions (CABEE, 2020). To achieve carbon neutrality, there is a need to improve energy efficiency and use renewable energy in buildings. Hydrogen has a potentially important role to play in that regard.

Air quality improvement as a driver of hydrogen deployment

The development and deployment of hydrogen and fuels cells is being driven not only by the desire to achieve carbon neutrality, but also by the need to improve air quality. In 2013, China launched its so-called "blue sky defense war," in an unprecedented effort to combat air pollution. Air quality has improved significantly as a result. From 2013 to 2020, the average concentration of particle matter (PM)2.5 in monitored cities[2] decreased from 72 μg/m³ to 33 μg/m³ (MEE, 2021; MEE, 2014). In Beijing, the PM2.5 concentration decreased by 57 percent from 89 μg/m³ in 2013 to 38 μg/m³ in 2020 (BMEEB, 2014; BMEEB, 2021). However, air pollution continues to pose a challenge. In 2020, the air quality of 135 out of 337 Chinese cities at or above prefecture level still did not meet national air quality standards, with a compliance rate of about 60 percent (MEE, 2021).

Vehicle emissions are often the biggest source of air pollution in large cities (figure 3). They account for 45 percent of air pollution in Beijing (BMEEB, 2018) and 29 percent in Shanghai (SEMC and SMRIEP, 2016). The pressure to reduce vehicle emissions is high and many cities are promoting the use of alternative energy vehicles to improve air quality.

Similarly, vehicles are major polluters in terms of NOx and PM (figure 4). NOx is a generic term for nitrous oxides that are typically produced by the reaction of oxygen and nitrogen in combustion engines, and which contribute to the formation of smog and acid rain. NOx is also a significant greenhouse gas. PM refers to a mixture of solid particles and liquid droplets found in the air, sometimes large or dark enough to be visible to the naked eye. In 2019, NOx emitted by motor vehicles accounted for around 51 percent of all NOx emissions in China (MEE, 2020a). Heavy-duty vehicles, especially trucks, accounted for the highest proportion of NOx and PM emissions, reaching 74 percent and 52 percent respectively (MEE, 2020b). Electrification of heavy, long-range vehicles with large load capacities to reduce their emissions is not feasible, because the batteries required would weigh too much. Hydrogen fuel cells with a high energy density and offering a long range could be a viable solution.

Figure 3. PM2.5 sources in Shanghai, 2015 (left) and Beijing, 2018 (right). Dust is soil and road dust. Living-related sources are from domestic sources such as cooking, heating, painting, etc.

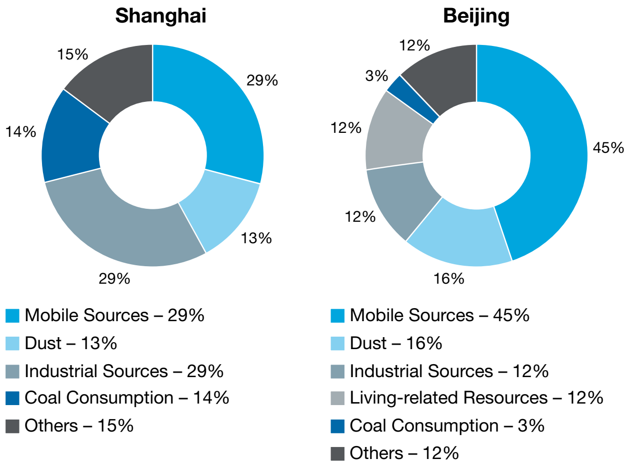
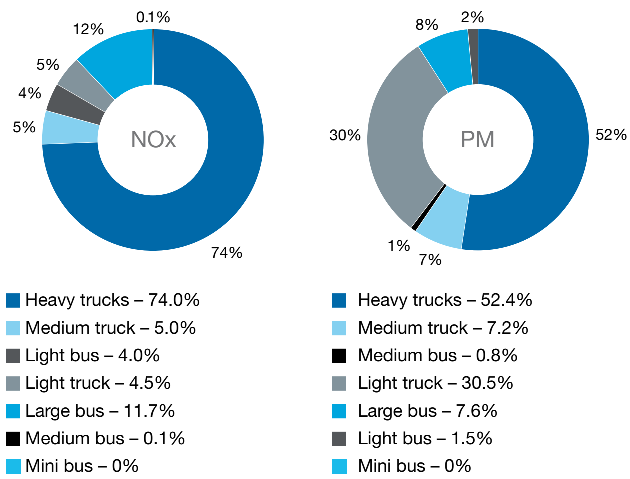


Figure 4. Share of NOx and PM emissions from various types of vehicles, 2019.



2 In 2013, 74 cities were included in the first phase of the new standard for monitoring. After 2013, 338 cities at or above prefecture level were monitored.

Patent perspective: a surge of fuel cell innovation in China

The development of the fuel cell industry is inseparable from R&D on related technologies. In recent years, and with the support of a series of large national projects, innovation in fuel cell technology has made rapid progress in China.

Lithium batteries versus fuel cells

At present, lithium batteries and fuel cells are the main technical approaches to replacing fossil fuel in vehicles. Since the implementation of the Ten Cities, Thousand Vehicles project, the development of lithium battery EVs in China has proceeded rapidly and they are already in commercial production. By the end of 2019, there were around 3.8 million lithium battery EVs in China, accounting for almost 1.5 percent of the total number of motor vehicles. Their number rose by more than 1 million a year for two consecutive years (MEE, 2020b). Presently, lithium battery-based vehicles are cheaper than fuel cell vehicles (FCVs). However, where long driving range, short refueling time and high sustained power output are required, as in the case of many heavy-duty vehicles, hydrogen fuel cells, with their high energy density, are likely to offer important advantages and development opportunities. China is planning to develop lithium batteries and hydrogen fuel cells, but in different directions. Lithium batteries are seen as more suitable for passenger cars, while hydrogen fuel cells are preferable for heavy vehicles such as trucks.

Statistics on patent applications can serve as a rough indicator, or proxy, of the level of innovation taking place in a given area of technology. This section contains a basic analysis of recent fuel cell-related patent applications in China. Compared with the United States and Japan, patent applications for fuel cells started relatively late in China (figure 5).[3] By 2018, however, the number of such applications from Chinese applicants had surpassed that of Japan, and the United States and China ranked first in the world. Patent data analyses are influenced by factors other than pure levels of innovation, such as general national patenting policies and processes, and corporate or university patenting strategies. The data show that Chinese fuel cell innovation, after a relatively slow start, is now on a par with or exceeding that of other frontrunner countries carrying out fuel cell innovation.

3 The analysis by BCAA is based on patent data from the PatSnap database. It shows the patent filing data of applicants from different countries. For example, "China" represents the number of patents filed by both Chinese local entities and individuals (addresses located in China) in a defined year.

A lithium battery electric car

(photo: Getty Images / athima tongloom)

As potentially the world's largest market for fuel cells, China has attracted several major international fuel cell industry players. Of the top 10 fuel cell-related applicants (patents filed with the China IP Office) between 1980 and 2019, six were foreign companies, including the three Japanese fuel cell frontrunner enterprises Toyota, Panasonic and Nissan (figure 6), which also shows the importance of the Chinese market. With reference to figure 5, Chinese innovators have played an increasingly important role in fuel cell development in recent years.

Case study 1: Dalian Institute of Chemical Physics

The Dalian Institute of Chemical Physics, a member of the Chinese Academy of Sciences, was one of the first research institutions to work on hydrogen energy and fuel cells in China. It has implemented many key national R&D projects on the subject. Analysis by BCAA shows that, by 2019, the Institute had filed more than 900 patent applications for key materials, core components and stack systems for fuel cells. As the leading domestic fuel cell technology patent applicant and the drafter of more than half of the national fuel cell standards, it has been key in developing the fuel cell industry in China. The Institute is now carrying out research on key materials and components of PEMFCs, fuel cell systems, hydrogen storage materials and related subjects (DICP, 2021).

Fuel cell electric buses in China (photo: Getty Images).

Figure 5. Trends of top 10 patent application countries for fuel cell technology, 1980–2019.

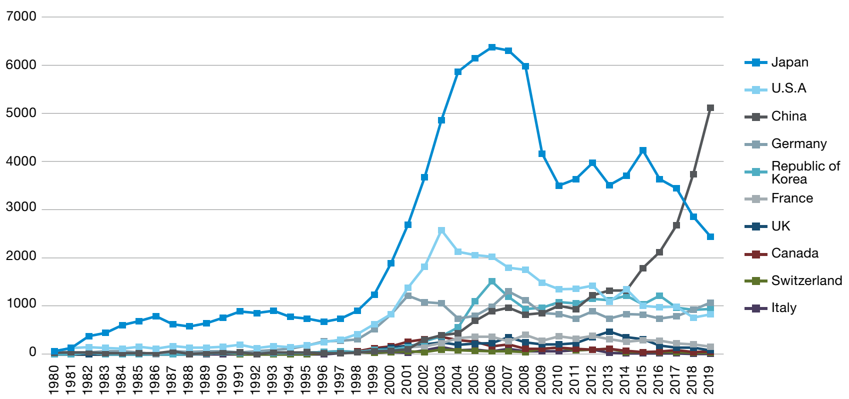
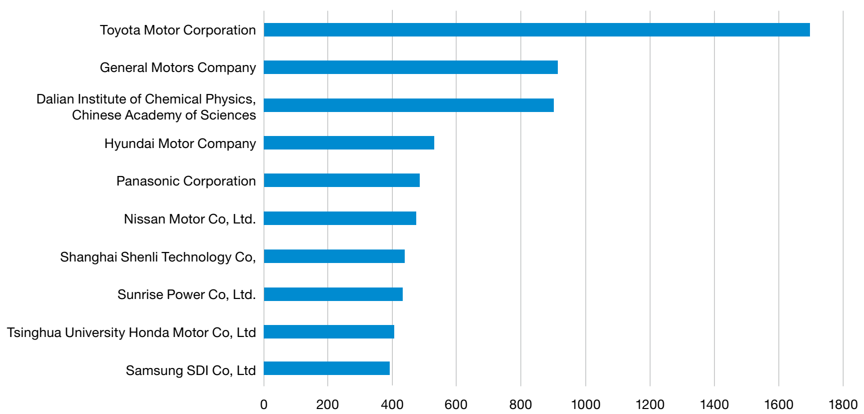


Figure 6. Top 10 fuel cell-related patent applicants in China, 1980–2019.



