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PROSPECTS OF A HYDROGEN ECONOMY WITH CHINESE CHARACTERISTICS

Kevin Jianjun TU

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Executive Summary

As the world's largest energy consumer and producer, the Chinese energy economy is full of contradiction. On the one hand, China's heavy reliance on carbon-intensive and pollution-prone coal makes it the world's undisputed leading carbon emitting economy. Consequently, the gigantic Chinese energy economy is always easy to be described from an eye-catching angle such as China alone burns more than half of global coal. Nevertheless, dirty coal, rising carbon emission and filthy air are far from the entire picture of the Chinese energy economy. As the largest clean energy market in the world, China has installed more than one third of global solar and wind capacities, and deployed near half of the world's electric vehicle (EV) stock by the end of 2019.

Given China's impressive track record of scaling up clean energy technologies in the past, when Dr. Wang Gang, vice chairman of the Chinese People's Political Consultative Conference, urged Beijing to strengthen its infrastructure investment for the distribution of hydrogen as a fuel to accelerate development of its fuel cell electric vehicle (FCEV) industry on 2 July 2020, the international community immediately paid attention to the so called "hydrogen economy" in China.

This study assesses the prospects of a hydrogen economy with Chinese characteristics. Against the backdrop of an escalating US-China trade war and the ongoing novel coronavirus (COVID-19) pandemic, key Chinese stakeholders become increasingly interested in moving the hydrogen economy agenda forward. During the first six months of 2020 alone, 37 policies in support of the hydrogen economy have been published by various level governments, including 7 by central government authorities, and 30 by local governments. Shandong alone issued 6 hydrogen supporting policies, followed with 5 by Guangdong. In sum, the hydrogen economy development not only gains traction in China, but is also in great danger of overheating.

Since 2010, China's national hydrogen production increased by an impressive 6.8% annually and reached 21 million tonnes (Mt) in 2018, accounting for 18% of global total and ranking the first in the world. Ammonia manufacturing represents a significant portion of national hydrogen demand in China: unlike the rest of the world where steam methane reforming (SMR) is the mainstream manufacturing route, the most common feedstock in China is coal via a partial oxidation process. Hydrogen is also used for methanol manufacturing, with the bulk derived from coal gasification as well.

The ambition in China is to expand hydrogen production and create new end-uses: in the transport segment (e.g. 1 million FCEVs and 1 000 hydrogen refueling stations by 2030), but possibly also, in other hard-to-abate sectors such as steel and cement manufacturing or in the electricity storage segment (Power to X). Hydrogen production from low carbon electricity could bring many benefits, notably to address curtailments of renewable electricity from wind, solar and hydro. It could also be blended into the nation-wide gas grid especially for low-concentration hydrogen (e.g. 5-10%).

Until recently, China's interest in developing the hydrogen economy has not been primarily triggered by the decarbonization objective. Nevertheless, on 22 September 2020, Chinese president Xi Jinping announced that China aims to peak national carbon emissions before 2030 and achieve carbon neutrality before 2060. Given the significant amount of carbon emissions reduction implied by the above announcement, hydrogen is now expected to play a much more important role to drastically decrease the country's greenhouse gas emissions (GHG) over time.

China's very large hydrogen production from fossil fuels, mainly coal, would make it quite challenging to consider decarbonizing the current uses of hydrogen. What decisively drives the current interest into hydrogen is innovation and technological leadership on the one hand, which China can achieve through industrial clusters and economies of scale, and energy security on the other: reducing dependence on imported oil and gas, with rising importance of air pollution control- and decarbonization-related considerations. It remains to be seen whether China can avoid the shortcomings of its EV supporting policies as it aims to boost a hydrogen economy with Chinese characteristics.

A simplified SWOT analysis presented in the report identifies the most important strength, weakness, opportunity and threat for hydrogen economy development in China:

- Strength - ability to significantly bring down unit manufacturing cost through industrial network clustering and economy of scale.
- Weakness – lag far behind advanced economies in key hydrogen-related technologies.
- Opportunity – enthusiasm on hydrogen economy by local governments against the backdrop of the COVID-19 pandemic.

- Threat - looming danger of global supply chain decoupling caused by an escalating US-China trade war.

In order to move the hydrogen economy agenda forward, a preliminary "to do list" for Chinese decision-makers in this field would include:

- A coordinated national mechanism should be established at the central government level to lay out principles for moving the hydrogen economy agenda forward in China.
- Comprehensive and transparent statistical reporting and accounting throughout the Chinese hydrogen value chain should be established.
- In the hydrogen production segment, renewable hydrogen should be prioritized for intensive R&D and deployment in the near future, and greening China's existing hydrogen flow should be on the Chinese government's policy radar especially in the longer term. In this regards, the timely establishment and subsequent coverage expansion of China's long-awaited national emissions trading scheme will be beneficial to green the Chinese hydrogen value chain in the years to come.
- In the hydrogen storage and transport segment, national and local government should continuously direct subsidies towards hydrogen refueling stations, and also consider to encourage low concentration blending of hydrogen into China's natural gas network.
- In the hydrogen consumption segment, China should selectively focus on R&D and deployment of advanced hydrogen end-use technologies notably for cement and steel, ideally coupled with expansion of the horizon of national energy planning framework.
- Opening up the Chinese market to better integrate technology innovations in advanced economies and manufacturing-related competitive advantages of the Chinese economy, aiming to create a win-win situation between China and the international community.

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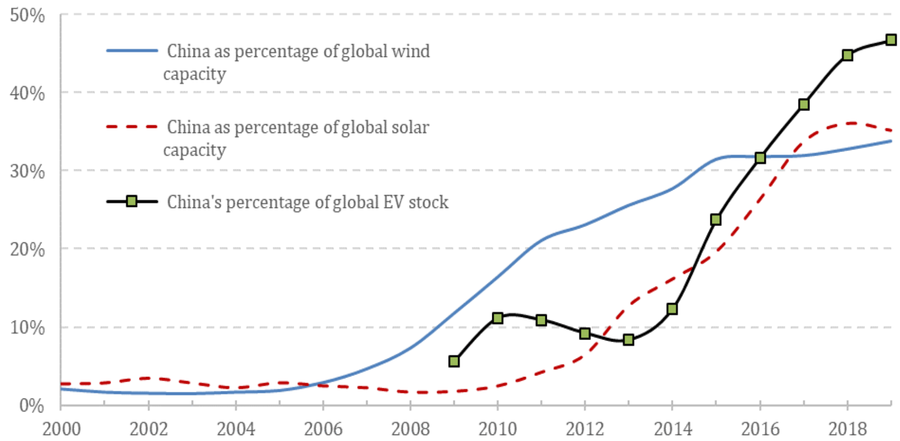
Introduction

As the world's largest energy consumer and producer, the Chinese energy economy is full of contradiction.

Since the Chinese former paramount leader Deng Xiaoping opened up China's inward-looking economy to the outside world in 1978, China experienced a remarkable economic expansion and surpassed the United States (US) as the world's largest economy in purchasing power parity in 2013. Even on a market exchange basis, China is bigger than the world's third, fourth, and fifth largest economies combined (namely Japan, Germany, and the United Kingdom).

Nevertheless, despite China's impressive economic gains, nearly one in three of the country's population lives in a household without access to clean cooking technologies, the majority of whom rely on biomass with the attendant health impacts, including premature death. Because of the aforementioned contradiction and similar ones, Benoit and Tu (2020) categorizes China as the first ever "hybrid superpower" in the modern era.[1] While China is not a developed country yet, its status as a developing country nevertheless becomes increasingly debatable, especially from the perspective of advanced economies.

Figure 1. China's rapid ascendance in global clean energy markets



Source: IRENA Renewable Database and IEA Global EV Outlook 2020.

1. P. Benoit and K. Tu, *Is China Still a Developing Country? And Why It Matters for Energy and Climate*, Center on Global Energy Policy, New York: Columbia University, 2020.

Because of its heavy reliance on carbon-intensive and pollution-prone coal, China is the world's undisputed leading carbon emitting economy, accounting for 29 % of global total carbon dioxide (CO_2) emissions. Consequently, the gigantic Chinese energy economy is always easy to be described from the following eye-catching angles: 1) China alone burns more than half of global coal; 2) coal-fired power plants in China represents near half of global capacity, and accounts for more than 11 percent of the world's carbon emissions; 3) among the world's 100 most polluted cities in 2019, 48 are Chinese.[2]

Nevertheless, dirty coal, rising carbon emissions and filthy air are far from the entire picture of the Chinese energy economy. As depicted in Figure 1, since the Global Financial Crisis in 2008, the Chinese energy economy has already started a journey of redemption. In less than one decade, the size of the Chinese clean energy market has grown from near negligible to the largest in the world. In 2019, both wind and solar installations in China exceeded one third of global total, with Chinese EV stock accounting for near half of the world fleet.

Given China's impressive track record of scaling up clean energy technologies in the past, when Dr. Wang Gang, vice chairman of the Chinese People's Political Consultative Conference, urged Beijing to strengthen its infrastructure investment for the distribution of hydrogen as a fuel to accelerate development of its FCEV industry on 2 July 2020, the international community immediately paid attention to prospect of the so called "hydrogen economy" in China. Dr. Wang is the same high-ranking Chinese politician who convinced Beijing to bet on EVs in the past and is often referred to as China's "father of EV" by state media.[3]

The term "hydrogen economy" — a hypothetical future system of delivering energy through the use of hydrogen — was first coined by John Bockris as early as 1970. Since then, hydrogen has seen several waves of boom and bust including an oil price shock-driven one in 1970s, a climate change-induced one in 1990s, followed with another renewed interest jointly driven by rising concerns for climate change and "peak oil" in early 2000s. Unfortunately, none of which has been fully translated into sustainable investment and scalable deployment. Not surprisingly, it is legitimate to wonder whether China's newly found enthusiasm on the hydrogen economy will make a real difference this time.

2. IQAir, "World's Most Polluted Cities 2019 (PM2.5)", 2020, accessed on 11 June 2020, available at: www.iqair.com.

3. Bloomberg, "Wan Gang, China's Father of Electric Cars, Thinks Hydrogen is the Future", 2020, accessed on 15 July 2020, available at: www.scmp.com.

To assess the prospect of a hydrogen economy with Chinese characteristics, the following questions can be raised:

- What is the status quo of the Chinese hydrogen value chain from production, storage, transport to end-uses?
- What hydrogen production technologies and end-uses have been considered by key Chinese stakeholders?
- What are the driving forces underlying the Chinese hydrogen economy?
- Who are its leading stakeholders?
- What are the main government policies in support of the development of the Chinese hydrogen economy?
- What criteria should be used to evaluate progress of hydrogen economy development in China?
- What are the roadmap and timeline of hydrogen economy development in China?
- What should be the priorities of the Chinese government in terms of hydrogen production and end-uses?

As a preliminary scoping research of the nascent but sizable Chinese hydrogen economy, this report has strived to answer the above questions but leave more in-depth coverage of the topic for a potential follow up study. Meanwhile, it is worthwhile to note that China's policy framework in support of the hydrogen economy could be dated back as early as 1950 under three categories: 1) the first category is research and development (R&D) programs such as space programs, 863 program, 973 program, and national key R&D program; 2) the second is the so-called Five Year Plan (FYP); and 3) the third is major law, regulation, guidelines, administrative orders issued by various government authorities.

This paper examines the prospect of a hydrogen economy with Chinese characteristics by starting with an overview of the Chinese hydrogen value chain from production, storage, transport to end uses, followed with an assessment of key driving forces underlying hydrogen economy development in China. Then the paper presents key stockholders and most relevant policies in China. Finally, some concluding remarks are made to explore how to move the hydrogen economy agenda forward in China.

Overview of the Chinese hydrogen value chain

Hydrogen production and consumption

According to various industrial sources, since 2010, China's national hydrogen production increased by an impressive 6.8% annually and reached 21 Mt in 2018, accounting for 18% of global total and ranking the first in the world.[4] By comparison, China's primary energy consumption only grew 3.2% annually during the same period, so hydrogen's importance in the Chinese energy economy has strengthened significantly, laying a solid foundation for promoting hydrogen economy development.

Based on Xue Deng and *et al.* (2010),[5] recent production and capacity data from National Bureau of Statistics (NBS) and various industrial sources, the following major sources of hydrogen consumption in China can be identified and estimated:

- **Ammonia synthesis**: Ammonia (NH_3) is one of the most synthesized chemicals worldwide, it is the precursor to most modern nitrogen-based fertilizer and have widespread use in manufacturing of explosives, pharmaceutics, fibers, plastics, paper and other essential chemicals and products. The Haber-Bosch process reacts atmospheric nitrogen with hydrogen to produce ammonia, which is 17.8% hydrogen by weight. Hydrogen is typically produced on-site at ammonia plants from fossil fuel feedstock.

  Unlike the rest of the world where steam methane reforming (SMR) is the mainstream manufacturing route, the most common feedstock in China is coal via a partial oxidation process. About 76.7% of China's ammonia output is derived from coal, followed with 20.8% from natural gas, 2.1% from coke oven gas and 0.5% from others. Assuming 178.18 to 182.44 kg of hydrogen consumption per tonne of ammonia

4. The author's own assessment indicates that this serial of hydrogen production statistics seems to be an underestimation of China's actual hydrogen flow. Nevertheless, the relative growth rate derived from this serial of data should still be useful.

