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中德能源与能效合作
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DEUTSCHLAND - CHINA

可再生氢在中国的前景及在工业脱碳中的作用

Prospects of Renewable Hydrogen in China and Its Role in Industrial Decarbonization

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Executive Summary 执行摘要

作为全球最大的氢能生产和消费国，中国每年生产氢气高达 3,400 万吨左右。中国当前制氢路线以煤为主（72%），并有约 450 万吨未被有效利用，未来可用于工业脱碳等领域，并能为可再生氢产业链的建设打好基础。中国的电解制氢仍处于起步阶段，各地规划的 32 个可再生氢气试点项目设计年度总产能已超过 29.7 万吨。推动中国可再生氢产业链发展重在下游应用端。然而，氢作为一种能源载体，在转换过程中伴随较大的能量损耗。因此，如何尽快明确最适合可再生氢应用的场景，即“无悔”选项，已成为当务之急。氢能有望成为大规模、长时间储能的解决方案，为风电、光伏等间歇性可再生能源发电提供托底保障。可再生氢也有望助力排放密集型工业流程的深度脱碳。在上述应用场景中，可再生氢能够有效替代化石燃料作为能源载体和生产原料的双重角色。以钢铁行业为例，氢直接还原铁可以大幅降低焦炭消费。在海运和长途飞行领域，直接通过电气化减少碳排放不但效率低下而且成本高昂，采用可再生氢被广泛认为是实现净零排放的不二法门。

中国和德国同为制造业大国，都设置了在本世纪中叶实现净零排放的气候目标，因此在清洁能源转型领域面临着诸多共同挑战。尽管俄乌冲突全面爆发导致了全球范围的能源安全焦虑，德国仍在为实现 2045 年气候中性目标而加速布局可再生氢能政策和产业，以有效支撑本国的清洁能源转型进程。作为极具气候雄心的发达经济体，德国在氢能经济领域的经验和教训可以帮助中国培育本国处于起步阶段的可再生氢产业链。本文从氢能治理结构、提高氢能经济可行性措施和促进氢能应用等方面剖析了德国 2020 年 6 月发布的《国家氢能战略》。结合中国 2021 年 3 月发布的《氢能产业发展中长期规划（2021-2035 年）》以及电动汽车在中国的发展历程，作者基于中国具体国情提出了以下有针对性的政策建议：

- 为更好更快建立工业化规模的低碳氢供应链，中国应在充分利用本国现有化石燃料制氢产能的同时激励可再生氢产能的持续增长。基于中国在电动车发展助力交通行业减排过程中所取得的经验，在氢能产业链规模化之前，扩大氢能的下游需求与上游的低碳生产应该区分对待。扩大可再生氢产能应与鼓励氢能大规模应用同时推进，从而在氢能产业链的上、下游之间产生正向激励效应。另一方面，本世纪初以来全国燃煤发电装机的快速扩张已提前锁定了巨量煤炭需求，中国应以此为鉴，尽量避免进一步扩大现有化石燃料制氢产能规模。
- 氢能管制应更多侧重其能源属性。目前，中国仍将氢气作为危险化学品进行标识和监管，对其能源属性没有予以充分考量和反映。对氢能的危化品定位在生产选址、道路运输、市场准入、终端应用以及标准化等方面带来了一系列重大挑战。中国未来是否能够更加合理地对氢能进行定位是实现氢能规模经济性的重要先决条件。
- 可再生氢在工业深度脱碳中的作用应被优先考虑，并重点聚焦钢铁、石油化工和煤化工产业。鉴于可再生氢在重工业应用中的巨大潜力，工业脱碳应成为中国实现可再生氢供应链规模经济性的重点领域。除了尽快将排放密集型的工业行业纳入全国碳排放交易体系，还应考虑将德国乃至欧洲的创新政策和金融政策工具针对中国国情进行定制和试点，尤其是绿钢的政府采购、碳差价合约和气候友好型原材料的需求配额。
- 为更好促进可再生氢在中国的发展，应建立氢能部际协调机制，并最好由国务院直接领导。否则，氢能治理的职责如果长期分散在不同部委之间，将会阻碍氢能的长足发展，并使中国错失先机。建议由该高层协调机制主导对建设跨省氢能管道这一无悔基础设施的必要性和规划展开调查研究，以积极应对中国氢气生产、消费地理错配的挑战。
- 中央和地方政府补贴氢能发展时，应在制度设计层面防范“骗补”乱象并促进公平竞争。根据以往补贴政策实施过程的经验教训——尤其是电动汽车领域——中国氢能监管框架应重视制约与平衡，并纳入多重监督机制。
- 为了缩小与发达经济体在氢能核心技术领域的差距，中国应考虑为包括跨国公司与本土企业在内的市场主体营造更加公平的竞争环境。如果能够大幅加强知识产权保护、积极消除市场准入壁垒，中国将能更好地深化与发达经济体在可再生氢领域的国际合作，并吸引欧盟特别是德国公司来华展开互利双赢的技术合作和商业投资。