Overview of hydrogen and fuel cell development

Current status

Although the development of hydrogen and fuel cell technologies and applications has increased rapidly in recent years worldwide, deployment of FCEVs is still in its infancy. By the end of 2020, there were approximately 34,500 FCEVs on the road, of which 8,500 were in China, composed mainly of buses and logistics vehicles (IEA, 2021). By mid-2021, China had built over 140 hydrogen refueling stations nationwide (Wang, 2021). At the national policy level, development of the hydrogen industry has been addressed in more than 30 national development plans in China. Of 31 provincial governments in the Chinese mainland,[4] 13 have published specific hydrogen or fuel cell development plans (BCAA, 2021). With such broad policy support and growing industrial investment and interest, the hydrogen and fuel cell sectors are expected to develop rapidly.

In 2019, China produced 22 million tons of hydrogen, representing one-third of the world's total production and making China the world's biggest hydrogen producer (China Economic, 2019). Only a small portion of that hydrogen was green, but abundant sources of renewable energy (hydro, wind and solar), especially in southwest and northwest China, mean that the potential for producing green hydrogen from electrolysis based on renewable energy is considerable.

In December 2020, with a view to better implementing the vision of "carbon peak and carbon neutrality," the China Industry-University-Research Institute Collaboration Association released its Standards and Evaluation of Low-Carbon Clean Hydrogen and Renewable Energy Hydrogen, the world's first green hydrogen standard. In it, limits are set for the carbon emissions resulting from the production of various types of hydrogen. For example, a threshold for clean and renewable hydrogen is set at 4.9 $kgCO_2e/kgH_2$. Examples of how this energy is used to produce hydrogen are provided below.

Case study 2: Lanzhou New District solar hydrogen based methanol production plant

In this demonstration project, methanol is produced with hydrogen and CO_2. The hydrogen is produced through solar-powered hydrogen electrolysis, while the CO_2 is collected from industrial emissions. Considered the first large-scale solar hydrogen fuel demonstration project, it boasts 19 ha of solar panels. About RMB 140 million has been invested in the project, which consists of a solar photovoltaic power generation unit, a water electrolysis hydrogen production unit and a CO_2 hydrogenation unit. The latter synthesizes hydrogen into methanol. The photovoltaic power unit will have a capacity of 10 MW, enough to supply power for two electrolysis units with a combined capacity for producing hydrogen of 2,000 m^3/h. The project is based on two key technologies developed by the scientist Li Can of the Dalian Institute of Chemical Physics. The first innovation is a large-scale process of water alkaline electrolysis hydrogen production, which reduces the energy required to 4.0–4.2 kWh/m^3 of hydrogen. That represents a new world record and greatly reduces green hydrogen costs. The second key innovation is the solid solution bimetallic oxide catalyst ($ZnO\text{-}ZrO_2$), which hydrogenates CO_2 into methanol with high selectivity and stability. The catalyst attenuates less than 2 percent after running for 3,000 hours (DICP, 2020).

4 Statistics in this report for the Chinese mainland do not include Chinese Hong Kong and Macao.

National policy analysis

The Chinese Government at all levels has in recent years paid increasing attention to hydrogen development, issuing supporting policies to develop related industries and technological R&D. These include national planning and policies on energy development and technological innovation. Ministries and commissions that are directly concerned have also released specific guidance on hydrogen and fuel cell industrial planning.

The incorporation of hydrogen into Chinese policymaking can be divided into three stages. Between 2000 and 2014, China began to include hydrogen and fuel cells in its development plans. The focus on hydrogen in planning was then stepped up in the next four years. In that period, several key national planning documents were released. In the State Council's Strategic Action Plan for Energy Development for the Period 2014–2020, hydrogen and fuel cells were listed as a national strategic pillar of energy science and technology innovation.

Since 2019, China has entered a new stage of promoting the hydrogen and fuel cell industry. In its New Energy Vehicle Industry Development Plan for the Period 2021–2035, the Ministry of Industry and Information Technology emphasizes the need to promote FCVs and build hydrogenation infrastructure. Under the Draft Energy Act of 2020, issued for comment by the National Energy Administration, hydrogen is listed as an energy category at the national level for the first time. In 2021, further relevant policies were issued. In February, the Guiding Opinions on Green and Low-Carbon Circular Development proposed to strengthen the infrastructure for new-energy vehicles, including charging and battery swapping for EVs and hydrogen refueling for FCEVs. In March, hydrogen energy and energy storage were listed as strategic emerging industries in the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Long-Range Objectives Through the Year 2035. Figure 7 provides a timeline of key policies.

The Lanzhou methanol production plant
(China Daily, 2020).

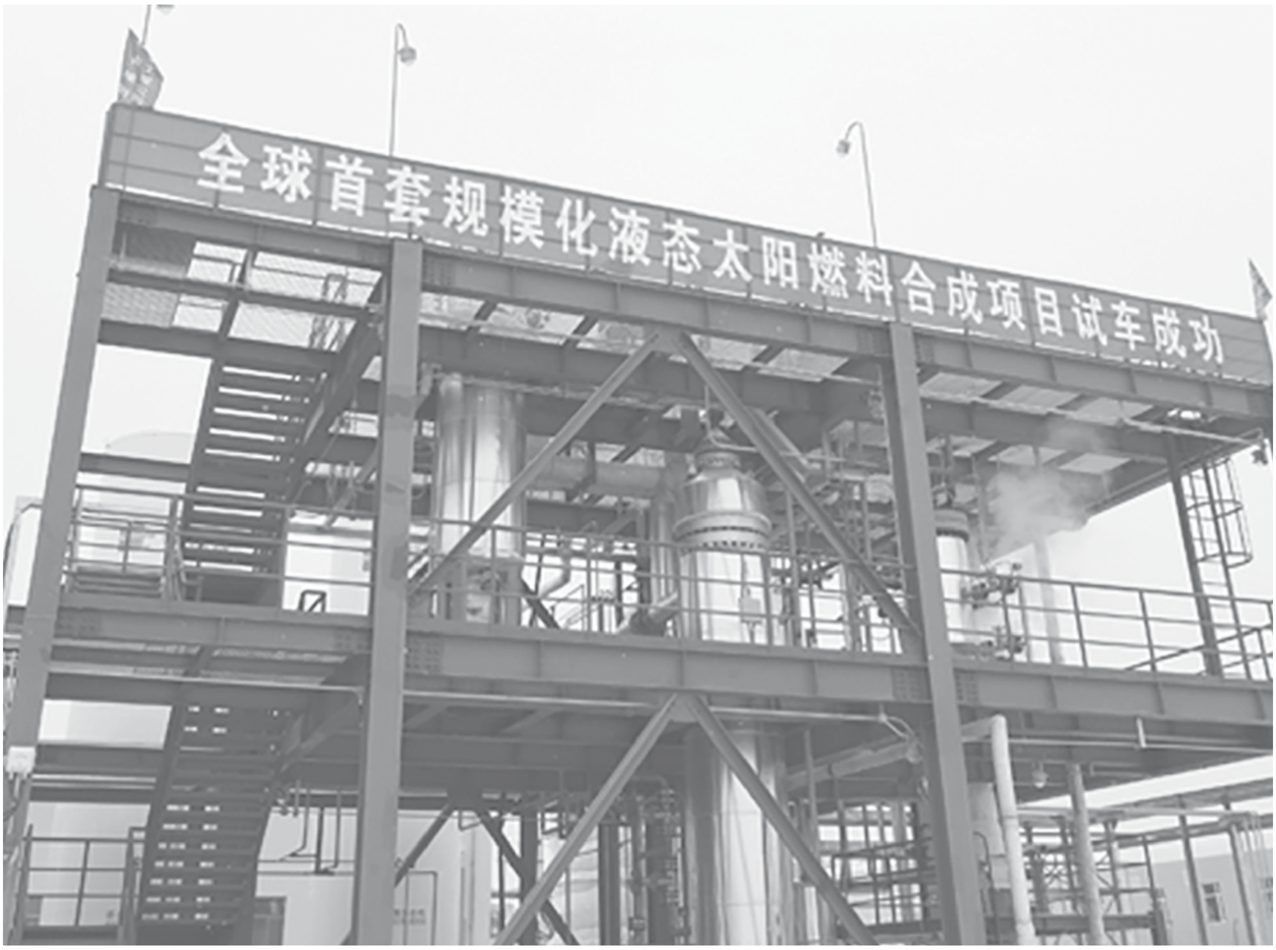
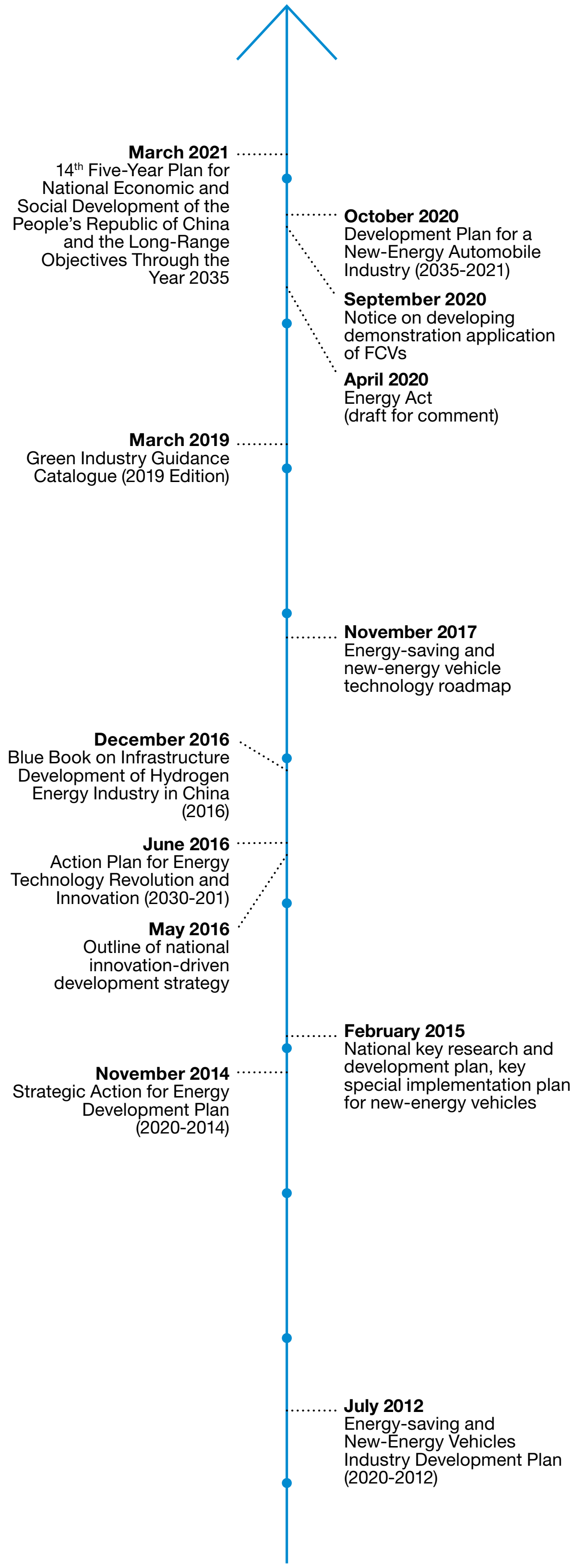