5. X. Deng and *et al.*, "Hydrogen Flow Chart in China", *International Journal of Hydrogen Energy*, Vol. 35, N° 13, 2010, pp. 6475-6481.

production, China's national ammonia output at 57.6 Mt in 2019 implies an annual hydrogen consumption of more than 10 Mt.[6]

- **Methanol synthesis**: Methanol (CH_3OH), also known as methyl alcohol, is a light, volatile, colorless, flammable liquid. It is not only an important raw material for many chemicals especially formaldehyde and dimethyl ether (DME), but also an emerging vehicle fuel for blending with gasoline. Most methanol plants circulate carbon monoxide and hydrogen under pressure and moderate temperature through a catalyst process to produce raw methanol. About 76% of China's methanol output is derived from coal, followed with 17% from coke oven gas, and 7% from natural gas. Assuming 126.45 to 142.26 kg of hydrogen consumption per tonne of methanol production, China's national methanol output at 62.2 Mt in 2019 implies an annual hydrogen consumption of around 8 Mt.[7]

- **Petroleum refining**: A petroleum refinery is consisted with many processes that convert crude oil into valuable products such as gasoline, diesel and jet fuel with utilization of hydrogen. The primary source of hydrogen within the refinery has been the catalytic naphtha reforming unit which supplies the needs of hydrocracking and hydrotreating processes. Nevertheless, due to rising hydrogen demand driven by increasingly stringent environment standards and higher share of heavy and sour crude input, only slightly more than 40 percent of a typical Chinese refinery's hydrogen demand could be supplied with on-site by-products, with the remaining met by either on-site hydrogen production or merchant supply. In recent years, coal gasification is routinely included in new refinery setups in China as a main or auxiliary hydrogen production unit. As a result, at least 10% of hydrogen consumed by Chinese refineries is derived from coal, which is a rather unique setting. Assuming 50 cubic meters (m^3) of hydrogen consumption per tonne of crude processed, China's refinery throughput at 652 Mt in 2019 implies annual hydrogen consumption of near 3 Mt. If a typical Chinese refinery's hydrogen requirement is similar as that of an American one (about 7 kg of hydrogen per tonne of throughput), annual hydrogen consumption by the Chinese petroleum refining industry in 2019 would stand at about 4.5 Mt.

6. China Nitrogen Fertilizer Industry Association, *Bulletin of Nitrogen Fertilizer Production and Economic Operation in 2019*, 2020, accessed on 15 October 2020, available at: www.nzdb.com.cn.
7. H. Chen, "Analysis of Manufacturing Capacity, Output, Imports and Apparent Consumption of the Chinese Methanol Industry in 2019," 2020, accessed on 15 October 2020, available at: www.huaon.com.

- **Commercial hydrogen:** The majority of hydrogen produced in China is consumed by chemical and petrochemical industrial applications, only a small percentage of commercial hydrogen is used for metal smelting, electronics, food processing, pharmaceuticals, glass manufacturing, laboratory research, and aeronautics & astronautics.

Currently, the mainstream processes for producing hydrogen in China are gasification of coal, catalytic steam reforming of natural gas, partial oxidation of heavy oil as well as electrolysis of water:

- **Gasification of coal**: Coal gasification is a thermo-chemical process in which the gasifier's heat and pressure break down coal into its chemical constituents. The resulting synthesis gas is comprised primarily of carbon monoxide and hydrogen, and could be used as either chemical "building blocks" or fuel for industrial purposes. As more than three quarters of ammonia and methanol output in China and at least 10% of hydrogen consumed by Chinese refineries are derived from coal, coal gasification in these three sectors alone represents more than 14 Mt of annual hydrogen production.
- **By-product hydrogen by coking**: Coking or coal carbonization is the heating of coal in the absence of air to drive off the volatile components of the raw coal to produce coke. Coke oven gas is the by-product of coking. Normally, for each tonne of coke output, around 420 m^3 of coke oven gas is generated as by-product, and typical coke oven gas is consisted of 52.2% to 55.6% of hydrogen, and 27.1% to 30.4% of methane. In 2019, national coke production in China reached 643 Mt, which implies around 9 Mt of by-product hydrogen output.
- **Hydrogen produced by natural gas**: Most hydrogen produced by natural gas in China is made via SMR, which is the most common method to supply hydrogen in ammonia plants, oil refineries, and methanol plants in most parts of the world. In these three sectors alone, natural gas accounts for around 3.5 Mt of hydrogen production in China.
- **Hydrogen produced from oil:** On-site by-product hydrogen produced at a petroleum refinery comes largely from catalytic naphtha reforming, a process that produces high-octane gasoline blending components and generates hydrogen at the same time. As by-product hydrogen accounts for slightly more than 40% of hydrogen consumed by Chinese refineries, it is the largest source of hydrogen produced from oil in China.

- **By-product hydrogen via electrolysis in the chlor-alkali industry:** China has a large chlor-alkali industry. The main process for producing sodium hydroxide involves the electrolysis of salt water, which splits salt in solution into sodium hydroxide, chlorine gas and hydrogen. Generally speaking, the production of 1 tonne of sodium hydroxide comes with 279 m^3 of by-product hydrogen. In 2019, national sodium hydroxide output in China reached 34.6 Mt, which implies near 0.9 Mt of by-product hydrogen output.

Novel applications of hydrogen production and consumption

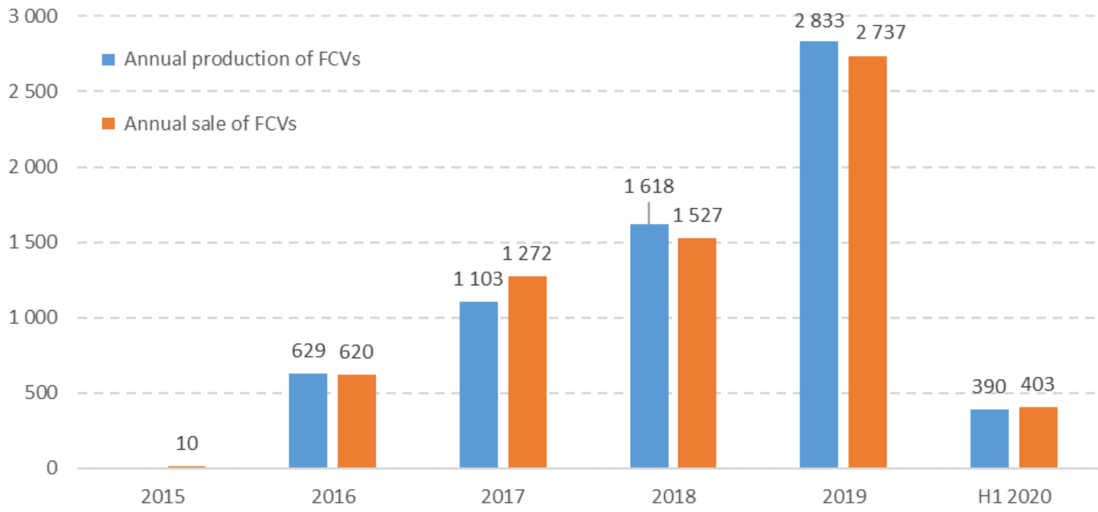
In recent years, "black", "grey" or "brown" has been used to describe the production of hydrogen from coal, natural gas and lignite, respectively. "Blue" is commonly used for the production of hydrogen from fossil fuels with carbon emissions reduced by the use of carbon capture, utilization and sequestration (CCUS). "Green" is a term applied to production of hydrogen from renewable power[8] Nevertheless, taking China's largely successful EV strategy as an example, when Beijing first kicked off its national EV program, the status quo of China's power generation mix did not bother Chinese decision makers much. In the end, what really matters is the economy of scale achieved by large scale deployment of EVs across the country, and optimization of national power mix over time especially with the rapid declining share of coal-fired power generation. Similarly, in the infant stage of China's hydrogen economy development, sources of hydrogen production should not be considered as the most important constraint. In the end, success should be measured by the extent novel applications of hydrogen production, storage, transport and consumption could be promoted across the country in short-, medium- and long-term, and their associated environmental and climate benefits.

Though electrolysis of water is a rather mature technology, this process can only be considered as a sustainable way to produce hydrogen if the electricity used comes from low carbon sources. Given the difficulty associated with lowering unit power generation cost of nuclear power plants due to increasingly stringent safety standards and rising public resistance, electrolysis of water by renewable power is widely considered as the most promising novel application of hydrogen production. As a result, the success of the Chinese hydrogen economy could also be partially benchmarked against annual production of renewable hydrogen.

8. IEA, *The Future of Hydrogen*. International Energy Agency, Paris, 2019.

In the consumption end, the most promising novel application considered by key Chinese stakeholders has been FCEVs so far. Similar as EVs, FCEVs rely on electricity to power an electric motor. In contrast to EVs, FCEVs produce electricity using a fuel cell powered by hydrogen, rather than drawing electricity entirely from a battery. Starting from a very low base, China has been quickly ramping up research, development (R&D) and deployment of FCEVs in recent years, and the success of the Chinese hydrogen economy could also be partially benchmarked against annual production and sales of FCEVs over time. Nevertheless, by the end of June 2020, cumulative sales of FCEVs in China were still less than 7,000. By comparison, cumulative stock of China's new energy vehicles[9] reached 4.17 million, with almost all of them being either battery EVs or plug-in hybrid EVs.[10]

Figure 2. Annual production and sale of FCEVs in China



Source: China Association of Automobile Manufacturers.

On 8 November 2006, BP and SinoHytec, a Chinese firm that specializes in developing and commercializing renewable energy and advanced transportation technologies, jointly opened China's first hydrogen refueling station. Located at Zhongguancun Yongfeng High-Tech Industrial Base, the Beijing International Hydrogen Park is the first demonstration project for new energy vehicles in China. With a total investment at 3.5 million US dollars, this station is capable of

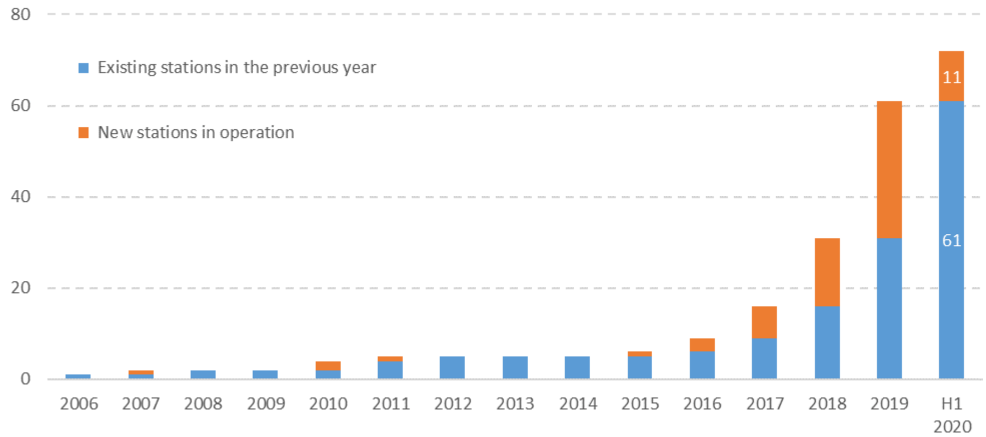
9. The Chinese government uses the term "new energy vehicles" to designate plug-in EVs eligible for public subsidies, and includes only battery EVs, plug-in hybrid EVs and FCEVs.

10. Auto Business Review, "The Five Million New Energy Vehicle Target Is Unattainable this Year, with Tesla as the Only Hope?" 2020, accessed on 15 September 2020, available at: www.d1ev.com.

supplying 25 kg of hydrogen for each of Beijing's then entire fuel cell bus fleet of just 4.[11]

Since then, the number of hydrogen refueling stations in China increased rapidly. In 2019, Shanghai Chemical Industry Hydrogen Refueling Station, the world's largest one, opened in Shanghai. With an acreage of 8,000 square meters (m^2), this station has a capacity of supplying 2 tonnes of hydrogen per day with its 35 megapascal (MPa) and 70 MPa refueling systems.[12] By the end of June 2020, 72 hydrogen refueling stations have already become operational in China, with many more under construction and planning across the country.

Figure 3. Annual addition of hydrogen refueling stations in China



Source: China Hydrogen Market Review 2019, and Forward Industry Research Institute.

The steel industry is one of the highest carbon emitting industries in the world, representing about 7% of global carbon emissions. By comparison, China's crude steel output was 996.3 Mt in 2019, accounting for 53.3% of global total.[13] Due to its high dependency on coal, its modest utilization rate of advanced technologies, and its low share of electric arc furnace production, the Chinese iron and manufacturing industry accounted for 16.5% of national energy consumption and 16.2% of national carbon emissions, with its energy and carbon intensities about 20% and

11. New Energy Vehicle Network, "China's First Hydrogen Refueling Station Started to Operate in Beijing in 2016," accessed on 30 July 2020, available at: www.xnyauto.com.
12. FuelCellsWork, "China: the World's Largest Refueling Station Opened in Shanghai," accessed on 30 July 2020, available at: https://fuelcellsworks.com.
13. World Steel Association, "Global Crude Steel Output Increases by 3.4% in 2019," 2020, accessed on 15 September 2020, available at: www.worldsteel.org.