Content

1 Status quo: hydrogen production in China dominated by fossil fuels

Except for rare circumstances, molecular hydrogen does not occur naturally in the earth's crust, but often combines with oxygen, carbon, nitrogen or other atoms to form compounds such as water (H2O), hydrocarbons (CxHy) or biomass (CxHyOzNa). Therefore, technologies to produce hydrogen gas at scale are essentially different manufacturing routes of separating hydrogen from its various compounds. What makes the hydrogen economy — a hypothetic future system of delivering energy and raw materials through the use of hydrogen — challenging is the fact that the hydrogen value chain including production, transportation, storage and end uses may not always come with clear boundaries. In other words, hydrogen production and consumption often occur in the same industrial facilities, and hydrogen prosumers include but are not necessarily limited to manufacturers of coke, ammonia, methanol, chlor-alkali, petrochemicals and the Chinese modern coal chemicals such as coal-to-oil, coal-to-gas, coal-to-olefin, and coal-to-ethylene glycol.

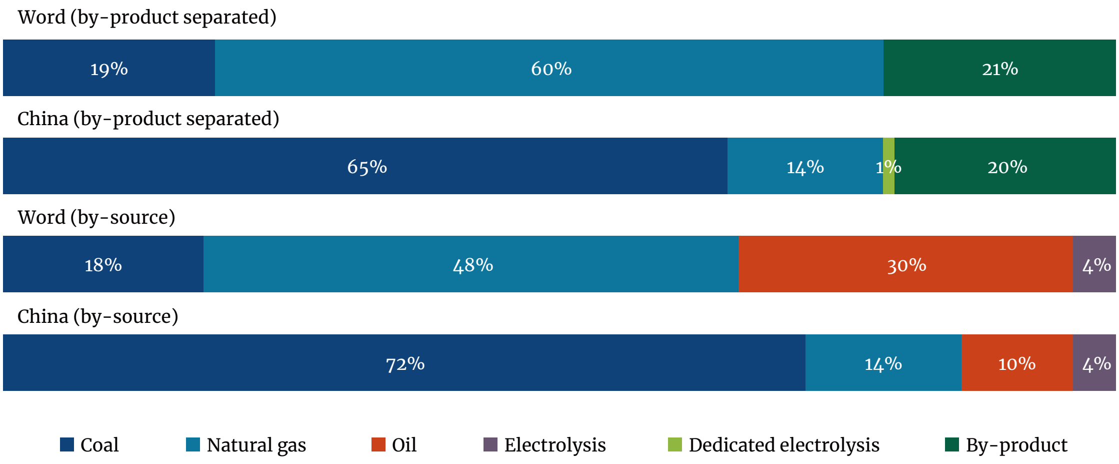
Hydrogen made with energy derived from renewable sources is typically known as "renewable hydrogen" in the international context, especially in the European Union (EU).[1] At present, China lacks a national standard for renewable hydrogen, but the EU definition is widely accepted. With more countries adopting national hydrogen strategies, and rising business enthusiasm towards demonstration projects, the concept of a renewable hydrogen economy has gained worldwide momentum. However, to date, 96% of global hydrogen supply still originates from fossil fuel-based production routes such as steam methane reformation (SMR), coal gasification and coke manufacturing.

To accelerate the global clean energy transition and achieve climate neutrality by mid-century, there is a consensus that the world must drastically curb fossil fuel consumption. Although hydrogen has been indispensable in the energy and chemical industries for decades, the environmental footprint of the existing hydrogen value chain is unsustainable. Hence, in jurisdictions with net-zero emission goals such as the EU and China, electrolytic hydrogen production powered by renewable energy has drawn attention as a versatile and sustainable energy vector with potential to help decarbonize the energy economy, especially in carbon-intensive industrial sectors.