Figure 7. Key policies timeline.



Standards analysis

Well-defined standards for producers and other stakeholders are a prerequisite for rapid scaling up, and enable communication and mainstreaming. In China, there are national and group standards for hydrogen and fuel cells. By mid-2021, more than 100 standards had been put in place to regulate the production and use of hydrogen in China.

National technical standards are divided into eight standard subsystems: hydrogen energy foundation and management; hydrogen quality; hydrogen safety; hydrogen engineering construction; hydrogen preparation and purification; hydrogen storage-transportation-filling; hydrogen energy application; and hydrogen-related detection. By March 2021 there were 87 national standards on hydrogen and fuel cells, of which 54 (more than 60 percent) relate to fuel cells (BCAA, 2021). National standards have been issued with some frequency since 2009, peaking in 2017 (figure 9). That underscores the importance that has been attached to developing a basic framework for hydrogen use.

Figure Group standards are voluntary standards released by relevant industrial associations or alliances, which companies may choose to adopt. By the end of 2020, approximately 50 group standards on hydrogen and fuel cells were in place (see Annex 2).

Case study 3: Ningxia green hydrogen plant

On April 20, 2021, the Ningxia green hydrogen plant officially started production in the Ningdong Energy and Chemical Industry Base. It is part of the Ningxia national comprehensive demonstration project of solar-based water electrolysis hydrogen production. Making use of the abundant renewable energy sources in Ningxia, the project includes a 200,000 kW photovoltaic power generation device and a 20,000 m^3/h water electrolysis hydrogen production unit. When fully operational, it will reduce coal consumption by 254,000 tons and CO_2 emissions by 445,000 tons per year (PIA, 2021).

Figure 8. National hydrogen standards by type (BCAA, 2021).

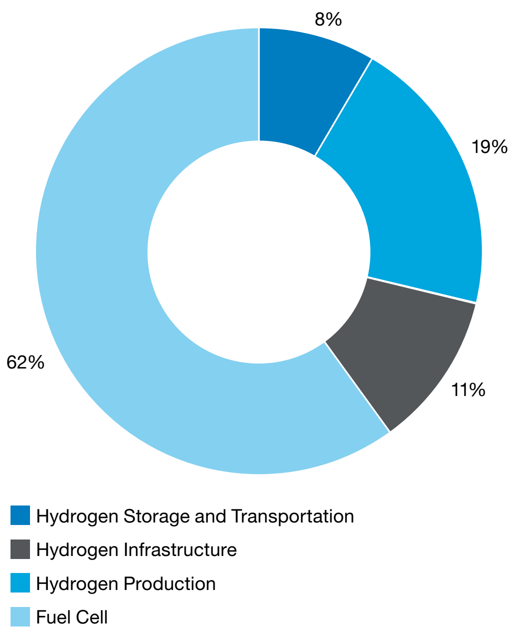
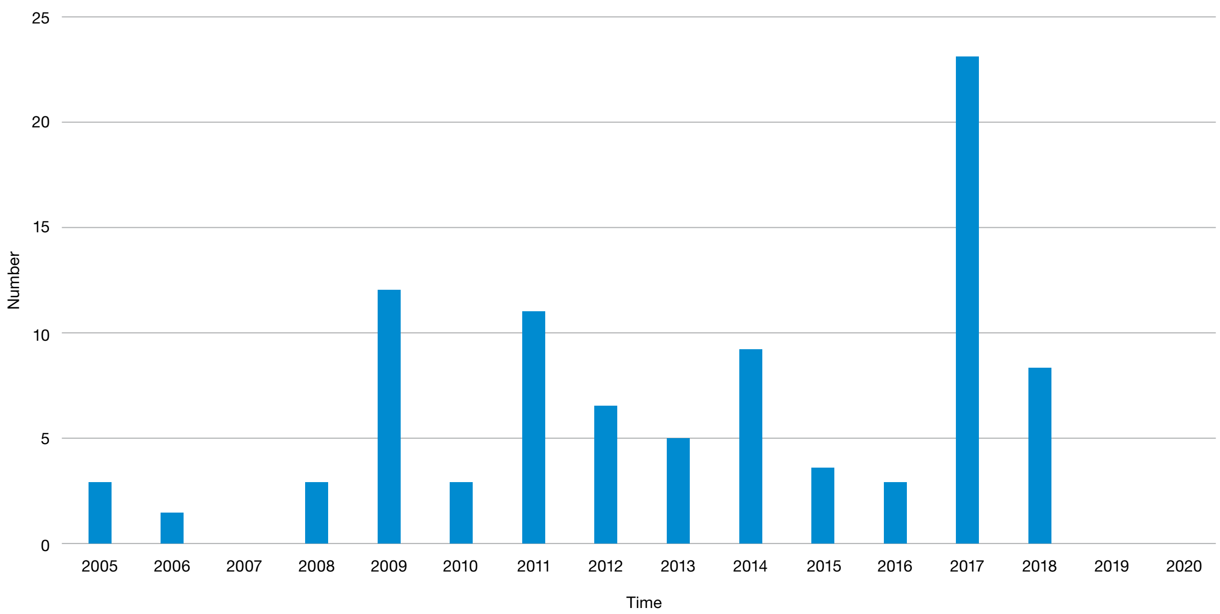


Figure 9. Number of national hydrogen or fuel cell standards by the end of 2020 (BCAA, 2021).



Overview of local policies

Since 2010, 12 provinces and cities in China have been proactive in developing hydrogen and full cells, and three key regional hydrogen energy industrial clusters have emerged: the Beijing-Tianjin-Hebei (Beijing and Zhangjiakou), Yangtze River Delta (Shanghai) and Pearl River Delta (Foshan) clusters. Recently, some provinces in central China (Henan, Hubei and Shanxi), eastern China (Shandong) and southwestern China (Chongqing and Sichuan) have joined the efforts to promote the hydrogen and fuel cell industry.