18% higher than those of advanced economies, respectively.[14] Not surprisingly, a successful decarbonization strategy is key for sustainable development of the Chinese steel manufacturing industry.

Nevertheless, the dominant blast furnace-based production route primarily relies on the use of coking coal and its mechanical properties, which makes it difficult to switch to other reduction agents in the blast furnace. Consequently, fundamental changes in steel manufacturing processes are required to decarbonize the industry. Except for the continuous use of fossil fuels with CCS configuration, the hydrogen direct reduction process has caught increasingly attention of the international community. For instance, in a hydrogen-based metallurgical process such as the HYBRIT concept, specially developed iron ore pellets are reduced by hydrogen gas in a direct reduction process. Reduction occurs in a solid state at a lower temperature than in the blast furnace process and produces an intermediate product, sponge iron or direct reduced iron, with water vapour emitted from the top of the furnace.[15] Given its dominant share of global steel production and related carbon emissions, China should seriously examine hydrogen direct reduction process' potential of decarbonizing its steel manufacturing industry.

Furthermore, given the interconnection of an increasingly complicated energy system, a deep decarbonization of the Chinese economy should certainly go far beyond novel applications of hydrogen production and consumption, which explains why it is necessary for Chinese decision makers to carefully examine the potential role of Power-to-X (also referred to as P2X or PtX)[16] and sector coupling in China's ongoing energy transformation.

While the Chinese energy economy becomes increasingly interconnected, it nevertheless remains largely fragmented, with numerous technical and institutional barriers that prevent the optimization of an energy- and carbon-intensive system. If the concepts of P2X and sector

14. Z. Li and *et al., Assessment of the Carbon Emissions Reduction Potential of China's Iron and Steel Industry Based on a Simulation Analysis,* Energy 183, 2019, pp. 279-290.

15. HYBRIT, "Steel Making Today and Tomorrow," accessed on 15 September 2020, available at: www.hybritdevelopment.com.

16. Michael Sterner, a professor at OTH Regensburg University in Regensburg in Germany, defines P2X as "the means to convert electricity, understood to be primary energy, into an energy carrier, heat, cold, product, or raw material. It is an umbrella term for different ways of generating energy, namely power-to-gas (including hydrogen), power-to-liquid, power-to-fuel, power-to-chemicals and power-to-heat." His definition shows that the X in P2X stands for a variety of products, processes, technologies and applications. Similarly, sector coupling (German: Sektorkopplung) refers to the idea of interconnecting (integrating) the energy consuming sectors - buildings (heating and cooling), transport, and industry - with the power producing and related industries such as the hydrogen value chain. See H2-international, "What Exactly is Power-to-X?" 2019, accessed on 15 September 2020, available at: www.h2-international.com.

coupling were incorporated into China's energy planning framework, the utilization of electricity and hydrogen in all energy-related processes, whether transport, heating, or manufacturing, would revolutionize the largely compartmented Chinese energy sector by introducing new momentum to deepen China's energy sector reform.

Hydrogen storage and transport

Under normal temperature and pressure conditions, 1 kilogram (kg) of hydrogen occupies a volume of 11.126 cubic meters (m^3) and an energy content of 33.3 kilowatt-hours (kWh),[17] whereas for the same energy content, the volume occupied by gasoline is only 0.03% of hydrogen. Consequently, for hydrogen to become a competitive energy carrier, its volume density must be drastically increased. Currently, three separate options for hydrogen storage are identified for intensive R&D and deployment:[18]

- **Compressed hydrogen storage** is a common storage form whereby hydrogen gas is kept under pressures to increase the storage density. Nevertheless, even at extremely high pressures (e.g. 700 bar), such technology suffers from low volumetric density and the energy content is lower than that of gasoline under the same conditions. Furthermore, safety issues are also a drawback due to the possible embrittlement of the cylinders. Finally, the high cost of the mechanical compression and the large pressure drop inside the gas cylinder are also considered as drawbacks of this storage option.[19]
- **Hydrogen storage in liquid form**: Hydrogen could be liquefied by reducing its temperature to - 253 degree Celsius (°C). Though energy density of liquid hydrogen has improved compared with compressed storage, the volumetric storage capacity is still relatively low. The high cost of liquefication is a major barrier that needs to be overcome, so do the safety regarding the handling of cryogenic tanks and hydrogen loss caused by evaporation.
- **Solid-state hydrogen storage**: The storage of hydrogen in solid-state form with the formation of metal hydrides, such as MgH_2, $NaAlH_4$, $LiAlH_4$, LiH, $LaNi_5H_6$, and $TiFeH_2$, is a very attractive

17. Lower heating value (LHV) basis.
18. M. Sankir and N. Demirci Sankir *Hydrogen Storage Technologies*, Beverly, MA: Scrivener Publishing LLC, 2018.
19. While 70 megapascal (MPa) Type IV composite cylinders that use high-strength carbon fiber is the mainstream on-board hydrogen storage technology used by FCEVs in advanced economies, 35 MPa Type III composite cylinders are widely used by Chinese FCEV manufacturers, with 70 MPa Type III composite cylinders starting to be deployed in China.

technology to store hydrogen in an efficient and safe manner. This technology is characterized by large volumetric capacities which do not suffer from the drawbacks of pressurized and liquid hydrogen. Due to the relative low pressures of operation, the hydrogen storage in solid form is considered as a relatively safe technique. Nevertheless, the persistent problems are the percentage weight of hydrogen that they carry and the reversibility of the storage process. For mainstream metal hydrides materials, their hydrogen storage capacity is still lower than 3.9 percent on a weight basis, though similar capacity of lightweight metal hydrides may exceed 7 percent on a weight basis, their poor kinetics and relatively high operating temperature needs to be further improved.[20]

Reliable, sustainable, and cost-effective transportation of hydrogen from production sites to where it is needed is a prerequisite to the competitiveness of hydrogen economy. Today, the transport of compressed gaseous or liquid hydrogen by trucks and of compressed gaseous hydrogen by pipeline to selected locations are the main transport options used in China:[21]

- **Compressed gas cylinders or cryogenic liquid tankers**: Gaseous hydrogen can be transported in small to medium quantities in compressed gas containers by trucks. For transporting larger volumes, several pressurized gas cylinders or tubes are bundled together on tube trailers. The large tubes are bundled together inside a protective frame. In China, 20 MPa tube trailers are often deployed to carry around 300 kg of hydrogen cargo.

  Alternatively, hydrogen can be transported in liquid form in trucks or other means of transport. In comparison to pressure gas vessels, more hydrogen can be carried with a liquid hydrogen trailer, as the density of liquid hydrogen is higher than that of gaseous hydrogen. As a result, cryogenic liquid tankers carried by truck, railway and barge normally contain 7, 8.4-14, and 70 tonnes of hydrogen cargo, respectively. At the time of writing, China has not yet deployed this type of hydrogen transport technology for civil use.

- **Dedicated hydrogen pipelines**: A pipeline network would be the best option for the comprehensive and large-scale application of hydrogen as an energy source. However, dedicated hydrogen pipelines require high levels of initial investment, which may pay off, but only

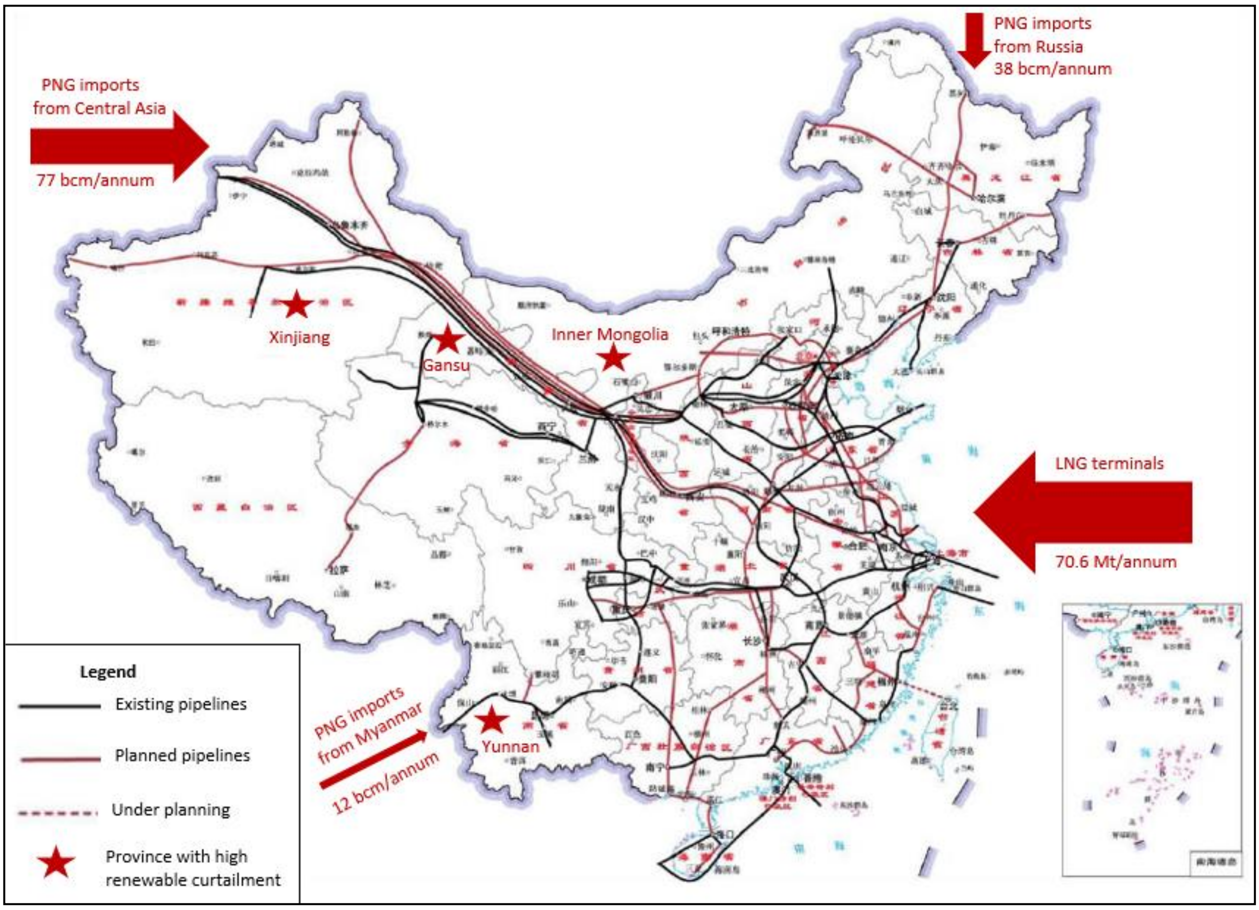
20. H2CN, *White Paper on China's Hydrogen Energy and Fuel Cell Industry*, China Hydrogen Alliance, 2019.

21. Hydrogen Europe, "Hydrogen Transport & Distribution," accessed on 19 July 2020, available at: https://hydrogeneurope.eu.

with correspondingly large volumes of hydrogen. Dedicated hydrogen pipelines normally operate at 1.0-4.0 MPa, and China has only built about 100 km of such pipelines.

- **Blending hydrogen with natural gas**: As a hydrogen delivery option, blending hydrogen into existing natural gas pipelines can avoid the high initial investment of building dedicated hydrogen pipelines or other expensive delivery infrastructure during the early market development phase. A blending strategy allows suppliers to deliver hydrogen to end users with existing gas pipeline networks.

Figure 4. China's natural gas trunk lines and key regions with high rates of renewable curtailment



Source: adapted from NDRC and NEA (2017) Medium- to Long-term Plan for National Oil and Gas Networks. National Development and Reform Commission, and National Energy Administration.

Note: PNG stands for pipeline natural gas. Renewable curtailment: in the energy industry, renewable curtailment is the act of reducing or restricting energy delivery from a renewable generator to the electrical grid. The primary driving force underlying renewable curtailment is the mismatch between intermittent nature of variable renewables and load profile of an electric grid.

In the context of China, blending hydrogen into the existing natural gas transmission system, which reached near 81 thousand km with an aggregate capacity of 350 bcm/annum by the end of 2019,[22] has also been proposed as a viable option of boosting renewable development. In certain Chinese provinces such as Gansu where curtailment rates of wind and solar power are high, and Yunnan where hydropower curtailment is a serious policy concern, using electrolyzers powered by otherwise curtailed renewables enables excess renewable energy to be converted to hydrogen. If implemented with relatively low concentrations (e.g. less than 5%–10% hydrogen by volume), this strategy possesses great potential to provide a hydrogen storage and delivery pathway across a wide range of geographic locations covered by China's massive and expanding natural gas network.