As China's second largest trading partner and an advanced economy with ambitious climate aspiration, the EU in general and Germany in particular play a leadership role in conceptualizing and nurturing the global development of a renewable hydrogen economy. Naturally, European practices and lessons, especially those from Germany, are particularly relevant to policy makers in China, the largest hydrogen producer and consumer in the world.

1.1 Coal-reliant hydrogen production in China

Figure 1. Hydrogen production mix by source in 2020: China versus the world



Source: IRENA, IEA, and the authors' own estimation.

[1] Source: The European Commission, accessed on 12 March 2022 at https://energy.ec.europa.eu/topics/energy-system-integration/hydrogen_en.

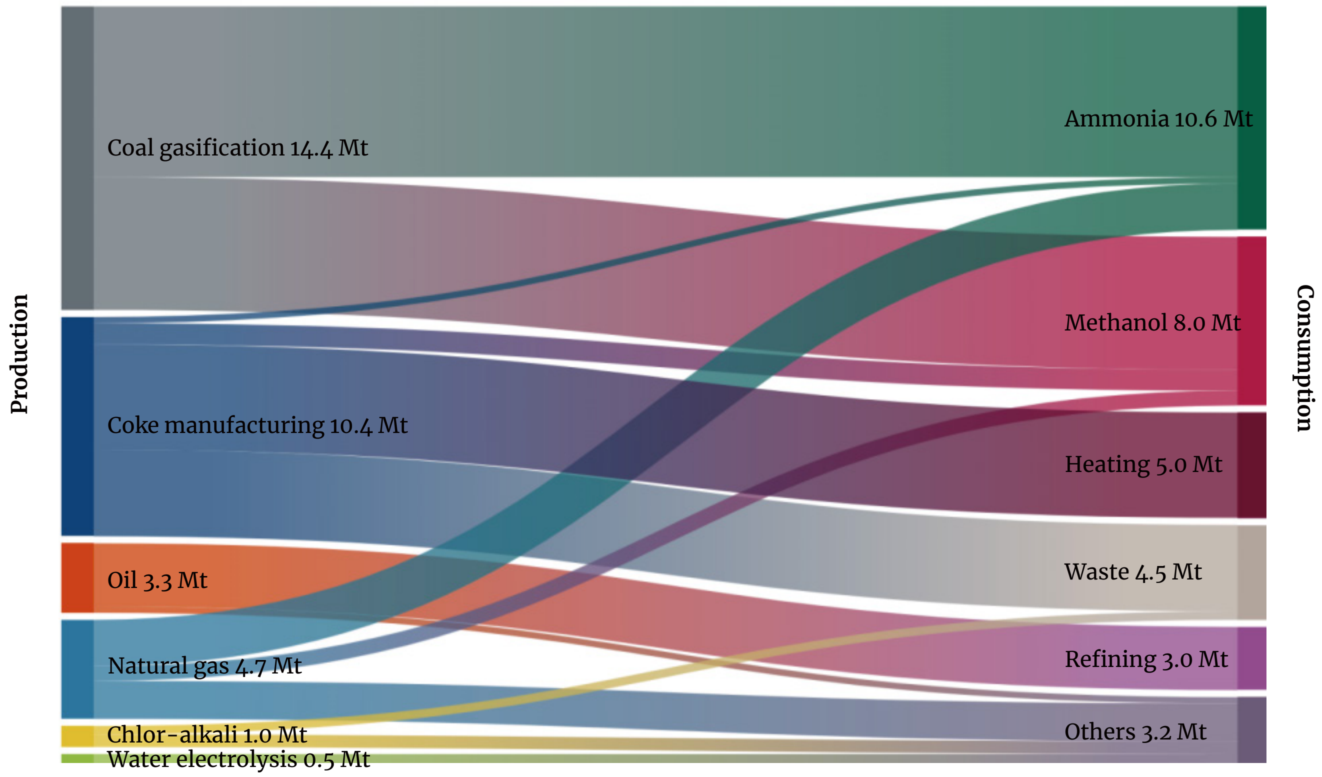
On the supply side, national hydrogen production across China is estimated to reach 34.1 million tons (Mt) in 2020, a slight 2% year-over-year (YOY) uptick from 33.4 Mt in 2019. Hydrogen manufacturing in China is dominated by fossil fuels, with 96% of supply coming from coal, natural gas or oil. Electrolysis including chlor-alkali by-production and water electrolysis only account for the remaining 4% of national output. Coal-based hydrogen production ranks the first with 72% of market share largely due to domestically abundant and affordable coal resources as well as Chinese government's largely supportive attitude towards the coal chemical industry, especially at the local government level (Figure 1).