Of the 31 provincial governments in the Chinese mainland,[5] 27 have addressed hydrogen and fuel cells in their development plans and 13 have released specific plans for their development (BCAA, 2021). In particular, Guangdong and Jiangsu provinces have issued numerous policies. Many hydrogen-related policies are integrated into broader policies, such as those on new-energy vehicles, environmental protection and energy policies. The activities in certain hydrogen pioneer cities in China are described in some detail in the next chapter.

In January 2009, the Ministry of Science and Technology, the Ministry of Finance, the Development and Reform Commission, and the Ministry of Industry and Information Technology jointly launched the Demonstration, Popularization and Application Project of 1,000 Energy-Saving and New-Energy Vehicles in the Ten Cities, Thousand Vehicles program. Its aim was to demonstrate battery-driven EVs by launching 1,000 of them in 10 cities each year over a three-year period (MST, 2009). The project played an important role in popularizing EVs and laid a popular foundation for FCEVs. In September 2020, an FCEV version of the project was launched under the auspices of the same institutions and the National Energy Administration. Under that program, interested cities could form a city cluster to apply to participate in the program and benefit from favorable policies and incentives from the Chinese Government for FCEV promotion. Every city cluster will promote more than 1,000 FCEVs by the end of the demonstration period of four years (MF, 2020). Alongside the program launched by the Government, some international organizations also participated in the FCEV promotion efforts by setting up local pilot programs.

5 Statistics in this report for Chinese Mainland do not include Chinese Hong Kong and Macao

UNDP project: Accelerating the Development and Commercialization of Fuel Cell Vehicles in China

The United Nations Development Programme in China (UNDP China) was established in 1979. Today it is cooperating with the Chinese Government to promote the country's development as well as the Sustainable Development Goals (SDGs). With support from the Global Environment Facility (GEF), UNDP China and the Ministry of Science and Technology (MoST) have since 2003 jointly implemented three phases of demonstration projects to promote hydrogen and FCVs in China. Pilot activities have been conducted in seven cities (Beijing, Shanghai, Zhengzhou, Foshan, Yancheng, Changshu and Zhangjiakou) to operate over 3,200 FCVs, accelerate the construction of hydrogen infrastructure, and support the national and local policymaking. Since 2016, those activities have already reduced carbon emissions, with 230,261 tons CO_2eq (UNDP, 2021), aiming to fast-track China's decarbonization through technological innovation in the transport and energy sectors.

Main hydrogen energy industrial clusters in China.

Type	Region	Representative Provinces and Cities
Hydrogen and Fuel Cell Industrial Clusters	Beijing-Tainjin-Hebei Industrial Cluster	Beijing, Tianjin, Zhangjiakou
	Yangtze River Delta Industrial Cluster	Shanghai, Suzhou, Jiaxing, Rugao
	Pearl River Delta Industrial Cluster	Guangzhou, Shenzhen, Foshan
Regions with Strong Interest to Promote Hydrogen and Fuel Cell	Cheng-Yu Region	Chongqing, Chengdu
	Middle of China	Henan Province, Hubei Province, and Shanxi Province
	Shandong Peninsula	Shandong Province

Pioneering cities

Considerable progress has been made in Beijing-Zhangjiakou, Shanghai and Foshan, which represent the three regional hydrogen energy industrial clusters. In August 2021, Beijing, Shanghai and Guangdong were listed as the first round of leading local governments for the establishment of FCEV demonstration and application city clusters (MF, 2021).

Beijing-Zhangjiakou (Beijing-Tianjin-Hebei industrial cluster)

City overview

Location	The Beijing-Zhangjiakou area is in the northernmost part of the North China Plain, which is the core of the Beijing-Tianjin-Hebei (Bohai Rim) economic circle.
Population (2019)	25.95 million
GDP (2019)	RMB 3.65 trillion
Area (2019)	53,200 km^2
Number of hydrogen refueling stations under construction or completed (by 2020)	8
Number of FCVs promoted (by 2020)	684
Number of policies issued (by March 2021)	9
Sample institutions	Tsinghua University, Peking University, Beijing Institute of Technology, Technical Institute of Physics and Chemistry of CAS, Beijing Aerospace Propulsion Institute

Source: ZMBS (2020), BCAA (2021).

In 2019, the Beijing Hydrogen Fuel Cell Vehicle Industry Development Plan (2020–2025) was released. The aim is to establish a hydrogen energy supply chain around Beijing in cooperation with Zhangjiakou, Tangshan and other cities in Hebei Province. It is expected that the deployment of hydrogen, especially in Zhangjiakou, will be accelerated in view of the 2022 Winter Olympics, which will be hosted in the region. An enterprise cluster established in the city region includes companies such as SinoHytec, PetroChina, Sinopec, Yutong Bus and Kerong Environment, which cover the whole hydrogen industrial chain. In addition, the Beijing-Zhangjiakou area is a base of leading hydrogen and fuel cell research institutions, such as Tsinghua University and Beijing Institute of Technology. Energy consumption in the Beijing-Tianjin-Hebei region is dominated by fossil fuels, especially coal. There is therefore significant demand for clean energy in order to reach carbon neutrality by 2060. Zhangjiakou has abundant wind and solar power potential, which can be used for electrolysis of water to produce hydrogen.

Selected case studies

Hydrogen energy industry demonstration, Winter Olympics

In 2022, Beijing and Zhangjiakou will jointly host the 24th Winter Olympic Games. The two governments plan to use the occasion to demonstrate and promote the hydrogen energy industry. Hydrogen energy will be used in various ways, including the deployment of some 2,000 FCEVs, and the Olympic torch will be fueled by hydrogen. Hydrogen production capacity will be increased to 34 tons per day. Local county and district governments, as well as municipal departments, will provide support by allocating land and covering construction costs for hydrogen refueling stations. The Zhangjiakou Municipality will also provide cheap renewable energy to support hydrogen production for five years (Zhangjiakou Mun., 2020).

The first fuel cell company on the "star market" of the Shanghai Stock Exchange

SinoHytec, established in 2012, is a high-tech enterprise focusing on R&D and the industrialization of hydrogen fuel cell technology based on cooperation with a research team at Tsinghua University. Having secured intellectual property (IP) rights, SinoHytec has taken the lead in developing core engine system and fuel cell stack technologies. Its products are mainly used in commercial vehicles, such as passenger cars and logistics vehicles, using a hydrogen fuel cell engine and its supporting DC/DC component, vehicle controller, hydrogen system and so on (SinoHytec, 2021). In August 2020, SinoHytec became the first fuel cell company to be listed on the Star Market of the Shanghai Stock Exchange. Its total market value in March 2021 exceeded RMB 16 billion (Stock Exchange: 688339 Yihuatong-U).

The 45 MPa high-pressure hydrogen storage facilities of Zhangjiakou Wangshan Hydrogen Production and Hydrogenation Station
(photo: Hui Zhao, Hypower Hydrogen Technology Co., Ltd, 2020).

Shanghai (Yangtze River Delta industrial cluster)

City overview

Location	Shanghai lies at the mouth of the Yangtze River in eastern China, bordering the East China Sea and connecting Jiangsu and Zhejiang provinces to the north and west
Population (2019)	24.3 million
GDP (2019)	RMB 3815.6 billion
Area (2019)	6,340 km^2
Number of hydrogen refueling stations under construction or completed (by 2020)	10
Number of FCVs promoted (by 2020)	More than 1,000
Number of policies issued (by March 2021)	13
Sample institutions	Tongji University, Shanghai Jiaotong University, Shanghai Advanced Research Institute of Chinese Academy of Sciences, Shanghai Yangtze River Delta Hydrogen Energy Research Institute, Shanghai Electric Vehicle Public Data Collecting, Monitoring and Research Center

In China, FCEV technology was first developed in Shanghai, with its strong industrial base. By the end of March 2021, 13 development plans for hydrogen and fuel cells had been launched in Shanghai and its Jiading and Qingpu districts, along with several local standards on hydrogen, storage cylinders and data collection. Shanghai is taking the lead in hydrogen infrastructure construction, with nine completed hydrogenation stations, mainly located in the Jiading, Fengxian and Baoshan districts. Led by SAIC Group, Linde Group and Shanghai SUNWISE, the city has created a full hydrogen industrial chain. SAIG Group was the first domestic automobile firm certified to produce commercial fuel cell passenger vehicles in China. Backed by Tongji and Shanghai Jiaotong universities, the city has strong potential for hydrogen and fuel cell innovation.

Related case study

Jiading hydrogen energy port

The Jiading hydrogen energy port is located in the core area of Anting Shanghai International Automobile City, and it is an important part of the city's global science and technology innovation center. The energy port boasts a comprehensive ecosystem, including hydrogen energy, a fuel cell power system platform, and FCV capacity and infrastructure to foster development of the hydrogen industry. A target value in excess of RMB 100 billion by 2025 has been set for the port's annual output (Jiading District, 2018).