Simplified SWOT analysis of hydrogen economy development in China

In this section, a simplified SWOT analysis is conducted to identify the most important strength, weakness, opportunity and threat for hydrogen economy development in China.[23]

Strength – ability to significantly bring down unit manufacturing cost through industrial network clustering and economy of scale: Chinese manufacturers and contractors have the capability to significantly bring down unit production cost offered by foreign competitors over a wide range of products. One of the key reasons for lower manufacturing cost in China is industrial network clustering, which refers to the practice of locating all or most of the key enterprises in an industry's supply chain in close physical proximity with each other. Following a rapid industrialization process starting from 1978, China has now formed an comprehensive modern industrial system comprising 41 large industrial categories, 207 medium industrial categories and 666 small industrial categories, and thus is the only country in the world that has all the industrial categories based on the industrial classification of the United Nations.[24] Consequently, though labor costs in China are expected

22. China Gas Association, "Development Status of China's Natural Gas Network," 2020, accessed on 30 July 2020, available at: www.chinagas.org.cn.

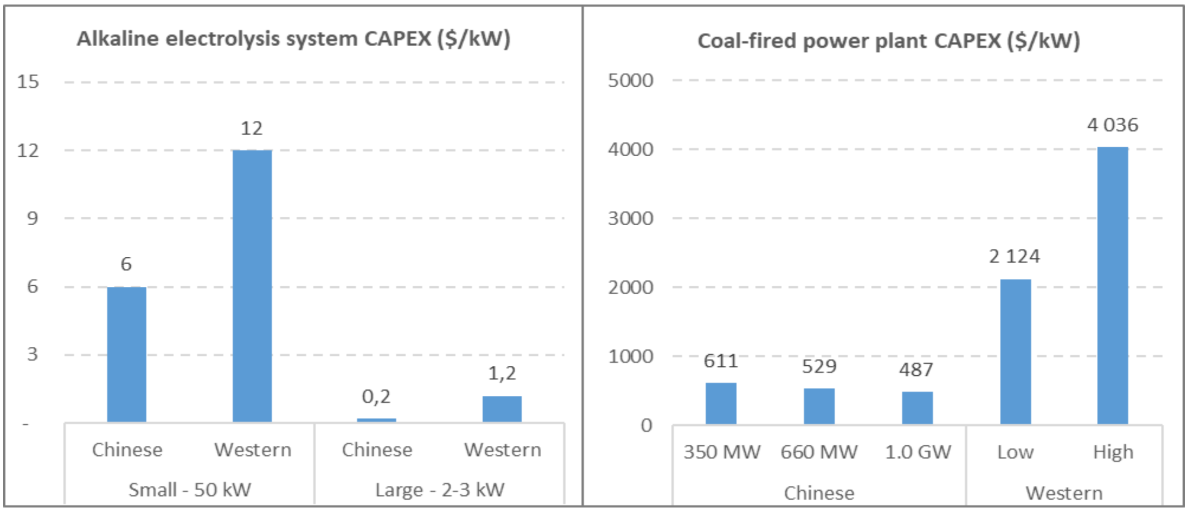
23. SWOT analysis is a strategic planning technique used to help identify strengths, weaknesses, opportunities, and threats related to business competition or project planning, it has been widely used for strategy formulation by constituting an important basis for learning about the situation of the studied object and for designing future strategies to solve the existing problems.

24. China National Online News Service, "The State Council Information Office Press Release: Development Status of Industry and Information Technology at the 70th anniversary of the People's Republic of China," 2019, accessed on 17 July 2020, available at: www.china.com.cn.

to rise over time, cost competitiveness of Chinese manufacturers and contractors is likely to stay in many years to come.

Take coal-fired power plants as an example: while capital expenditures (CAPEX) of such type of facilities range from more than US $2,000/kW to US $4,000/kW in western countries, CAPEX for state-of-the-art ultra-supercritical pulverized coal power plants with desulphurization and denitrification (deNOx) configuration in China could be as low as less than US $500/kW. One important factor leading to the above cost discrepancy is because Chinese contractors have already built near half of global coal-fired generation capacity domestically, thus are well positioned to lower CAPEX through economy of scale. Even though Chinese contractors could not realize similar level of cost advantage when building greenfield coal-fired power plants in overseas market, the ability of Chinese manufacturers and contractors to bring down unit production cost will still become a key advantage of promoting hydrogen economy in China, which partially explains the extreme difficulty associated with coal transition in China.

Figure 5. Cost advantage of Chinese manufacturers and contractors



Source: BloombergNEF, EPPEI, Netherland actual cost data, and US EIA.

Similarly, while alkaline water electrolysis is one of the most convenient methods for hydrogen production, CAPEX of alkaline electrolysis systems in western countries are still rather expensive. By comparison, depending on unit capacity, CAPEX of Made in China systems is only half or even one sixth of pricing levels offered by western manufacturers. Such type of cost discrepancies between Chinese and western manufacturers are expected to serve as a catalyst to continuously bring down unit costs of hydrogen-related equipment in the global market.

Weakness – lag far behind advanced economies in key hydrogen-related technologies: The lack of advanced hydrogen technologies is the weakest link of the Chinese hydrogen economy. Mainstream options of hydrogen production in China such as coal gasification and SMR cannot meet increasingly stringent environmental requirements especially against the backdrop of rising global concern on climate change. While water electrolysis with low carbon power especially renewables is expected to gain traction over time, China currently lacks the key technologies in support of renewables-based hydrogen production. As mentioned in previous section, China also lags behind advanced economies in hydrogen storage and transport technologies. Similar as the battery's importance for EVs, fuel cell-related technologies have been identified by Chinese government as a top priority for promoting deployment of FCEVs. Nevertheless, China still rely on imports for many fuel cell-related key materials including catalysts, proton exchange membranes and carbon papers, and the country's capacity of manufacturing other key materials such as membrane humidifiers, bipolar plates, air compressors, and hydrogen circulation pumps is also lagging behind advanced economies.

Opportunity – enthusiasm on hydrogen economy by local governments against the backdrop of the COVID-19 pandemic: In March 2019, Chinese Ministry of Finance (MOF) announced to scrap subsidy for the EVs, while keeping subsidy support to hydrogen vehicles. MOF especially emphasized to use the funding saved from EVs on hydrogen refueling infrastructure and services instead, which has soon contributed to a de facto hydrogen hype in China, where over 20 cities announced to forge their hydrogen industry clusters by the end of July 2019.[25] Since then, more and more localities across the country initiated increasingly higher number of so called "hydrogen valley" or "hydrogen capital". The newly discovered enthusiasm on hydrogen economy by local governments inevitably leads to concerns for major bubble that mimics the boom and bust cycle of the Chinese EV manufacturing industry in a not so distant past, though it has been a largely positive driving force that accelerates development of the nascent Chinese hydrogen value chain so far.

Threat – looming danger of global supply chain decoupling caused by an escalating US-China trade war: Since 2018, the rising trade tensions between the United States and China have increased both the cost and uncertainty of manufacturing in China. To lower the risk of over reliance on one single country, some companies have already started

25. Energy Iceberg, "China's Hydrogen Push: Sizzling Market Fueled by Local Subsidy Schemes," 2019, accessed on 17 July 2020, available at: https://energyiceberg.com.

to move at least part of their supply chain out of China. Due to deteriorating US-China relations exacerbated by the ongoing COVID-19 pandemic, more and more international companies operating in China and even some Chinese manufacturers may consider relocation as an option to diversify their supply chains. To make matters worse, the ongoing US-China tech war that is evidenced by Trump Administration's increasingly stringent sanctions on chip supply to Huawei is prompting Chinese government to double down efforts on indigenization, with the potential of leading to two independent but parallel supply chains and separate sets of technological standards. If such a scenario materialized in future, it would become much more difficult for China to create synergies with other countries to move the hydrogen economy agenda forward through international cooperation.

Driving forces underlying the Chinese hydrogen economy

Hydrogen can be used as a feedstock, a fuel or an energy carrier and storage, and has many possible applications across industry, transport, power and buildings sectors, thus offers numerous opportunities for sector coupling. Starting with Japan in 2017, there has been increasingly intensified interest of promulgating national hydrogen strategies amongst advanced economies, followed by South Korea (2019), New Zealand (2019), Australia (2019), Netherlands (2020), Norway (2020), Portugal (2020), Germany (2020), France (2018 and updated in September 2020) and most noticeably by the European Union (EU) on 8th July 2020.

Given China's sizable share in global carbon emissions in general and worldwide hydrogen production in particular, it is legitimate to closely examine the exact driving forces underlying China's new enthusiasm for hydrogen.

Innovation-driven economic competitiveness

Chinese leadership has long recognized the importance of technological innovations, and China's hydrogen-related R&D activity could be dated back to early 1950s when liquid hydrogen-oxygen propellant rocket engine was foreseen by Chinese scientists as a key component of the country's infant space programs, with breakthrough finally achieved in 1975. Meanwhile, research on fuel cells in China started at Dalian Institute of Chemical Physics as early as mid-1950s.

At the Conference on Scientific and Technological Work in January 1963, former Chinese Premier Zhou Enlai called for Chinese scientists to realize "the Four Modernizations." After the end of the Cultural Revolution in 1976, "the Four Modernizations" with science and technology advancement as one of its four pillars were quickly adopted by Beijing as a means of rejuvenating the Chinese economy.

After the 863 program or State High-Tech Development Plan was initiated by the Chinese government in 1986 to stimulate the development of advanced technologies in a wide range of fields, a pilot FCEV project was commissioned by Chinese Ministry of Science and Technology (MOST) as part of the 863 key program on EV in 2001. This project, led by Dr. Wang Gang in the capacity of vice president of Tongji University, was successfully completed in August 2003.[26]

The high profile Made in China 2025 (MIC 2025) strategy was introduced in May 2015 by the State Council to secure China's position as a global powerhouse in high-tech industries by integrating China's increasingly sophisticated technological know-how with the country's formidable manufacturing capacity. The government-affiliated high-level National Manufacturing Strategy Advisory Committee then soon designated new energy vehicle development as an important part of the MIC 2025 strategy. In particular, as FCEV is one type of new energy vehicles, the committee recommends that by 2025, hydrogen infrastructure such as hydrogen production and refueling station should be basically available, deployment of FCEVs should archive community-level operations. Last but not least, R&D of rare earth hydrogen storage materials should be prioritized.

Since the inception of the US-China trade war in 2018, the Trump administration's increasing hostility towards China's ascendance in the high-tech arena has convinced Beijing to double down its efforts to promote technology innovation-driven economic growth with much more emphasis on indigenization. In March 219, for the first time in history, hydrogen energy has been incorporated into the State Council's work report at the second session of the 13th National People's Congress, the equivalent of a national policy signal to encourage hydrogen infrastructure development across the country.

After an unprecedented economic slump caused by the COVID-19 pandemic in early 2020, Beijing has so far refrained from a massive monetary and credit stimulus package to avoid the similar drawbacks associated with its post-2008 economic stimulus. To better comply with Chinese leadership's desire of promoting technology innovation-driven economic growth, both central and local government authorities started to issue increasingly higher number of policies, regulations and administrative orders in support of hydrogen economy development, which will be discussed in the next section.

Following near seven decades of incubation, the time has finally arrived to move an innovation-driven hydrogen economy agenda forward in China.

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26. H2CN, "History of Hydrogen Development in China," 2019, accessed on 25 July 2020, available at: www.h2cn.org.

Bottlenecks embedded in the Chinese clean energy market

Though China has already become the largest clean energy market in the world, its impressive achievement not only comes with experience that could be shared with the rest of the world, but also exposes numerous institutional and technical weaknesses that may delay further growth of incumbent clean energy technologies in China.

Since Beijing launched the "ten cities, thousand vehicles" program in 2009, the Chinese EV stock soon exploded, reaching 3.35 million by the end of 2019. Nevertheless, due to rampant local protectionism, China has never been able to establish a truly national EV market to foster fair competition, with local governments in key regional markets guarding their turfs against each other to favor local manufacturers. Coupled with generous subsides poured by both the central and local governments, some 500 manufacturers once registered across the country to make EVs. Such a high number does not make any economic sense even for the largest car market in the world, and it turned out that many of them were involved in subsidy fraud, and led to a national scandal in 2016.[27] Consequently, though China has developed the largest EV market in the world, its national champion BYD still lags far behind leading international EV manufacturer Tesla in terms of technological sophistication.

The second disappointment of China's EV success comes from technical bottleneck associated with battery technologies. With significant progress made by lithium-ion battery on energy density, EVs have gained traction in passenger vehicle and light duty truck market. Nevertheless, for the heaviest classes of trucks and the shipping industry, fuel cells are potentially a much more advantageous source of power supply than batteries. Consequently, to avoid the danger associated with putting all eggs in one single basket, Beijing has realized the importance of continuously supporting EVs without ruling out the potential possessed by FCEVs.