Among coal-derived hydrogen methods, coal gasification outweighs by-product hydrogen production of both coke and chlor-alkali manufacturing, with their output standing at 14.4 Mt, 10.4 Mt, and 1.0 Mt respectively in 2020 (Figure 2).

Currently, electrolytic hydrogen production in China is still at its infant stage, comprising of about 510 thousand tons per year (kt/year) output from renewable hydrogen demonstration projects (see Annex A: A List of renewable hydrogen projects in China) and 925 kt/year supply from chlor-alkali by-production. Consequently, water electrolysis by renewable power (renewable hydrogen) is even more negligible.

1.2 Significant potential to scale up hydrogen utilization in China

Figure 2. China hydrogen flow 2020



On the demand side, ammonia manufacturing is the largest hydrogen consuming industry in China, followed by methanol synthesis, petroleum refining, chlor-alkali and other industrial processes with by-product hydrogen, which utilize hydrogen on-site for either process heat or as a feedstock. The 4.5 Mt/year gap between national hydrogen production and sector-specific consumption represents hydrogen waste flows. A number of factors account for this. Coke oven gases produced in coke furnaces and synthesis gases generated in coal gasifiers are a mixture of hydrogen, methane, carbon monoxide (CO) and other impurities. Before China introduced the demonstration city clusters for hydrogen fuel cell vehicles, it used to be economically unattractive to separate hydrogen for use rather than for on-site combustion to heat the coke ovens (5.0 Mt) or as feedstock gases for methanol synthesis (1.0 Mt/year) and ammonia manufacturing

(0.3 Mt/year), or simply being vented as waste discharge. Meanwhile, another 0.4 Mt/year of by-product hydrogen is wasted in various chlor-alkali manufacturing facilities due to a lack of appropriate planning and process optimization. As a result, great potential exists to further improve material efficiency throughout the Chinese hydrogen supply chain in the years to come.

Considering the magnitude and composition of hydrogen production in China, it is natural to kick off the country's fledgling hydrogen economy by focusing on utilization of by-product hydrogen. In this regard, about 1.3 Mt/year of by-product hydrogen from coke manufacturing has been turned into methanol or ammonia, driven largely by China's increasingly stringent environmental protection and industrial efficiency standards.

In 2021, the Chinese central government approved five demonstration city clusters centered in Beijing, Shanghai, Guangdong, Henan and Hebei Provinces. This four-year pilot program was designed to promote commercialisation of key technologies related to fuel cell electric vehicles (FCEV), to establish an FCEV supply chain, to explore effective FCEV business models, and to improve regulation and industrial standards.

The central government's strong support for FCEV commercialization has sent a clear signal to the business community, which has started to ramp up industrial by-product hydrogen utilization. According to Liu & Shi (2021), the unit production cost of industrial by-product hydrogen in China is at ¥6.2-22.3/kg (€0.9-3.1/kg), much lower than that via water electrolysis at ¥22.9-51.5/kg (€3.2-7.1/kg)(Liu et al., 2022).[2]

Though renewable hydrogen supply is not widely available across China, its applications in FCEVs could help encourage hydrogen utilization in selected city clusters. As a result, the 5.0 Mt/year of hydrogen that were burned on-site for heating and the 4.5 Mt/year of waste hydrogen flow could be tapped first for more utilization or recovery.

Obsolete regulations are one major barrier that prevents China from developing an internationally competitive hydrogen economy. Government regulations require labeling and handling hydrogen as a hazardous chemical, as distinct from other major energy fuels. This specific policy has imposed tremendous challenges in terms of siting production facilities, transportation especially via roads, qualification of new industrial entrants, application scenarios as well as standardization.