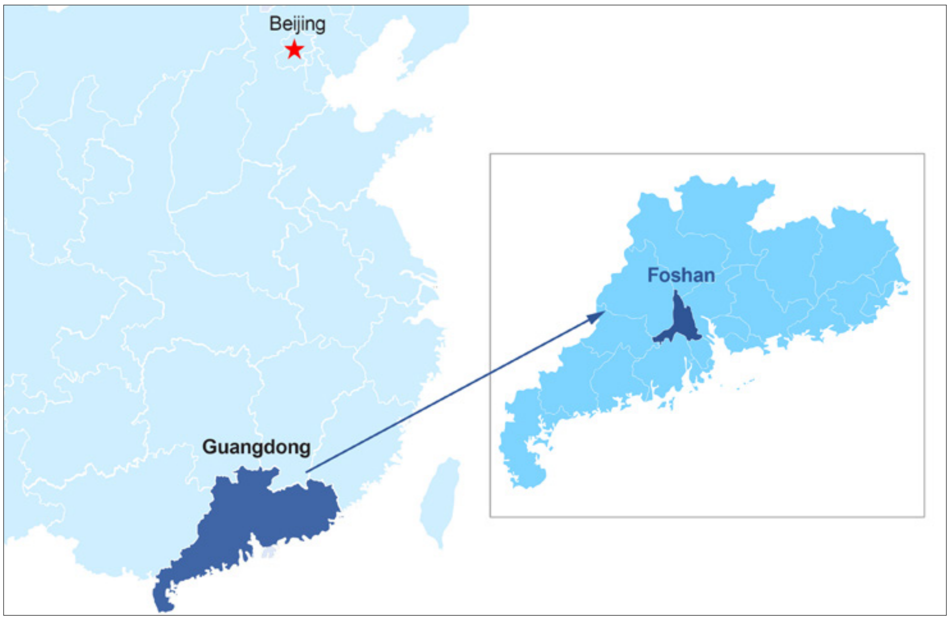
Foshan
(Pearl River Delta industrial cluster)

City overview

Location	Foshan is located in the central part of Guangdong Province and the hinterland of the Pearl River Delta, adjacent to Hong Kong and Macao. Together with Guangzhou, Foshan constitutes the Guangzhou-Foshan Metropolis Circle.
Population (2019)	8.2 million
GDP (2019)	RMB 1 trillion
Area (2019)	3,797 km^2
Number of hydrogen refueling stations under construction or completed (by 2020)	23
Number of FCVs promoted (by 2020)	1,457
Number of policies issued (by March 2021)	10
Sample institutions	Foshan Xianhu Laboratory, Ji Hua Laboratory, Foshan Nanhai District South China Hydrogen Safety Promotion Center, Foshan Institute of Environment and Energy Technology, Foshan Green Development Innovation Research Institute

Source: FMBS (2020).

Foshan is a hydrogen pioneer city, especially for the large-scale commercial deployment of hydrogen-fueled vehicles. It was the first city to put a hydrogen development plan in place, and the city government provides strong incentives. In Foshan, a high-level leadership group dedicated to hydrogen and fuel cell promotion has been created. The group is chaired by the mayor of the city, with group members comprising directors of relevant agencies such as the Development and Reform Bureau, the Housing and Urban-Rural Development Bureau and the Industry and Information Technology Bureau. Foshan has three major hydrogen energy industrial bases and has brought together more than 90 hydrogen-related enterprises and science and technology innovation platforms.

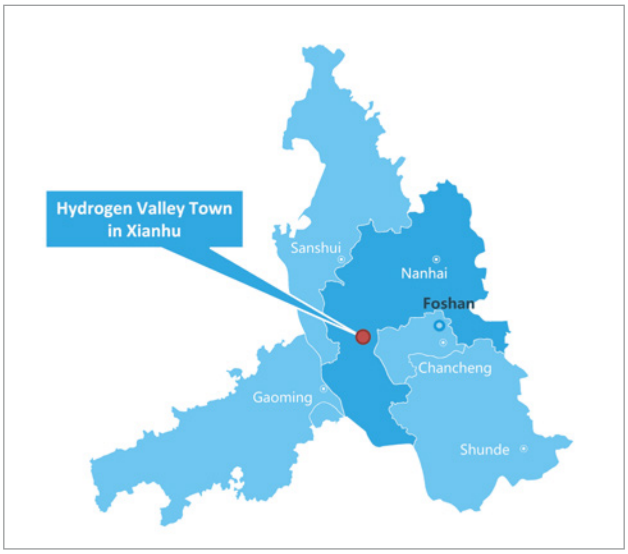


Related case studies

The first hydrogen tram in China

On November 29, 2019, the first commercial hydrogen tram in China was launched in Gaoming District, Foshan City. The demonstration tram line has a planned total length of 17.4 km and 20 stations. The first phase, which is 6.6 km long and has 10 stops, starts at Cangjiang Road and Zhongshan Road, and ends at Zhihu Lake in Xijiang New Town. In December 2020, construction for a second demonstration tram started in Nanhai District, Foshan (Gong *et al.*, 2021).

Hydrogen tram in Gaoming District, Foshan City (Guangzhou Daily, 2020).



Hydrogen Valley in Xianhu, Foshan

The Hydrogen Valley is located in the Xianhu area, Nanhai District, Foshan, with a planned area of 47.3 km^2 (NPGF, 2020). Relying on the existing automobile industry foundation, the valley focuses on technological innovation in and the promotion and deployment of new-energy vehicles, in particular FCEVs. It is hoped that the Valley will become a "Silicon Valley of hydrogen," with a full hydrogen industrial chain including storage materials, hydrogen production equipment, hydrogen production and fuel cells.

Conclusion

Hydrogen is gaining momentum in many industrialized countries, and several major hydrogen technologies are being developed. The public and private sectors in some countries see much potential in hydrogen and are developing policies and standards, improving technologies and coming closer to scaling up solutions. However, it is also clear that hydrogen is a field that is still under development; there are many obstacles to overcome to make it economically feasible, especially in the case of green hydrogen. Whether green hydrogen will be able to compete with hydrogen produced using fossil fuel in the foreseeable future without strong support measures is not known. Current use of hydrogen is almost entirely based on fossil fuels, especially natural gas. Hydrogen today is therefore not a green energy source.

China, the world's largest market for EVs, sees important advantages in hydrogen and is rapidly preparing to use hydrogen to meet its commitment to peak carbon emissions by 2030 and carbon neutrality by 2060. That concerns not only the transport sector, with the emphasis on heavy-duty and long-haul vehicles, but also industry, construction and the energy sector. The degree of innovation, as measured by patent applications, shows that China has caught up with other hydrogen innovation frontrunner countries such as Germany, Japan, the Republic of Korea and the United States.

Numerous supporting policies and standards have been issued and an array of successful demonstration projects launched. Many of the latter are located in established industrial cluster areas, where large-scale research, innovation and deployment infrastructure and facilities already exist, which can boost the process of delivering hydrogen-based goods and services.

It is probable that, for example, hydrogen will not compete with battery-driven EVs in small passenger vehicles or light, short-haul transport. However, hydrogen is definitely an option for heavy-duty and long-haul transport (trains, trucks and buses), aviation and shipping (both most likely based on ammonia), processes requiring very high temperatures (such as in the steel, cement and glass industries), fertilizer (for which hydrogen is almost irreplaceable), mixing into domestic gas grids (to avoid large-scale and complex replacement of existing boilers with, for instance, heat pumps), and for the storage of intermittent renewable energy. These are not niche areas, but major sources of greenhouse gas emissions.

Important factors favor hydrogen. The continuous drop in the price of renewable energy will also lower the cost of hydrogen electrolysis. Research is being conducted on new hydrolyzer technology with the aim of increasing efficiency and lowering costs. Lastly, economies of scale make it likely that green hydrogen will follow the path of wind and solar power, with dramatic cost reductions as a result of innovation and mass-production.

The road to scaling up and mainstreaming hydrogen in the world economy may still seem long and strewn with technical and economic obstacles, but the advantages of hydrogen as a potentially clean, energy-dense, versatile, climate-friendly and unlimited energy medium are so appealing that there is reason to be optimistic about hydrogen's future role in the transition towards a green economy.