While China ranks the first in the world in terms of installed wind and solar power capacity, the country trails behind the United States for power generation by variable renewables. According to the International Energy Agency (IEA), grid integration of variable renewables (GIVAR) has six phases, depending on the overall share of variable renewables. Since wind and solar power accounts for just 8.6 % of national generation

27. Tencent News App, "New Energy Vehicles-related Fraud," 2020, accessed on 16 September 2020, available at: https://new.qq.com.

in 2019, China is only in the second phase, where variable renewables only have minor to moderate impact on system operation, and updated dispatching procedures and better utilization of transmission are sufficient to integrate variable renewables.[28] Nevertheless, curtailment rates of wind and solar power in China were as high as 17% and 11% respectively in 2016. Though they have been lowered to 4% and 2% in 2019, part of the progress was unfortunately achieved by the central government's restriction of permitting greenfield renewable projects in regions with high curtailment rates.

Since flexibility retrofits of coal-fired power plants are beneficial for GIVAR, Beijing has established a 220 GW retrofitting target by 2020. Nevertheless, China is on track to miss the above target as it has only retrofitted one quarter of the target level by the end of 2019.[29] To make matters worse, instead of improving GIVAR by doubling down efforts on lower cost options such as removing institutional barriers that prevent economic dispatching, demand side management and inter-regional power trade, at least 12 Chinese provinces have mandated some amount of mandatory energy storage requirement for greenfield wind and solar projects during the first half of 2020, the equivalent of suppressing growth potential of variable renewables within their administrative boundaries.[30]

Given the energy intensity bottleneck of battery storage and limited site availability of pumped hydro, hydrogen economy has been identified as a promising option that offers potential of a theoretically sound technical fix of China's GIVAR challenges and thus avoid or at least delay more difficult institutional reform of a gigantic power sector that is dominated by politically powerful interest groups.

Rising energy security anxiety as the US-China rivalry escalates

Since China lost its long-cherished status of energy self-reliance (i.e. net oil exporter) in 1993, the country imports increasingly higher amount of crude oil to meet its surging demand. After China surpassed the United States as the largest oil importer in 2017, its appetite for crude oil shows no sign of satisfaction, with its dependency rate on oil imports reaching 71% in 2019,

28. IEA (2019) *Status of Power System Transformation 2019*. International Energy Agency: Paris.

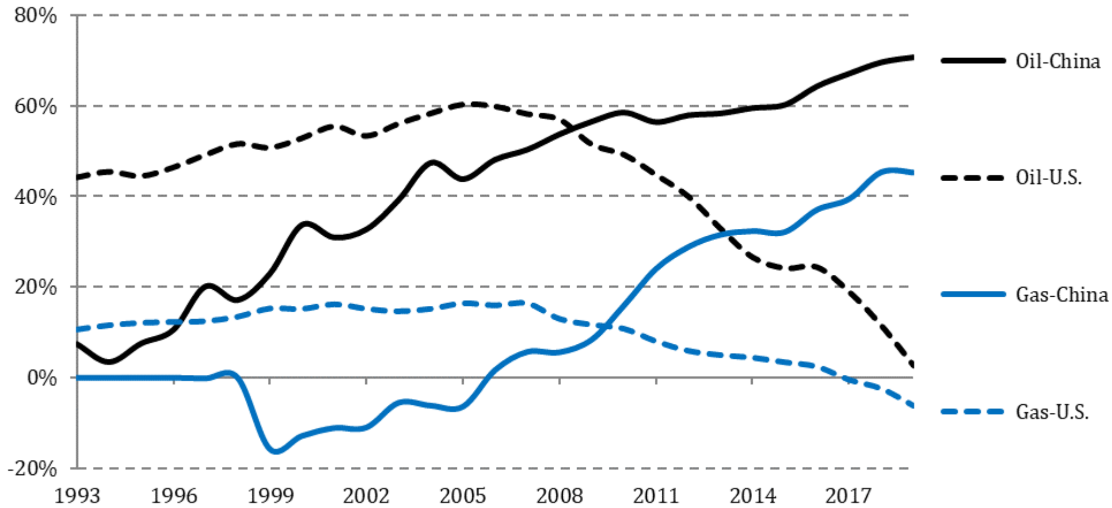
29. Bjx-power, "With a Target of More Than 200 GW and Compliance Rate of Only around One Quarter, Why Flexibility Retrofitting of Coal-fired Power Plants Are So Slow?" 2020, accessed on 19 July 2020, available at: http://news.bjx.com.cn.

30. Eastmoney Securities, "Mandatory Storage Requirement for New Energy Projects do not Make Sense," 2020, accessed on 30 July 2020, available at: http://finance.eastmoney.com.

just when American oil dependency rate fell to its lowest level in decades. Consequently, the tone of US-China energy relations has gradually shifted from the looming danger of oil resource access competition-induced hostility in the beginning of the millennium towards bilateral energy trade's increasingly prominent role in reducing American trade deficit with China in recent years.

Similarly, in the case of natural gas, complementarity instead of resource competition becomes the status quo. After the global financial crisis in 2008, China's national gas consumption skyrocketed. As domestic supply has been unable to meet the burgeoning demand, China's dependency rate on gas imports reached 45% last year. By comparison, the shale gas revolution has already made the world's largest gas consumer United States a net gas exporter in 2017.

Figure 6. Dependency rates on oil and gas imports: China vs. U.S., 1993-2019



Source: US EIA, IEA, and CNPC ETRI.

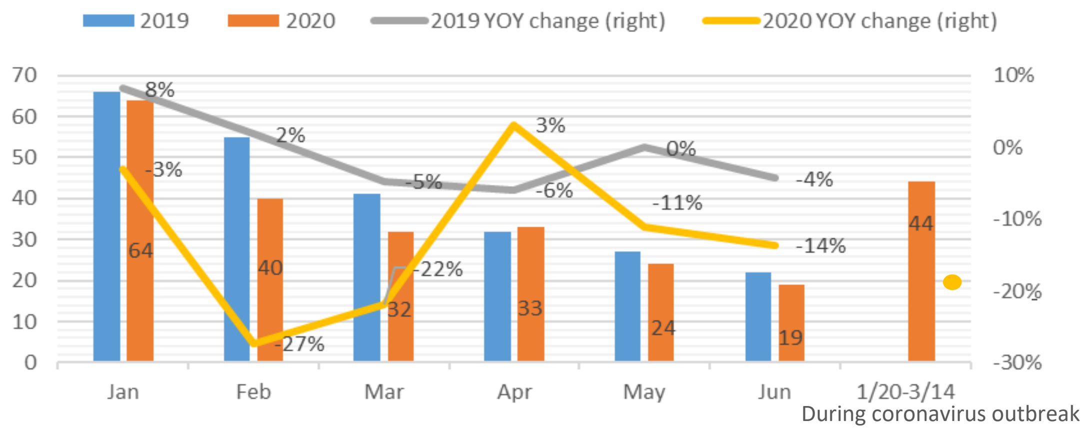
Unfortunately, the increasing complementarity of US-China energy trade potential has not led to sustained and strengthened oil and gas ties between these two countries. The US-China trade war, especially the Trump administration's sanctions on Chinese national champions such as Huawei and China General Nuclear Power Group, has heightened China's anxiety over energy supply security by highlighting the dangers of excessive reliance on foreign countries for critical inputs into the Chinese economy. As a result, reliance on oil and especially gas imports from United States has been perceived as a national security vulnerability by the Chinese leadership, which explains why Chinese president Xi Jinping repeatedly called for government authorities and state-owned oil companies to rapidly increase upstream exploration and production to ensure national energy security.

Consequently, the hydrogen economy's great potential of substituting oil and gas imports and diversifying sources of primary energy supply looks increasingly appealing to anxious Chinese decision makers. Above all, hydrogen could bring substantial energy storage potential to the rather inflexible Chinese energy economy. If hydrogen's role in China's energy sector could become even remotely close to that of electric power, flexibility of switching among different sources of primary energy is expected to significantly improve China's national energy security, with the caveat that China's coastal provinces might become dependent on hydrogen imports if water scarcity and bottleneck of hydrogen infrastructure hinder cost competitiveness of domestic hydrogen production especially in an increasingly carbon-constrained world.

Pressure to alleviate air pollution

Due to rising fossil fuel consumption especially distributed combustion of coal, frequent outbreak of haze pollution in China has trigger widespread anger and pressurized the State Council to issue the Action Plan on Prevention and Control of Air Pollution in 2013. Since then, average concentration of fine particulate matter (PM2.5) in China has decreased significantly from 61.8 μg/m³ in 2013 to 36.0 μg/m³ in 2019. Nevertheless, among the 100 most polluted cities in the world in 2019, 48 were still Chinese.

Figure 7. China's monthly $PM_{2.5}$ concentration: 2019 vs. 2020



Source: Kevin Tu and Zhou Yang (2020) COVID-19 China Energy Impact Tracker: issue 1. Agora Energiewende: Berlin.

Following the unpresented lockdown of Wuhan, the epicenter of the COVID-19 outbreak in China, the resulting factory closures and fall in motor traffic has meant a sustained drop in major precursors of air pollution including $PM_{2.5}$ and nitrogen oxides (NOx) emissions. Nevertheless, once COVID-19 is largely under control in March 2020, ramping up of manufacturing activity and recovery of traffic has led to resurgence of air pollution outbreak across China especially in major urban centers. The coronavirus-induced air quality improvement in China is not only short-lived, the average $PM_{2.5}$ concentration in April 2020 even rebounded above similar level last year.

As air pollutants discharged by heavy duty trucks, barges, ocean-going vessels, and distributed coal combustion are important sources of air pollution in China, which is evidenced by the fact that diesel trucks alone account for 78% of NOx emissions and 89.9% of PM emissions discharged by the Chinese vehicle fleet in 2019,[31] hydrogen economy's potential to achieve clean end uses make it increasingly attractive for China's "blue sky" campaign.

Rising concern for climate change

Back in 2009, the author made the following observation about China's climate policy: "China's importance in the international climate politics is expected to keep rising especially given China's recent CO_2 championship. Unfortunately, China will continuously reject mandatory emissions cap on the ground of the necessity for developing its economy. Nevertheless, Beijing has realized the mounting pressure on its climate stances, and prepared itself by formulating increasingly proactive and comprehensive climate policy. If developed countries were able to meet their GHG abatement commitments, it would not be unimaginable that China may accept an intensity-based emissions target. Even so, the global effort to combat climate change is still expected to fall short as it is the absolute emissions, rather than GHG intensities, that matter most. Fortunately, advanced emissions abatement techniques such as CCS possess great potential for reducing a country's absolute emissions. Beijing should seriously assess costs and benefits of funding the commercialization of such techniques. Finally, it is in Beijing's best interest to remove all barriers that suppress the intellectual potential of its climate policy research community."[32]

31. MEE, *China Mobile Source Environment Management Annual Report*. Chinese Ministry of Ecology and Environment: Beijing, 2020.

32. K. Tu, *Future Prospects of China's Policy on Climate Change*, 2009, accessed on 17 July 2020, available at: https://jamestown.org.

Since then, one decade has passed, and China's climate relevance indeed keeps rising, and accounts for nearly 30% of global carbon emission, replacing the similar role played by both the United States and the EU in mid-1960s. Though global climate ambitions have been still insufficient to achieve Paris Agreement goals, China did vigorously examine the feasibility of commercializing CCS techniques in the past. Nevertheless, once it became apparent that the prospect for Chinese companies to export CCS technology to advanced economies dimmed, China's enthusiasm on CCS soon faded.

Compared with one decade ago, China has already moved from a lower medium-income country to an upper middle-income one. On a per capita basis, Chinese carbon emissions have even exceeded the average level of the EU. Consequently, China is widely expected by the international community to further upgrade its climate ambitions beyond its Paris Agreement commitment (e.g. peaking national carbon emissions at an absolute level ahead instead of around 2030). Given hydrogen economy's potential climate benefits, boosting clean hydrogen's role in the Chinese energy economy become increasingly attractive. The fundamental question is, with both domestic deployment and export market in mind, whether the future of the Chinese hydrogen economy will differ from the boom and bust cycle encountered by CCS in the past.

Speaking via video link to the United Nations General Assembly on 22 September 2020, Chinese president Xi Jinping announced that China aims to peak national carbon emissions before 2030 and achieve carbon neutrality before 2060.[33] As a one-party state, China is highly unlikely to make the similar U-turn on its international climate commitments as the United States. Considering that both the current and future Chinese administrations need to take president Xi's climate neutrality pledge seriously, and given the significant amount of carbon emissions reduction implied by the above announcement, the equivalent of decarbonizing the entire French economy on an annual basis for 30 years consecutively, hydrogen is expected to play a much more important role to drastically decrease the country's carbon emissions over time than otherwise would be the case.

While China's recent carbon neutrality announcement is a landmark milestone for moving global climate agenda forward, and is expected to make a real difference in the longer term. Nevertheless, as it is not a legally binding international commitment yet, and China's climate commitment

33. Xinhua News Agency, "Xi Announces China Aims to Achieve Carbon Neutrality before 2060," 2020, accessed on 24 September 2020, available at: www.chinadaily.com.cn.

under the Paris Agreement was only marginally upgraded from peaking national carbon emissions around 2030 to before 2030, it is still a big question mark to what extent China's climate neutrality pledge could be translated into short-term tangible climate actions, especially in area of hydrogen economy development among other clean energy technology deployment during the 14^{th} FYP period between 2021 and 2025.