Annex 1 – Key hydrogen and fuel cell policies in China

Date	Department	Policy title
2001	Ministry of Science and Technology	Special Project of National 863 Program
2006	State Council	Outline of National Medium- and Long-Term Science and Technology Development Plan (2006–2020)
2009	Ministry of Finance, Ministry of Science and Technology	Interim Measures for the Administration of Financial Subsidy Funds for Demonstration and Promotion of Energy-Saving and New Energy Vehicles
2010	State Council	Decision on Accelerating the Cultivation and Development of Strategic Emerging Industries
2011	The National People's Congress	Vehicle and Vessel Tax Act of the People's Republic of China
June 2011	Development and Reform Commission, Ministry of Science and Technology, Ministry of Industry and Information Technology, Ministry of Commerce and Intellectual Property Office	Guide to Key Areas of High-Tech Industrialization with Priority Development at Present (2011)
March 2011	Development and Reform Commission	Guidance Catalogue of Industrial Structure Adjustment (2011 edition)
July 2012	State Council	Energy-Saving and New Energy Automobile Industry Development Plan (2012–2020)
November 2014	State Council	Energy Development Strategic Action Plan (2014–2020)
2014	Ministry of Finance, Ministry of Science and Technology, Ministry of Industry and Information Technology, Development and Reform Commission	Notice on Reward for Construction of Charging Facilities for New Energy Vehicles
2015	Ministry of Finance, Ministry of Science and Technology, Ministry of Industry and Information Technology, Development and Reform Commission	Notice on the Financial Support Policy for the Promotion and Application of New Energy Vehicles (2016–2020)
2015	Ministry of Science and Technology	National Key R&D Special Implementation Plan for New Energy Vehicles (draft for comment)
2015	Ministry of Transport	Implementation Opinions on Accelerating the Promotion and Application of New Energy Vehicles in the Transportation Industry
May 2015	Ministry of Industry and Information Technology	Made in China 2025
June 2016	Development and Reform Commission, Energy Bureau	Action Plan for Energy Technology Revolution and Innovation (2016–2030)
June 2016	Development and Reform Commission, Energy Bureau	Roadmap for Key Innovation Actions of the Energy Technology Revolution
December 2016	Standardization Institute	Blue Book on Infrastructure Development of the Hydrogen Energy Industry in China (2016
2016	CPC Central Committee and State Council	Outline of the National Innovation-Driven Development Strategy
2016	State Council	The 13th Five-Year National Strategic Emerging Industry Development Plan
November 2017	Commissioned by the Ministry of Industry and Information Technology and compiled by China Society of Automotive Engineers	Energy-Saving and New Energy Vehicle Technology Roadmap
2017	Ministry of Industry and Information Technology, Development and Reform Commission, Ministry of Science and Technology	Medium- and Long-Term Automobile Industry Development Plan
2017	Ministry of Science and Technology, Ministry of Transport	Special Plan for Science and Technology Innovation in Transportation During the 13th Five-Year Plan
2018	Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology, Development and Reform Commission	Notice on Adjusting and Perfecting the Financial Subsidy Policy for the Promotion and Deployment of New Energy Vehicles
November 2019	Development and Reform Commission, Ministry of Industry and Information Technology, etc.	Implementation Opinions on Promoting the Deep Integration and Development of Advanced Manufacturing and Modern Service Industries
March 2019	State Council	Government Work Report of 2019
October 2019	Development and Reform Commission	Guidance Catalogue for Industrial Structure Adjustment (2019 edition)
2019	Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Natural Resources, Ministry of Ecology and Environment, etc.	Green Industry Guidance Catalogue (2019 edition)
2019	Ministry of Ecology and Environment, Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Public Security, etc.	Action Plan for Tackling the Diesel Truck Pollution
April 2020	Energy Bureau	Energy Act of the People's Republic of China (draft for comment)
April 2020	Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology, Development and Reform Commission	Notice on Improving the Financial Subsidy Policy for the Promotion and Deployment of New Energy Vehicles

Date	Department	Policy title
June 2020	Energy Bureau	Guiding Opinions on Energy Work in 2020
September 2020	Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology, Development and Reform Commission, Energy Bureau	Notice on Demonstration Application of Fuel Cell Vehicles
October 2020	Ministry of Industry and Information Technology	New Energy Vehicle Industry Development Plan (2021–2035)
October 2020	Ministry of Industry and Information Technology, China Society of Automotive Engineering	Energy-Saving and New Energy Vehicle Technology Roadmap 2.0
December 2020	Development and Reform Commission of the Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology	Notice on Further Improving the Financial Subsidy Policy for the Promotion and Deployment of New Energy Vehicles
February 2021	State Council	Guidance on Accelerating the Establishment and Improvement of the Green Low Carbon Circular Development Economic System

Annex 2 – Hydrogen and fuel cell group standards in China

Number	Name of standard
T/DLSHXH 003—2020	Safety Management Requirements for On-Site Operation of Hydrogen Refueling Stations
T/DLSHXH 002—2020	Operation Service Specifications for Hydrogen Refueling Stations
T/DLSHXH 001—2020	Guidelines for Technical Acceptance of Hydrogen Refueling Stations.
T/GDASE 0017—2020	Periodic Inspection and Evaluation of Fully Wrapped Carbon Fiber Reinforced Cylinders with an Aluminum Liner for the On-Board Storage of Compressed Hydrogen as Fuel for Land Vehicles
T/EPIAJL 1—2018	Technical Specification for Detecting Hydrogen Content of Internal Cooling Water Tank and Hydrogen Leakage of Internal Cooling Water System in Water-Cooled Generators
T/GHDQ 47—2019	Technical Conditions of Fuel Cell Stack Life Test at Sub-Zero Environment for Fuel Cell Vehicles in Frigid Zones
T/GHDQ 38—2019	Test Methods of Onboard Hydrogen System of Fuel Cell Electric Vehicles in Frigid Zones
T/GHDQ 37—2019	Technical Conditions of On-Board Hydrogen Systems for Fuel Cell Electric Vehicles in Frigid Zones
T/GHDQ 28—2018	Performance Requirements and Test Methods for Nickel-Metal Hydride Batteries in Electric Vehicles in Frigid Zones
T/GHDQ 46—2019	Performance Requirements and Test Methods for Fuel Cell Systems in Electric Vehicles in Frigid Zones
T/GHDQ 45—2019	General Technical Conditions for Automotive Fuel Cell Stack Sub-Zero Character in Frigid Zones
T/GHDQ 44—2019	General Technical Conditions for Automotive Proton Exchange Membrane Fuel Cell Stack Subzero Startup in Frigid Zones
T/GHDQ 39—2019	Technical Conditions for Vehicle-Based Fuel Cell Engine Cold-Start in Frigid Zones
T/GHDQ 36—2019	Comprehensive Evaluation Index on the Performance of Fuel Cell Electric Passenger Cars in Frigid Zones
T/GHDQ 35—2019	Technical Conditions for Fuel Cell Electric Passenger Cars in Frigid Zones
T/SDAS 188—2020	General Technical Specifications for Hydrogen Fuel Cell Trams
T/SDAS 185—2020	Fuel Cell Rolling Stock – Safety Requirements for On-Board Hydrogen Systems
T/SDAS 184—2020	Fuel Cell Rolling Stock – Technical Specifications for On-Board Hydrogen Systems
T/SDAS 182—2020	Fuel Cell Rolling Stock – Technical Specifications for On-Board Hydrogen Systems
T/SDAS 187—2020	Fuel Cell Rolling Stock – Performance Test Methods for Fuel Cell Stacks
T/SDAS 186—2020	Fuel Cell Rolling Stock – Technical Specifications for Fuel Cell Cooling Systems
T/SDAS 183—2020	Fuel Cell Rolling Stock – Safety Requirements
T/SZAS 8—2019	Specifications of Methanol Reforming and Hydrogen Generation Power Systems for Vehicles
T/ZZB 1479—2019	Detachable Multi-Point Flexible Armored Thermocouple for Hydrogenation Units
T/CAB 0084—2021	Technical Specifications for Small-Sized Proton Exchange Membrane Water Electrolysis Systems for Hydrogen Production
T/CAB 0078—2020	Standard and Evaluation of Low-Carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen
T/CAB 0064—2020	Technical Specifications for Remote Service and Management Information System for Hydrogen Refueling Stations
T/CAB 1038—2020	Determination of Hydrogen Storage Density of Hydrogenated Liquid Organic Hydrogen Carrier – Water Displacement Method
T/CEEIA 265-2017	Technical Specifications for Fuel Cell Fuel Systems in Unmanned Aerial Vehicle
T/CEEIA 264-2017	Technical Specifications for Fuel Cell Power Systems in Unmanned Aerial Vehicle
T/CCGA 40002—2019	Application Management Specification for the Electronic Label for Hydrogen Energy Vehicle Cylinders
T/CCGA 40001—2019	Liquid Hydrogen
T/CATSI 02007—2020	Fully Wrapped Carbon Fiber Reinforced Cylinder with a Plastic Liner for the On-Board Storage of Compressed Hydrogen for Land Vehicles
T/CATSI 05003—2020	Special Technical Requirements for Hydrogen Storage Pressure Vessels Used in Hydrogen Refueling Stations
T/CSTE 0017—2020	Operation Specifications for Hydrogen Fuel Cell Logistics Vans
T/CSTE 0016—2020	Regulations for Operation Management of Hydrogen Fuel Cell Buses
T/CSTE 0015—2020	Regulations for Operation Management of Hydrogen Fuel Cell Buses
T/CSTE 0007—2020	Determination of Trace Carbon Monoxide in Hydrogen Fuel – the Method of Mid-Infrared Laser Spectroscopy for PEMFC
T/CSTE 0006—2020	Standard Format of the Safety Assessment Report for Hydrogen Refueling Stations
T/CSTE 0005—2020	Technical Specifications for Hydrogen Production from Coke Oven Gas
T/CSTE 0012—2019	Technical Requirements for Control Systems of Hydrogen Refueling Stations
T/CSTE 0077—2020	Technical Requirements for Video Security Monitoring Systems at Hydrogen Refueling Stations
T/CSTE 0076—2020	Centrifugal Air Compressor for Vehicle Hydrogen Fuel Cells
T/CECA-G 0015—2017	Fuel Specifications for Proton Exchange Membrane Fuel Cell Vehicles—Hydrogen
T/CSAE 123—2019	Fuel Cell Electric Vehicles – Test Methods and Safety Requirements for Hydrogen Leakage and Emissions in Confined Space
T/CSAE 122—2019	Test Methods for Cold-Start Performances of Fuel Cell Electric Vehicles in Sub-Zero Temperatures
T/CAAMTB 21—2020	Technical Requirements for Vibration Tests of On-Board Hydrogen Supply Systems in Fuel Cell Electric Vehicles
T/CAAMTB 14—2020	DC/DC Converter for Fuel Cell Electric Vehicles
T/CAAMTB 13—2020	Methods for Air Compressors in Fuel Cell Vehicles
T/CAAMTB 12—2020	Test Methods for Membrane Electrode Assemblies in PEMFC

References

Alstom (2021). Trial runs of Alstom's hydrogen train in the Netherlands deemed officially successful. Alstom. [online] available: https://www.alstom.com/press-releases-news/2020/9/trial-runs-alstoms-hydrogen-train-netherlands-deemed-officially [accessed March 2021].

Andersen, K.B. (2021). Haldor Topsøe vil erobre globalt brintmarked – FINANS. Finans. [online] available: https://finans.dk/erhverv/ECE12784381/haldor-topsoee-vil-erobre-globalt-brintmarked/?ctxref=ext [accessed March 2021].

Barnard, M. (2021). Carbon capture will make fossil-sourced hydrogen 2.5–9× more expensive. CleanTechnica. [online] available: https://cleantechnica.com/2021/03/23/carbon-capture-will-make-fossil-sourced-hydrogen-2-5-9x-more-expensive/ [accessed March 2021].

BCAA (2021). BCAA Fuel Cell Data Analysis. Beijing: Bluetech Clean Air Alliance, unpublished.

Bloomberg (2021). Explore the first-ever hydrogen economy ranking system. Bloomberg. [online] available: https://sponsored.bloomberg.com/news/sponsors/features/hyundai/explore-the-global-hydrogen-economy-today/?adv=16713&prx_t=aXwFABAY_At_sQA [accessed February 2021].

BMBF (2021). BMBF bringt Wasserstoff-Leitprojekte auf den Weg. Bundesministerium für Bildung und Forschung. [online] available: https://www.bmbf.de/de/bmbf-bringt-wasserstoff-leitprojekte-auf-den-weg-13530.html [accessed March 2021].

BMEEB (2014). Bulletin on the Environmental Status of Beijing in 2013. Beijing: Beijing Municipal Ecology and Environment Bureau. [online] available: http://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/zfxxgk43/fdzdgknr2/xwfb/607213/index.html [accessed November 2021].

BMEEB (2018). The Latest Scientific Research Results of The New Round of PM2.5 Source Analysis in Beijing. Beijing: Beijing Municipal Ecology and Environment Bureau. [online] available: http://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/zfxxgk43/fdzdgknr2/xwfb/832588/index.html [accessed November 2021].

BMEEB (2021). Beijing Ecology and Environment. Beijing: Beijing Municipal Ecology and Environment Bureau. [online] available: http://sthjj.beijing.gov.cn/bjhrb/resource/cms/article/1718882/10985106/2021051214515686015.pdf [accessed November 2021].

Burgess, M. (2021). New hydrogen-based fuel developed for small vehicles. H2 View. [online] available: https://www.h2-view.com/story/new-hydrogen-based-fuel-developed-for-small-vehicles/ [accessed March 2021].

CABEE (2020). China Building Energy Consumption Research Report (2020). China Association of Building Energy Efficiency, Committee of Building Energy Data. [online] available: http://adminht.cabee.org/upload/file/20201231/1609385858606010.pdf [accessed November 2021].

Casey, T. (2021). Yara kickstarts green ammonia industry with green hydrogen. CleanTechnica. [online] available: https://cleantechnica.com/2021/03/01/yara-kickstarts-green-ammonia-industry-with-green-hydrogen/ [accessed March 2021].

China Economic (2019). China produces about 22 million tons of hydrogen every year, accounting for one-third of the world's hydrogen production. China Economic. [online] available: http://www.ce.cn/cysc/ny/gdxw/201907/08/t20190708_32548351.shtml [accessed May 2021].

China EV100 (2020). China Hydrogen Industry Development Report 2020 (no. 104). Beijing.

China Hydrogen Alliance (2019). White Paper on Hydrogen Energy and Fuel Cell Industry in China. Beijing.

China Daily (2020). The world's first large-scale solar fuel synthesis demonstration project successfully runs to produce "liquid sunshine." China Daily. [online] available: http://ex.chinadaily.com.cn/exchange/partners/82/rss/channel/cn/columns/j3u3t6/stories/WS5e229de5a3107bb6b579aa6d.html [accessed May 2021].

CORDIS (2020). BIONICO: A pilot plant for turning biomass directly into hydrogen. Horizon 2020, EU Publications Office. [online] available: https://cordis.europa.eu/article/id/394984-bionico-a-pilot-plant-for-turning-biomass-directly-into-hydrogen [accessed February 2021].

DICP (2020). The world's first large-scale demonstration project of solar fuel synthesis was successfully tested. Dalian Institute of Chemical Physics. Chinese Academy of Sciences. [online] available: http://www.dicp.cas.cn/xwdt/ttxw/202001/t20200116_5488931.html [accessed November 2021].

DICP (2021). Dalian Institute of Chemical Physics. Chinese Academy of Sciences. Division of hydrogen energy and advanced materials. [online] available: http://www.dicp.cas.cn/yjxt_1/dnl03/gkjj/ [accessed May 2021].

Engie (2020). Promising hydrogen innovations around the world. ENGIE Innovation. [online] available: http://innovation.engie.com/en/news/news/new-energies/Hydrogen-innovation-global-breakthrough/13681 [accessed February 2021].

Farmer, M. (2020). What colour is your hydrogen? A power technology jargon-buster. Power Technology. [online] available: https://www.power-technology.com/features/hydrogen-power-blue-green-grey-brown-extraction-production-colour-renewable-energy-storage/ [accessed March 2021].

FMBS (2020). Foshan Statistical Yearbook 2020. Foshan: Foshan Municipal Bureau Statistics. [online] available: http://www.foshan.gov.cn/attachment/0/153/153028/4654170.zip [accessed November 2021].

Global Energy Prize (2021). Chile holds world's first national hydrogen tender. The Global Energy Association. [online] available: https://globalenergyprize.org/en/2021/09/23/chile-holds-worlds-first-national-hydrogen-tender/ [accessed October 2021].

Godske, B. (2021a). Tyskland investerer 5,2 mia. kroner i tre brint-projekter. Ing. Teknologiens Medihus. [online] available: https://ing.dk/artikel/tyskland-investerer-52-mia-kroner-tre-brint-projekter-242870 [accessed March 2021].

Godske, B. (2021b). Verdens (foreløbig) største elektrolyseanlæg bygges i Tyskland. Ing. Teknologiens Medihus. [online] available: https://ing.dk/artikel/verdens-foreloebig-stoerste-elektrolyseanlaeg-bygges-tyskland-243636 [accessed March 2021].

Gong, Q., N. Wan, Q. Du, L. Li, H. Chen and J. Wang (2021). Research on Intelligent Transportation Operation of Hydrogen Fuel Cell Light Rail – Taking the First Commercial Hydrogen Tram in Foshan Gaoming as an Example. China Industry & Information Technology.

Guangzhou Daily (2020). Build Gaoming China hydrogen city! The world's first commercially operated hydrogen energy tram goes online. Guangzhou Daily. [online] available: https://www.gzdaily.cn/amucsite/web/index.html#/detail/1077938 [accessed November 2021].

Hydrogen Council and McKinsey (2021). Hydrogen Insights. A Perspective on Hydrogen Investment, Market Development and Cost Competitiveness. Geneva: Hydrogen Council, McKinsey & Company. [online] available: https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf [accessed November 2021].

Hydrogen Europe (2021). Fuel Cells | Hydrogen. Hydrogen Europe. [online] available: https://hydrogeneurope.eu/fuel-cells [accessed February 2021].

IEA (2019). The Future of Hydrogen. Paris: International Energy Agency. [online] available: https://www.iea.org/reports/the-future-of-hydrogen [accessed November 2021].

IEA (2021). Fuel cell EVs stock by region and by mode, 2020. IEA. [online] available: https://www.iea.org/data-and-statistics/charts/fuel-cell-electric-vehicles-stock-by-region-and-by-mode-2020 [accessed October 2021].

Jiading District (2018). Hydrogen energy and fuel cell industrial park unveiled Jiading District People's Government of Shanghai Municipality. [online] available: http://www.jiading.gov.cn/zwpd/zwdt/content_478343 [accessed May 2021].

MEE (2014). Report on the State of the Environment in China 2013. Beijing: Ministry of Ecology and Environment of the People's Republic of China. [online] available: http://english.mee.gov.cn/Resources/Reports/soe/soe2011/201606/P020160601591756378883.pdf

MEE (2020a). Statistical Report of National Ecological Environment from 2016-2019. Beijing: Ministry of Ecology and Environment of the People's Republic of China. [online] available: http://www.mee.gov.cn/hjzl/sthjzk/sthjtjnb/202012/P020201214580320276493.pdf

MEE (2020b). China Mobile Source Environmental Management Annual Report (2020). Beijing: Ministry of Ecology and Environment of the People's Republic of China. [online] available: http://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/202008/P020200811521365906550.pdf

MEE (2021). Report on the State of the Ecology and Environment in China 2020. Beijing: Ministry of Ecology and Environment of the People's Republic of China. [online] available: https://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/202105/P020210526572756184785.pdf

MF (2020). Ministry of Finance, Ministry of Industry and Information, Ministry of Science and Technology, Development and Reform Commission, National Energy Administration: Notice on the Demonstration Application of FCVs. Ministry of Finance of the People's Republic of China. [online] available: http://www.mof.gov.cn/gkml/caizhengwengao/202001wg/wg202009/202012/t20201230_3638265.htm [accessed November 2021].