Key stakeholders and major policy development

Given hydrogen's flexible options of production, multiple means of storage and transport, and versatile applications of end uses, hydrogen possesses great potential to sprawl across the entire energy economy. Consequently, governance of hydrogen economy is often fragmented among various government authorities. Further, since many advanced technologies associated with hydrogen economy are far from mature, how governments may use their authority to set rules and create a policy environment in which industry and other key stakeholders are empowered to accelerate hydrogen deployment is key for the future of hydrogen in China and beyond.

Selected key stakeholders

There are many key stakeholders that are important to move hydrogen economy agenda forward in China. At the central government level, the following authorities are considered particularly relevant for formulating a desirable policy framework in support of development of the Chinese hydrogen economy:

- **Ministry of Science and Technology**: MOST, formerly the State Science and Technology Commission before 1998, formulates and facilitates the implementation of strategies and policies for innovation-driven development, and plans and policies for S&T development and the attraction of foreign talent. Consequently, R&D of hydrogen-related advanced technologies especially fuel cell and its application has long been sponsored by MOST and its predecessors in China.
- **National Development and Reform Commission (NDRC)**: NDRC is a macroeconomic management agency under the State Council, which has broad administrative and planning control over the Chinese energy economy including sector planning, project permitting and energy pricing. NDRC is often nicknamed as "mini-state council" as it is the most politically powerful ministry in China, thus it is expected to play a key role to formulate development plans and promote commercialization of advanced hydrogen technologies.

- **National Energy Administration (NEA)**: NEA is a deputy ministerial level agency under NDRC. The NEA drafts China's national energy strategy, implements energy policy, and regulates energy sector from fossil fuels to new energy. As the agency overseeing the Chinese energy sector, NEA has broad authorities over hydrogen's production, transport, and fuel-related utilization.
- **Ministry of Industry and Information Technology (MIIT)**: MIIT is responsible for regulation and development of the postal service, Internet, wireless, broadcasting, communications, production of electronic and information goods, software industry and the promotion of the national knowledge economy. MIIT is expected to play an important role in establishing Chinese hydrogen supply chain.
- **Ministry of Finance**: MOF is responsible for administering macroeconomic policies and the annual budget, and it also handles fiscal policy, economic regulations and government expenditure for the state. MOF is expected to play an important role to allocate central government funding in support of hydrogen economy development.
- **Ministry of Transport (MOT)**: MOT is responsible for railway, road, air and water transportation regulations, it is an important state agency to regulate transport-related hydrogen economy activity.
- **State-owned Assets Supervision and Administration Commission of the State Council (SASAC)**: SASAC is a ministerial level commission under the State Council. It is responsible for managing state-owned enterprises (SOEs), including appointing top executives and approving any mergers or sales of stock or assets, as well as drafting SOE-related laws and regulations. As many SOEs are involved in hydrogen-related activities, SASAC becomes a key stakeholder due to its broad authorities over SOEs.
- **State Administration for Market Regulation (SAMR)**: SAMR has diverse portfolio including regulating areas such as market competition, monopolies, intellectual property, and drug safety. It is a key agency in areas of standardization, quality control and safety of the Chinese hydrogen economy.
- **National Bureau of Statistics**: NBS is a deputy ministerial level agency directly under the State Council. It is responsible for collection, investigation, research and publication of statistics concerning the nation's economy, population and other aspects of the society. Starting from 2020, hydrogen energy is covered by NBS's statistical reporting mechanism.

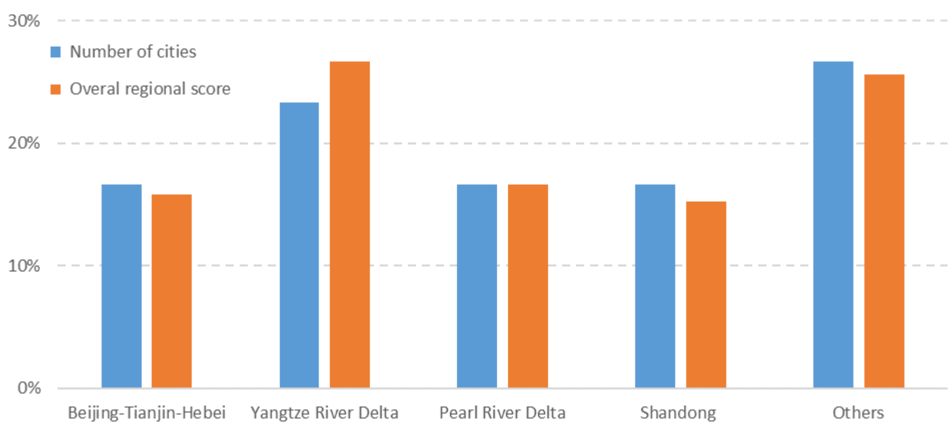
Local governments: there are five de facto levels of local government in China: the provincial (province, autonomous region, municipality, and special administrative region), prefecture-level municipality, county, township, and village.

Against the backdrop of a politically powerful central government in Beijing, Chinese local governments especially provinces, prefecture-level municipalities and counties still play a rather important role in the local economy, controlling the allocation of land, and exercising substantial authority over the allocation of resources within their administrative boundaries.

For each central government ministry, there is normally corresponding agency at local government level. For instance, while NDRC is a macroeconomic management agency at the central government level, similar role in Shanxi province is played by Shanxi Development and Reform Commission, with Datong Development and Reform Commission being one of the 11 such prefecture-level agencies within Shanxi province.

In terms of competitiveness of hydrogen economy in China, with Shanghai ranking No. 1 amongst the 30 most competitive cities in China, Yangtze River Delta is the most competitive region in China, followed with Pearl River Delta, Beijing-Tianjin-Hebei (or Jing-Jin-Ji) and Shandong.

Figure 9. Competitiveness of hydrogen economy by region in China



Source: Appendix A.

Once breakthrough is made in hydrogen technological innovation, the industry is expected to play a rather important role in areas of demonstration and commercialization. In the context of China, there are three type of enterprises that are key to move the above agenda forward:

- **Central SOEs**: A central SOE is a legal entity that undertakes commercial activities on behalf of the Chinese central government. Currently, SASAC oversees 97 central SOEs. As of 2018, these companies had a combined asset of 80.8 trillion yuan, making it one of the most formidable economic forces in China.[34] After China's coal giant Shenhua and key power company Guodian merged as China Energy Investment Group (China Energy) in 2017, China Energy has shown strong interest in hydrogen economy especially hydrogen production, and played a leadership role to establish China Hydrogen Alliance (H2CN) in 2018. In addition, central SOEs specializing in car manufacturing such as China FAW Group and Dongfeng Motor Group are expected to become increasingly active in hydrogen economy activity, especially the development of FCEVs.
- **Local SOEs**: A local SOE is a legal entity that undertakes commercial activities on behalf of an owner local Chinese government. As of 2018, these companies had a combined asset of 129.6 trillion yuan, thus play a very important role in local economies. Though SOEs are supposed to be established to operate in commercial affairs, they may also have public policy objectives. For instance, after Shandong provincial government showed strong interest in hydrogen economy, two provincial SOEs including Shandong Heavy Industry Group and Shandong Port Group recently teamed together to promote hydrogen infrastructure building in seven ports in Shandong.[35]
- **Private enterprises**: Since the start of the reform era in 1978, non-state economy in China had steadily grown, along with rising importance of private enterprises in the Chinese energy economy. Nevertheless, in recent years, SOEs' role has been strengthened at the expense of private enterprises specially in the energy sector. For instance, the number of private enterprises in the Chinese coal mining industry declined drastically from 4472 in 2012 to 2258 in 2018, and there were only 9 private enterprises in the Chinese upstream oil and gas sector in 2018. Even so, as hydrogen economy is a niche market that has not been entirely monopolized by SOEs, private enterprises are expected to play a rather important role especially in areas of demonstration and commercialization, similar as what happened in the formation of the Chinese solar power market in the past.

34. People's Daily, "State Council's Report on Management of State-owned Assets in 2018," 2019, accessed on 19 July 2020, available at: www.gov.cn.
35. Qingyunlian, "Shandong Province Promotes Hydrogen Infrastructure in Seven Ports with Assistance from Two Local SOEs," 2020, accessed on 20 August 2020, available at: www.thepaper.cn.

Other key Chinese stakeholders include:

- **China National Institute of Standardization (CNIS)**: CNIS is a national social service institution affiliated with SAMR, it is dedicated to standardization researches, with focus on global, strategic and comprehensive standardization issues in national economy and social development of China. CNIS is expected to play an important role in hydrogen-related standardization in China. For instance, the National Standardization Technical Committee for Hydrogen Energy (SAT/TC 309) is in charge of the standardization work in the production, storage and use of hydrogen energy in China. It is one of the members of ISO Technical Committee (ISO/TC 97). CNIS currently hosts the secretariat of the above Committee.
- **H2CN**: The Alliance was formally established in February 2018 to promote hydrogen economy development in China. Chaired by China Energy, and supervised by central government authorities including NDRC, MOST, MIIT, MOF, MOT, NEA and SASAC, it was founded by 19 key SOEs (operating in areas of energy production, equipment manufacturing, transport, and basic materials), universities, and financial institutions. At the writing of the report, membership of the Alliance has increased from 20 to 87, including 24 central SOEs, 14 local SOEs, 12 universities and research institutions, 27 private enterprises, and 10 foreign entities.
- **Universities:** Various Chinese universities have dedicated R&D activities in areas of hydrogen economy. For instance, Tsinghua University's research interests cover fuel cell engines and fuel cell buses, production, storage and transport of hydrogen. Zhejiang University's research interests include catalysts for hydrogen production, renewable hydrogen, hydrogen storage, and FCEVs. Shanghai Jiao Tong University's research interests cover proton-exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), and modelling and control of fuel cell systems.
- **Government- or SOE-affiliated think tanks**: Government affiliation is a prerequisite for a fully functionable think tank in China. Not surprisingly, government-affiliated think tanks such as Chinese Academy of Science, Chinese Academy of Engineering, Chinese Academy of Social Science, Development Research Center of the State Council, and Energy Research Institute of NDRC are expected to play an important role to advise the Chinese government on hydrogen economy-related policy issues.

- **Environmental non-governmental organizations (eNGO)**: Along with the rising public concern on environmental pollution in the past, eNGOs with both international and domestic origins become increasingly active in China. Following the promulgation of Foreign NGO Law in 2017, eNGOs' role in the Chinese civil society become increasingly uncertain. Nevertheless, given hydrogen economy's importance in clean energy transition and global climate agenda, eNGOs are expected to actively participate in hydrogen-related policy discussion and international cooperation.
- **Key advocates**: Key politicians, senior executives and experts have the capacity to move hydrogen-related agenda forward in China. For instance, Dr. Wang Gang, a senior Chinese politician who is sometimes nicknamed as "father of EV" in China, recently called Chinese government to double down efforts on hydrogen infrastructure building. Similarly, Dr. Ling Wen, former CEO of China Energy, played a key role in establishing H2CN in February 2018. After Dr. Ling was promoted as deputy governor of Shandong province in April 2019, Shandong under his leadership issued an ambitious medium- to long-term development plan for hydrogen in June 2020, aiming to promote deployment of FCEVs and hydrogen refueling stations, establishment of relevant standards, and development of renewable hydrogen among other activities.
- **General public:** Similar as the rest of the world, public perception and social acceptance of hydrogen energy systems is crucial to avoid resistance to the deployment of hydrogen technology and infrastructure. In the case of China, because of hydrogen's potential environmental benefits and the country's unique political system, public resistance is unlikely to become a major barrier during the infant stage of hydrogen economy development. Nevertheless, the evolving safety record of hydrogen deployment in China could easily shift public perception and social acceptance. For example, after an explosion in Zhangjiakou in November 2018 that killed 24 people,[36] media once linked the accident to hydrogen. While it was later proved to be a rumor, the above accident has nevertheless caused widespread public concern about the safety of hydrogen utilization.

36. Y. Zhang, "12 Convicted in Hebei Chemical Plant Explosion that Killed 24," 2019, accessed on 17 July 2020, available at: www.chinadaily.com.cn.

Table 1. List of selected key stakeholders

Key stakeholder	Sector	Major role
Ministry of Science and Technology	Central government	Funding R&D and development of technology innovations in China
National Development and Reform Commission	Central government	The most politically powerful ministry with broad mandate on economic planning, permitting, and pricing
National Energy Administration	Central government	A deputy ministerial agency under NDRC in charge of energy sector development
Ministry of Industry and Information Technology	Central government	Industrial sector planning, promote innovation of key industry equipment
Ministry of Finance	Central government	State subsidies
Ministry of Transport	Central government	Planning, regulation and enforcement of transport especially in road and waterway
State-owned Assets Supervision and Administration Commission of the State Council	Central government	Manage SOEs, including appointing top executives and approving any mergers or sales of stock or assets, as well as drafting laws related to SOEs.
State Administration for Market Regulation	Central government	Standardization, safety and market regulation
National Bureau of Statistics	Central government	Statistical collection of hydrogen-related activity including hydrogen energy
Central SOEs	Industry	There are 97 centrally SOEs, with those operating in the energy sector most active in hydrogen economy
China National Institute of Standardization	National social service institution	Global, strategic and comprehensive standardization issues in national economy and social development of China
China Hydrogen Alliance	Industrial alliance	Industry lobby
Universities	R&D	Many Chinese universities are active in hydrogen-related R&D
Government- or SOE-affiliated think tanks	Think tank	Hydrogen economy-related policy research
Environmental NGOs	Think tank	Advocate hydrogen economy in support of various environmental agenda
Key advocates	Personnel	Key politicians, executives and experts who advocate hydrogen economy development

Local governments	Provincial and municipal governments	Provincial and local planning and subsides in support of hydrogen economy
Local SOEs	Industry	Local SOEs are often guided by local governments to promote local hydrogen-related development
Private companies	Industry	Private companies are active in commercializing various hydrogen-related technologies
General public	General public	Public perception and social acceptance of hydrogen economy development
International stakeholders	International community	International organizations, foreign government, international companies, international industrial alliances, universities, and etc.

Source: compilation by the author.

Policy framework in support of the hydrogen economy in China

China's policy framework in support of hydrogen economy could be classified into three categories. The first category is R&D programs, which could be dated back as early as 1950s:

- **Space programs**: When hydrogen and fuel cells research in China began in the 1950s by the Dalian Institute of Chemical Physics (DICP), it had an emphasis on applications for space programs. Similarly, in early 1950s, liquid hydrogen-oxygen propellant rocket engine was foreseen by Chinese scientists as a key component of the country's infant space programs, with breakthrough finally achieved in 1975.
- **863 program or State High-Tech Development Plan**: 863 program was kicked off in 1986 to stimulate development of advanced technologies in a wide range of fields for the purpose of rendering China independent of financial obligations for foreign technologies. Before its conclusion in 2016, it has accelerated research-based commercialization of advanced hydrogen technologies.
- **973 program or National Basic Research Program**: The program was initiated in 1997 to develop basic research, innovations and technologies aligned with national priorities in economic and social development. With the first hydrogen project started in 2001, 973 program had funded various hydrogen-related basic research before its conclusion in 2016.

- **National Key R&D Program**: In 2016, China consolidated different government R&D programs including 863 and 973 under National Key R&D Program. From then on, increasingly amount of resources have been spent on hydrogen-related R&D through the new program managed by MOST.

The second category is the so-called Five Year Plan. While planning is a key characteristic of centralized socialist economies, a plan established for the entire country normally contains detailed economic development guidelines for all regions, and China's FYPs are a series of such economic development initiatives. As China has transitioned from a planned economy before 1978 to an increasingly market-oriented one, the name for the 11th FYP between 2006 and 2010 was officially changed from plan to guideline. Nevertheless, it is still commonly referred to as a plan.

- **13th FYP:** China's 13th FYP, issued in March 2016, set out the objectives and overarching principles of the country's continued economic and social development between 2016 and 2020. Under the overarching guidelines, detailed plans for each sector were prepared by relevant government departments. The 13th FYP for energy issued by NDRC and NEA in December 2016 encourages R&D on advanced energy storage technologies especially fuel cell, coupled with pilot projects of hydrogen production. The 13th FYP for Transport Technology Innovation issued by MOST and MOT in June 2017 aims to promote R&D on fuel cell technologies, and encourage development of pilot hydrogen infrastructure.
- **14th FYP:** According to past practices, China's overarching 14th FYP for economic and social development between 2021 and 2025 will be finalized and approved in early 2021, followed by more detailed sectorial plans over the next year, with the 14th FYP for energy and other energy subsectors most likely to be released during winter 2021–2022. The stakeholder consultancy, scoping, and drafting process has already been started within the government system, with many Chinese think tanks, research centers, and academic institutions tasked with study projects in support of the planning process. Given the rising interest in hydrogen economy, this topic is expected to be more extensively covered by sub-sector plans issued by MOST, NDRC, NEA, and MIIT among other central government agencies.

Table 2. Policy framework in support of the hydrogen economy in China

Category	Year	Areas of support
R&D program		
Space programs	1950s-present	Fuel cell, liquid hydrogen-oxygen propellant rocket engine and etc.
863 program	1986-2016	Fuel cell and hydrogen technologies
973 program	1997-2016	Fuel cell and hydrogen technologies
National Key R&D Program	2016-present	Fuel cell and hydrogen technologies
Five Year Plan		
8th FYP	1991-19995	Proton exchange membrane fuel cell, SOFC technology research
9th FYP	1996-2020	Proton exchange membrane fuel cell, battery materials and system
10th FYP	2001-2005	FCEV, Proton exchange membrane fuel cell, hydrogen storage
11th FYP	2006-2010	Under 863, 973 program, R&D on hydrogen production, storage, fuel cell component technology
12th FYP	2011-2015	Fuel cell innovation
13th FYP	2016-2020	Technological Innovation in Transportation
Major policies		
Outline of National Medium- to long-term Science and Technology Development Program	2006	List hydrogen and fuel cell technology as priority areas of innovation
Interim Measures for Energy Saving and New energy vehicles Subsidies	2009	Subsidies for FCEVs in pilot cities
State Council's Decision on Accelerating the Cultivation and Development of Strategic Emerging Industry	2010	R&D on fuel cell-related advanced technologies
Guidelines for Current Priority Areas of High Technology Industrialization	2011	Hydrogen production and utilization as priority area
Development Plan for Energy Saving and New Energy Vehicles 2012-2020	2012	R&D on fuel cell and key materials
Notice for Financial Incentives Related to New Energy Vehicle Charging Infrastructure	2014	Financial incentives for hydrogen refueling stations

Made in China 2025	2015	Continuous support for FCEV-related R&D
National Innovation Driven Development Strategy Program	2016	Develop hydrogen and FCEV technologies
Roadmap for Energy Saving and New Energy Vehicles	2016	Roadmap for FCEVs
13th FYP for Energy	2016	R&D on advanced storage especially fuel cell, pilot projects of hydrogen production
13th FYP for Transport Technology Innovation	2017	R&D on fuel cell technology, promote pilot hydrogen infrastructure
Medium- to Long-term Plan for Car Industry	2017	Expand pilot deployment of FCEVs step by step
Notice regarding Adjusting and Improving Financial Subsidies for New Energy Vehicles	2018	Setting standards for subsidizing FCEVs
Catalogue for the Guidance of Green Industries 2019	2019	Encourage hydrogen infrastructure, fuel cell, new energy vehicle and hydrogen's application in shipping
State Council's Work Report	2019	Include hydrogen infrastructure for the first time in such reports
Energy Statistical Reporting Mechanism 2019	2019	Starting from 2020, hydrogen is covered by NBS's energy statistical reporting
Draft Energy Law	2020	Hydrogen is classified as an energy carrier for the first time
37 hydrogen-related polices	H1 2020	Issued by various central and 22 local governments

Source: Various publicly available documents published by Chinese government, and Holland Innovation Network China (2019) Overview of Hydrogen and Fuel Cell Developments in China.

The third category is major law, regulation, guidelines, administrative orders issued by various government authorities, with several most noticeable ones as below:

- **Made in China 2025:** Under MIC 2025 launched by Chinese premier Li Keqiang in 2015, China plans to continuously support for fuel cell-related R&D, which is a strong indication of China's intention to commercialize advanced hydrogen technologies to further upgrade Chinese manufacturing value chain.
- **State Council's Work Report in 2019:** For the first time, development of hydrogen infrastructure was mentioned in one of the most important report presented by the Chinese premier.

- **Energy Statistical Reporting Mechanism 2019:** NBS plans to connect hydrogen-related statistics starting from 2020, which is a clear signal that hydrogen has gained more prominent role in China.
- **Draft Energy Law in 2020:** NEA released China's draft Energy Law for public consultation in April 2020. Compared with the first version of the draft Energy Law published in December 2007, hydrogen is classified as an energy carrier for the first time. As a result, energy-related utilization of hydrogen is expected to gain traction in China.
- **Increasing number of supporting policies issued by various levels of Chinese governments:** During the first six months of 2020, 37 policies in support of the hydrogen economy have been published by various level governments, including 7 by central government authorities, and 30 by 22 local governments. Shandong alone issued 6 hydrogen supporting policies, followed with 5 by Guangdong.[37] Given the increasingly intensive interest shown by various levels of governments, hydrogen economy development not only gains traction in China, but also is in great danger of overheating.

Roadmap and timeline

At the central government level, China has not issued an official standalone national hydrogen strategy so far. Nevertheless, entrusted by National Manufacturing Strategy Advisory Committee, a high-level government-affiliated advisory platform in support of MIC 2025, and MIIT, China Society of Automotive Engineering organized more than 500 experts, and published the Energy Saving and New Energy Vehicle Technology Roadmap in 2016, which includes a Technology Roadmap for Hydrogen FCEVs.

In 2017, a dedicated but almost identical Roadmap for Development of FCEVs in China was published by China Automotive Technology and Research Center (CATARC). As CAARC is a central SOE supervised by SASAC, the roadmap below could be considered as a quasi-official roadmap for fuel cell-related development in China, which covers hydrogen infrastructure development including production, transport, storage and refueling stations:

- In terms of the number of FCEVs, it should be increased from 5,000 in 2020 to 1 million in 2030. China has already overshot the 2020 FCEV deployment target by the end of 2019. The ambitious target set for

37. Qingyunlian, "Within Half a Year, 37 Hydrogen Policies Have Been Issued by Central and Local Governments," 2020, accessed on 20 July 2020, available at: www.chinaautoms.com.

2030 requires an orderly roll out of a well-designed national hydrogen strategy for the coming decade.

- In terms of fuel cell stack specific power, it should be increased from 2 kW/kg in 2020 to 2.5 kW/kg in 2025, which indicates that significant progress needs to be made during the 14th FYP period.
- In terms of fuel cell stack durability, it should be increased from 6,000 hours in 2020 to 8,000 hours in 2030. Coupled with continuous cost reductions, the achievement of fuel cell stack-related targets is the prerequisite to meet China's ambitious FCEV deployment target by 2030.
- In terms of the number of hydrogen refueling stations, it should be increased from 100 in 2020 to 1,000 in 2030. By the end of June 2020, there are 72 operational hydrogen refueling stations in China with more under construction or planning, so it is still possible for China to meet the target set for 2020.

Figure 10. Roadmap for development of FCEVs in China

Development Goals

Move from pilot to large scale deployment between 2020 and 2030.

- No. of fuel cell vehicles

2020	2025	2030
5k	50k	1,000k

- Fuel cell stack specific power (kW/kg)

2020	2025	2030
2	2.5	2.5

- Fuel cell stack durability (hours)

2020	2025	2030
5,000	6,000	8,000

- No. of refueling stations

2020	2025	2030
100	350	1,000

Technical Roadmap

- Key fuel cell materials
- Fuel cell stack technology
- System integration and control technology
- Fuel cell electric drive system
- Design and system integration of fuel cell vehicles
- Improvement of power density
- Cost reductions
- Improve onboard hydrogen safety

Development Focus

- Novel key fuel cell materials
- Advanced fuel cell stack
- Key auxiliary system components
- High performance fuel cell electric drive system
- Hybrid fuel cell power system
- Hydrogen infrastructure in areas of production, transport, storage and refueling

Source: Energy-saving and New Energy Vehicle Technology Roadmap Strategy Advisory Committee (2016) Energy Saving and New Energy Vehicle Technology Roadmap; CATARC (2017) Roadmap for Development of FCEVs in China.

In June 2019, H2CN released a landmark White Paper on China's Hydrogen and Fuel Cell Industry, which is widely regarded as a key publication in support of Chinese government's decision making on hydrogen. Key targets recommended by the Alliance are as below:

- **Hydrogen as percentage of China's primary energy consumption** should increase steadily from 2.7% in 2019 to 10% in 2050. Coupled with the expected expansion of the Chinese energy economy, the above target is considered as rather ambitious.
- **Hydrogen economy-related revenue** is expected to increase from 300 billion yuan (43.5 billion US dollars) in 2019 to 12,000 billion yuan (1,740 billion US dollars) in 2050, the equivalent of near 13% year-over-year (YOY) growth during the planning period.
- **Manufacturing capacity**: The number of hydrogen refueling stations should increase to 10,000 by 2050, the equivalent of near 18% YOY growth in the next three decades. In addition, the number of FCEVs should increase to 5 million by 2050. As China's civil vehicle stock reached 262 million by the end of 2019, with sales of new vehicle at 25.8 million last year, the deployment target of FCEVs in 2050 is expected to account for only a small fraction of the Chinese vehicle stock. Consequently, fuel substitution and climate benefits of the above plan will be relatively small unless the planned FCEV stock in 2050 primarily consists of fuel cell buses or trucks.

Furthermore, the number of refueling stations in China should increase to 10,000 in 2050. By comparison, in September 2020, the number of EV charging piles in China reached 1.418 million.[38] As a result, while China's EV deployment is primarily targeting passenger vehicle market, FCEV deployment with an emphasis on fuel cell buses and trucks makes more sense for China to kick off hydrogen's application in the transport sector.