MF (2021). Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology, National Development and Reform Commission, & National Energy Administration: Notice of Starting Demonstration Applications of Fuel Cell Vehicles. Ministry of Finance of the People's Republic of China.

MST (2009). Notice on the Implementation of Energy-Saving and New Energy Vehicle Demonstration and Promotion Pilot Work. Beijing:

Ministry of Science and Technology of the People's Republic of China. [online] available: http://www.most.gov.cn/tztg/200902/t20090211_67363.htm [accessed November 2021].

Nahar, G., D. Mote and V. Dupont (2017). Hydrogen production from reforming of biogas: Review of technological advances and an Indian perspective. Renewable and Sustainable Energy Reviews, 76, 1032–52.

NBSC (2020). China Statistical Yearbook 2020 (No. 9–1). Beijing: National Bureau of Statistics of China. [online] available: http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm [accessed November 2021].

NPGF (2020). Foshan Nanhai District Hydrogen Industry Development Plan (2020–2035). Nanhai People's Government of Foshan. [online] available: http://www.nanhai.gov.cn/attachment/0/82/82806/4191926.pdf [accessed November 2021].

PIA (2021). Baofeng Solar Electrolysis Water Hydrogen Production Comprehensive Demonstration Project Was Officially Put Into Operation. Beijing: Petrochemical Industry Application.

Rapier, R. (2021). Estimating the carbon footprint of hydrogen production. Forbes Magazine. [online] available: https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/ [accessed February 2021].

Saur, G. and A. Milbrandt (2014). Renewable Hydrogen Potential from Biogas in the United States. Golden, Colorado: National Renewable Energy Laboratory. [online] available: https://www.nrel.gov/docs/fy14osti/60283.pdf?gathStatIcon=true [accessed November 2021].

Saurabh (2021). India plans green hydrogen auctions. CleanTechnica. [online] available: https://cleantechnica.com/2021/02/28/india-plans-green-hydrogen-auctions/ [accessed March 2021].

SEMC and SMRIEP (2016). Study on Source Analysis and Control Countermeasures of PM2.5 in Shanghai. China Science and Technology Achievements. Shanghai: Shanghai Environmental Monitoring Center. Shanghai Municipa Research Institute of Environmental Protection. [online] available: https://doi.org/10.3772/j.issn.1009-5659.2016.18.008 [accessed November 2021].

SinoHytec (2021). Company profile. SinoHytec. [online] available: http://www.sinohytec.com/en/page.php?id=1 [accessed May 2021].

SMBS (2020). Shanghai Statistical Yearbook 2020. Shanghai Municipal Bureau of Statistics.

UNDP (2021). Accelerating the Development and Commercialization of Fuel Cell Vehicles in China. United Nations Development Programme in China.

Wang, Z. (2021). Thoughts on the Policy Trend of Hydrogen Industry and the Transformation of Electric Power Industry. Shanghai, China: Hydrogen from Renewable Energy Forum.

WEF (2018). These countries are pioneering hydrogen power. World Economic Forum. [online] available: https://www.weforum.org/agenda/2019/01/these-countries-are-pioneering-hydrogen-power-d941536b-4206-4fa1-8932-8596d7b856bd/ [accessed February 2021].

World Steel Association (2020). Steel Statistical Yearbook 2020 Concise Version. [online] available: https://www.worldsteel.org/zh/dam/jcr:5001dac8-0083-46f3-aadd-35aa357acbcc Steel%2520Statistical%2520Yearbook%25202020%2520%2528concise%2520version%2529.pdf Shanghai Municipal Bureau Statistics.

Yara (2021). Yara partners with Statkraft and Aker Horizons to establish Europe's first large-scale green ammonia project in Norway | Yara International. Yara. [online] available: https://www.yara.com/corporate-releases/yara-partners-with-statkraft-and-aker-horizons-to-establish-europes-first-large-scale-green-ammonia-project-in-norway/ [accessed March 2021].

Zhangjiakou Mun. (2020). Implementation Plan of Phase I Project of Zhangjiakou Hydrogen Energy Guarantee Supply System. Zhangjiakou: The People's Government of Zhangjiakou Municipality.

ZMBS (2020). Statistical Bulletin on Economic and Social Development of Zhangjiakou in 2019. Zhangjiakou Municipal Bureau Statistics. [online] available: http://tjj.zjk.gov.cn/content/2020/28681.html [accessed November 2021].

Santos, D. K., R. D. Rufino, J. M. Luna, V. A. Santos and L. A. Sarubbo (2016). Biosurfactants: Multifunctional Biomolecules of the 21st Century. *International Journal of Molecular Sciences*, 17(3), 401.

Sencrop (2020). Sencrop – The connected ag-weather station available to all. [online], available: https://sencrop.com/en/ [accessed July 2020].

Sharma, D., E. Gupta, J. Singh, P. Vyas and D. Dhandjal (2018). Chapter 10. Microbial biosurfactants in food sanitation. In Galanakis, C. M., (ed.) *Sustainable food systems from agriculture to industry: improving production and processing*, Waltham: Elsevier

Sigma Aldrich [online], available: https://www.sigmaaldrich.com/ [accessed 2020].

Siracusa, V. and M. D. Rosa (2018). Sustainable Packaging. In Galanakis, C. M., (ed.) *Sustainable food systems from agriculture to industry: improving production and processing*, Waltham: Elsevier.

SKAGINN 3X [online], available: https://www.skaginn3x.com/ [accessed 2020].

Stoica, M. (2018). Chapter 9. Sustainable sanitation in the food industry. In Galanakis, C. M., (ed.) *Sustainable food systems from agriculture to industry: improving production and processing*, Waltham: Elsevier

Tanaka, T., K. Fujihara, M. S. Jami and M. Iwata (2014). Constant-current electroosmotic dewatering of superabsorbent hydrogel. Colloids and Surfaces A. *Physicochemical and Engineering Aspects*, (440), 116-21.

Tavman, S., S. Otles, S. Glaue and N. Gogus (2019). Food Preservation technologies. In Galanakis, C. M., (ed.) *Saving Food: Production, Supply Chain, Food Waste and Food Consumption*, Waltham: Elsevier.

Torti, M. J., C. A. Sims, C. M. Adams and P. J. Sarnoski (2016). Polysaccharides as alternative moisture retention agents for shrimp. *Journal of Food Science*, (81), S728–S35.

Toshiba (2019). Electrode for electrolysis, electrode unit, electrolyzer, etc. capable of efficiently performing various electrolysis such as generation of hypochlorous acid water used as sterilization disinfection water. [online], available: https://www3.wipo.int/wipogreen-database/SearchDetailPage.htm?query=toshiba%20electrode&type=all&id=T-GREEN20114 [accessed 2020].

Tuku [online], available: https://tukuinc.com/intelligent-packaging/ [accessed 2020].

UN (2020). SDG 12 Sustainable consumption and production. [online], available: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/ [accessed July 2020].

USDA (2017). USDA and EPA Join with Private Sector, Charitable Organizations to Set Nation's First Food Waste Reduction Goals. [online], available: https://www.usda.gov/media/press-releases/2015/09/16/usda-and-epa-join-private-sector-charitable-organizations-set [accessed 2017].

WEF (2020). Locusts are putting 5 million people at risk of starvation – and that's without COVID-19. [online], available: https://www.weforum.org/agenda/2020/06/locusts-africa-hunger-famine-covid-19/ [accessed July 2020].

WFP (2019). *Zero Food Loss Initiative Update, no. 2 (January)*. December 3rd, 2019. Rome: World Food Programme.

WITT-Gasetechnik [online], available: https://www.wittgas.com/ [accessed 2020].

World Bank (2017). *ICT in Agriculture: Connecting Smallholders to Knowledge, Networks, and Institutions. Updated Edition*, Washington, DC: World Bank.

WRI (2019a). Major Food Retailers & Providers Join New "10x20x30" Food Loss and Waste Initiative. [online], available: https://www.wri.org/news/2019/09/release-major-food-retailers-providers-join-new-10x20x30-food-loss-and-waste-initiative [accessed 2020].

WRI (2019b). *Reducing food loss and waste: Setting a Global Action Agenda*, Washington, DC: World Resource Institute.

Xue, L. and G. Liu (2019). Introduction to global food losses and food waste. Eds by, Elsevier Inc: Waltham. In Galanakis, C. M., (ed.) *Saving Food: Production, Supply Chain, Food Waste and Food Consumption*, Waltham: Elsevier Inc.

About Us

The WIPO Global Challenges Division is responsible for addressing innovation and IP at the nexus of interconnected global issues, with a particular focus on global health, climate change and food security. The Division's activities, including the two multi-stakeholder platforms it administers and trilateral cooperation with the World Health Organization and World Trade Organization, aim to harness the power of innovative partnerships to generate practical solutions for the benefit of all – especially developing countries.

Cover: Getty Images / Wladimir Bulgar / Science Photo Library

WIPO Reference No. RN2022-4E
DOI: 10.34667/tind.44764