Finally, the number of stationary power projects and fuel cell systems should grow from 200 and 10,000 in 2019 to 20,000 and 5.5 million in 2050, the equivalent of 16% and 22% YOY growth, respectively.

38. China Electric Car Charge Infrastructure Promotion Alliance, "National EV Charging Pile Stock Reached 1.418 million in September, a 27.2% year-over-year growth," 2020, accessed on 14 October 2020, available at: www.sohu.com.

Table 3. Overall targets for hydrogen and fuel cell development

Development target		Status in 2019*	Short-term targets (2020-2025)	Medium-term targets (2026-2035)	Long-term targets (2036-2050)
Hydrogen as % of primary energy		2.7%	4.0%	5.9%	10.0%
Sector revenue (billion yuan)		300	1,000	5,000	12,000
Manufacturing capacity	No. of refueling stations	23	200	1,500	10,000
	No. of FCEVs (thousand)	2	50	1,300	5,000
	No. of stationary power projects	200	1,000	5,000	20,000
	No. of fuel cell systems (thousand)	10	60	1,500	5,500

Source: H2CN (2019) White Paper on China Hydrogen and Fuel Cell Industry.

*: Status when the paper was released in June 2019. Baseline data reported by H2CN may not be entirely compatible with statistics from other Chinese industrial sources.

Concluding remarks and recommendations

If appropriately promoted and implemented, the hydrogen economy possesses great potential of improving China's economic competitiveness, national energy security, air quality as well as decarbonizing the country's energy- and emission-intensive economy. Nevertheless, the opposite scenario cannot be simply ruled out as a looming hydrogen hype especially at the local government level could easily lead to a boom and bust cycle, with tremendous amounts of taxpayer money at stake.

Based on an extensive literature review, conversation with various industrial insiders, and observation of increasingly active hydrogen-related policy dialogues among key Chinese stakeholders, the author has presented a preliminary "to do list" as a reference for moving hydrogen economy agenda forward in China, aiming to trigger interest in a more in-depth follow up study on the prospect of a hydrogen economy with Chinese characteristics.

A coordinated national mechanism should be established at the central government level to lay out principles for hydrogen economy development in China.

Though various government-affiliated stakeholders have published hydrogen-related strategic documents in recent years, they nevertheless focus primarily on technological roadmaps of hydrogen economy development. While increasingly higher number of supporting policies issued by central and local governments have been translated into tangible investment, China is still in urgent need of a coordinated national approach to bring order to the Chinese hydrogen value chain that is in great danger of overheating. In particular, a coordinated national mechanism should aim to tackle the following sticky issues:

- Which central government agency should be designated by the State Council as the primary national authority regulating the Chinese hydrogen economy? In case the above regulatory model is unacceptable among key stakeholders, how should an inter-ministerial mechanism be established and sustained to coordinate hydrogen economy development in China?

- What should be hydrogen's role in China's energy transition in general and carbon neutrality pathway in particular?
- Should hydrogen be primarily regulated as an energy carrier or a hazardous chemical product?[39]
- How should local protectionism be removed to establish to a truly national market throughout the Chinese hydrogen value chain?
- How should an appropriate set of rules be set to regulate subsidies poured by local governments, allowing healthy regional competition but avoiding excess waste of public funding?
- How could rampant subsidy fraud similar to the recent one occurred in the Chinese EV manufacturing industry be prevented from the beginning?
- How should protection of intellectual property rights be drastically strengthened to encourage both domestic innovations and international cooperation?
- To hedge against the danger of a new round of boom and bust cycle, how should an appropriate set of criteria be set to phase out government subsidies on hydrogen technology deployment over time?

Comprehensive and transparent statistical reporting and accounting throughout the Chinese hydrogen value chain should be established.

Reliable statistical reporting is the basis of sound and sensible decision-making in the energy sector and beyond. Given that China's enthusiasm on hydrogen economy is a newly found one, statistical reporting and accounting of hydrogen-related activity is still preliminary with limited coverage and high uncertainty. For instance, In October 2018, a senior executive of Sinopec mentioned that annual hydrogen output by Sinopec is between 2 to 3 Mt.[40] In July 2020, it is reported that annual hydrogen output by Sinopec is more than 3 Mt, accounting for around 14% of national total.[41] The wide range of Sinopec's annual hydrogen production indicates the necessity of improving both accounting and transparency of hydrogen-related data in China.

39. Currently, hydrogen is classified as hazardous chemical product in China. On-site hydrogen generation is only allowed inside chemical parks, and liquid hydrogen transport is permitted for military purposes only.

40. The Paper, "Sinopec Pilots Hydrogen Refueling Station Business by Launching the First Combined Hydrogen and Gasoline Refueling Station in Guangdong," 2019, accessed on 15 July 2020, available at: https://m.thepaper.cn.

41. Yicai Daily, "Sinopec: Annual Hydrogen Output Exceeded 3 Mt," 2020, accessed on 29 July 2020, available at: www.yicai.com.

In the hydrogen production segment, renewable hydrogen should be prioritized for intensive R&D and deployment in the near future, and greening China's existing hydrogen flow should be on the Chinese government's policy radar especially in the longer term. In this regards, the timely establishment and subsequent coverage expansion of China's long-awaited national emissions trading scheme will be beneficial to green the Chinese hydrogen value chain in the years to come.

With extremely low carbon footprint, renewable hydrogen may be converted through various production routes. As renewables-powered electrolyzer is the most common option, it possesses great potential to utilize large amounts of renewable electricity for hard-to-abate sectors such as industry, buildings and transport, as well as in niche applications such as remote localities that are far away from existing grid infrastructure. Given the difficulties associated with power sector reform in China, promotion of renewable hydrogen offers the option of a technical fix of GIVAR-related challenges.

Following Chinese president Xi Jiping's recent carbon neutrality announcement, renewable hydrogen is expected to play a much more important role in decarbonizing the Chinese energy economy than otherwise would be the case. Ideally, the Chinese government should consider to significantly scale up the country's renewable hydrogen capacity starting from the 14^{th} FYP period.

As fossil fuels especially coal gasification and coking currently dominate China's hydrogen production mix, it is unwise not to utilize low cost production opportunities offered by China's sizable fossil fuel-based hydrogen flow. Consequently, it is unnecessary for Chinese stakeholders to differentiate colors of hydrogen production in the near future. Nevertheless, as China alone consumes more than half of global coal, and coal-to-oil, coal-to-gas, coal-to-olefin, and coal-to-ethylene glycol projects in China alone are estimated to consume near 100 Mt of coal in 2018, the looming danger of the overheating of the coal chemical industry makes optimization of China's national energy mix more difficult. Therefore, the central government should better balance short-term economic gains with long-term strategic interest. At a minimum, the concept of hydrogen economy should not be abused as an excuse to promote coal chemical development across the country.

China's very large hydrogen production from fossil fuels, mainly coal, would make it quite challenging to consider decarbonizing the current uses of hydrogen. Nevertheless, in order to better prepare the country to achieve carbon neutrality before 2060, it is necessary for China to seriously examine the feasibility of greening its existing hydrogen flow, especially in the longer term. In this regards, the timely establishment and subsequent coverage expansion of China's long-awaited national emissions trading scheme will be beneficial to green the Chinese hydrogen value chain in the years to come.

In the hydrogen storage and transport segment, national and local government should continuously direct subsidies towards hydrogen refueling stations, and also consider to encourage low concentration blending of hydrogen into China's natural gas network.

Similar as the fact that charging infrastructure is the weakest link of kicking off EV deployment in different parts of the world, the lack of hydrogen refueling stations is also a stumbling block of promoting hydrogen economy development in China and beyond. Not surprisingly, during the infant phase of hydrogen economy development, it is necessary for various level Chinese governments to channel public subsidies towards hydrogen refueling stations to break the "chicken and egg" dilemma associated with FCEV deployment.

Though low concentration blending of hydrogen with natural gas can avoid the high initial investment of building dedicated hydrogen pipelines or other expensive delivery infrastructure during the early market development phase, this technologically viable transport route of hydrogen has been fiercely opposed by vested interest groups, often citing safety as a key concern. Luckily, to encourage third party access of natural gas transmission network, the Chinese central government recently launched China National Oil & Gas Piping Network Company (PipeChina) by stripping oil and natural gas transmission assets from China's three national oil companies. Given the fact that PipeChina becomes one of China's 97 central SOEs with similar ranking as CNPC, Sinopec and CNOOC, the above central SOE restructuring has opened a window of opportunity of moving low concentration hydrogen blending agenda forward in China.

In the hydrogen consumption segment, China should selectively focus on R&D and deployment of advanced hydrogen end use technologies notably for cement and steel, ideally coupled with expansion of the horizon of national energy planning framework.

When the hydrogen value chain is closely examined, the weakest link is apparent at the end use segment. Above all, the growth of a hydrogen economy needs to be demand-driven in the end. Given the versatile applications of hydrogen end uses in a wide spectrum of sectors, it may be unwise if hydrogen-related R&D and deployment efforts in China are not coordinated with a pick and choose attitude. Because of China's heavy investment in EV manufacturing and EV charging infrastructure, a large-scale subsidy-driven passenger FCEV strategy may not make much sense for China. Consequently, at the end use segment, the Chinese government should seriously consider to focus on R&D and deployment of fuel cell buses and trucks along with other novel applications.

While the Chinese energy economy becomes increasingly interconnected, it nevertheless remains largely fragmented, with numerous technical and institutional barriers that prevent the optimization of an energy- and carbon-intensive system. If the concepts of P2X and sector coupling were incorporated into China's energy planning framework, the utilization of electricity and hydrogen in all energy-related processes, whether transport, heating, building or manufacturing, would revolutionize the largely compartmented Chinese energy sector by introducing new momentum to deepen China's energy sector reform.

Opening up the Chinese market to better integrate technology innovations in advanced economies and manufacturing-related competitive advantage of the Chinese economy, aiming to create a win-win situation between China and the international community.

Though China has an impressive track record of scaling up clean energy technologies such as solar panels, wind turbines and EVs in the past, the country still lags far behind leading economies in terms of advanced hydrogen technologies. In order to better integrate technology innovations in advanced economies and its own manufacturing-related competitive advantage, China should seriously consider to further open up its domestic market with drastically stringent protection of intellectual property rights. Only under such a scenario, a reciprocity-based integration of the Chinese hydrogen value chain with the rest of the world may be well received by the international community, with tremendous potential to move global clean energy transition and climate agenda forward in the years to come.

More in-depth follow up study should be conducted to further investigate the prospect of a hydrogen economy with Chinese characteristics.

This report is the first attempt by Ifri to investigate the prospect of a nascent but sizable hydrogen economy in China. Given the complexity of the research topic and strong interest from a wide range of international and Chinese audiences, more in-depth follow up study could be conducted to investigate some of the following research questions:

- What should be hydrogen's role in China's clean energy transition in general and carbon neutrality pathway in particular?
- What are the status quo and prospect of hydrogen production costs in China?
- How could China decarbonize the existing uses of carbon-intensive hydrogen processes?
- Would China support a global effort to decarbonize all existing hydrogen uses, so no individual country would face economic disadvantages?
- How much is the Chinese government ready to spent to move the hydrogen economy agenda forward?
- What are the impacts of the COVID-19 pandemic on China's hydrogen economy agenda?
- What are the impacts of an escalating US-China trade war on China's hydrogen economy agenda?
- How do key Chinese stakeholders view international developments of the hydrogen economy in the EU, United States, Japan and South Korea?
- Is it possible to formulate a win-win collaboration between advanced economies especially the EU and China in area of hydrogen economy?

Appendix: Hydrogen energy city competitiveness ranking for China

Ranking	City	Province	Score	Ranking	City	Province	Score
1	Shanghai	Shanghai	75.84	16	Qingdao	Shandong	40.8
2	Suzhou	Jiangsu	50.53	17	Jinan	Shandong	40.33
3	Foshan	Guangdong	49.48	18	Maoming	Guangdong	39.39
4	Chengdu	Sichuan	47.14	19	Shenzhen	Guangdong	39.14
5	Zhangjiakou	Hebei	46.01	20	Dalian	Liaoning	38.83
6	Jiaxing	Zhejiang	44.08	21	Yunfu	Guangdong	38.68
7	Wuhan	Hubei	43.91	22	Weifang	Shandong	38.46
8	Chongqing	Chongqing	43.79	23	Taiyuan	Shanxi	37.34
9	Ningbo	Zhejiang	43.78	24	Weifang	Shandong	37.1
10	Nanjing	Jiangsu	43.37	25	Yancheng	Jiangsu	36.17
11	Guangzhou	Guangdong	42.67	26	Changzhi	Shanxi	35
12	Beijing	Beijing	42.64	27	Datong	Shanxi	34.74
13	Tianjin	Tianjin	41.69	28	Handan	Hebei	34.6
14	Nantong	Jiangsu	41.6	29	Jining	Shandong	34.53
15	Zhengzhou	Henan	40.94	30	Baoding	Hebei	33.86

Source: Trendbank (2020) China Hydrogen Energy Competitiveness Ranking. Accessed on 15 July 2020, available at: https://www.jetro.go.jp.

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