Recommendations have been made by prominent decision makers including former minister of science and technology, Dr. Wan Gang, who suggested in November 2018 that hydrogen should be regulated in accordance with its energy nature, similar as gasoline or diesel, so that hydrogen refuelling stations could enjoy greater flexibility in terms of siting. This recommendation has been noted in subsequent government policy documents. For instance, the draft Energy Law published in April 2020 and the 2021 Government Work Report both categorize hydrogen as an energy carrier.

The Chinese central government's support for establishing a hydrogen supply chain was further underpinned in March 2022 by the Medium- and Long-term Plan for the Development of the Hydrogen Energy Industry (2021-2035), the equivalent of China's national hydrogen strategy. Just one month later, the 14th Five-Year-Plan (FYP) for National Production Safety outlined the requirement of speeding up production safety standards for emerging industries including hydrogen. In June 2022, the 14th FYP for Renewable Energy Development features a section entitled Promoting Large-scale Utilization of Hydrogen Production by Renewable Energy, which mentions sectors such as chemicals, coal mining and transportation.

Last but not least, to foster an integrated hydrogen supply chain has been incorporated into the State Council's Opinions on Completely, Accurately and Comprehensively Implementing the New Development Concept and Accomplishing Carbon Peaking and Carbon Neutrality, which is the overarching "1" of China's "1+N" policy framework for achieving its Dual-Carbon Goals. Following the release of China's Medium- and Long-term Hydrogen Plan on 23 March 2022, more detailed "N's" are expected to promote the development of hydrogen production, storage, transportation and utilization, especially in carbon-intensive industrial sectors such as in the steel and chemical industries.

[2] Exchange rate: €1 = ¥7.23.

1.3 Rationale for China's renewable hydrogen economy

At the 75th United Nations General Assembly on 22 September 2020, China announced plans to peak national carbon emissions before 2030 and achieve carbon neutrality before 2060, a commitment known in Chinese as the dual carbon goals. Since the announcement, experts have debated potential pathways to completely decarbonize the energy economy in general and industrial sectors in particular. Hydrogen serves as a potentially carbon-free energy carrier and industrial feedstock and could thereby assist China's transition from a highly fossil fuel-reliant economy to an increasingly renewables-dominated system.

1.3.1 Versatile hydrogen

Hydrogen provides a potential solution for large-scale, long-duration energy storage that could compensate the variability of renewable energy generation, especially wind and photovoltaic power. Compared with other technologies including batteries, compressed air and flywheels, hydrogen is well positioned to enable long-duration storage, from weeks to months, and is the most promising emerging technology to be deployed at scale for long duration storage. Since 1972, the Teesside salt field in the UK has been storing almost pure hydrogen (95% H2, 3–4% CO2) in three shallow salt caverns (at a depth of around 400 meters), each of which has a capacity of around 70,000 cubic meters (m3) of hydrogen at 45 bar,[3] or 25 GWh.[4] The exploration of utilizing renewable hydrogen for seasonal energy storage is highlighted in China's hydrogen plan for 2021-2035.

Hydrogen also has the potential help decarbonize carbon-intensive industrial sectors where fossil fuel is utilised both as an energy carrier and as a feedstock. Renewable hydrogen is an emerging carbon-neutral reducing agent in iron and steel manufacturing, and thus has potential to eliminate otherwise hard-to-abate CO2 emissions from steelmaking in China, which accounts for more than half of global steel output and about 15% of China's national CO2 emissions. A number of China's leading steel enterprises, such as Hebei Iron and Steel (HBIS), Baowu and Jianlong, begun experimenting with hydrogen metallurgy, aiming to explore potential low carbon and net-zero solutions with renewable hydrogen. Renewable hydrogen also promotes sector coupling between the chemical industry and renewable power, leading to low-carbon substitution of fossil fuel-based hydrogen in ammonia, methanol and other chemical manufacturing fields.

Hydrogen also has applications in fields where direct electrification might represent an inefficient or high-cost pathway to net-zero, such as in the fields of long-haul heavy-duty trucking, maritime shipping and aviation. In these sectors, renewable hydrogen and its derivatives (such as green ammonia, green methanol) may serve as the last resort of industrial decarbonization once all other options are exhausted.

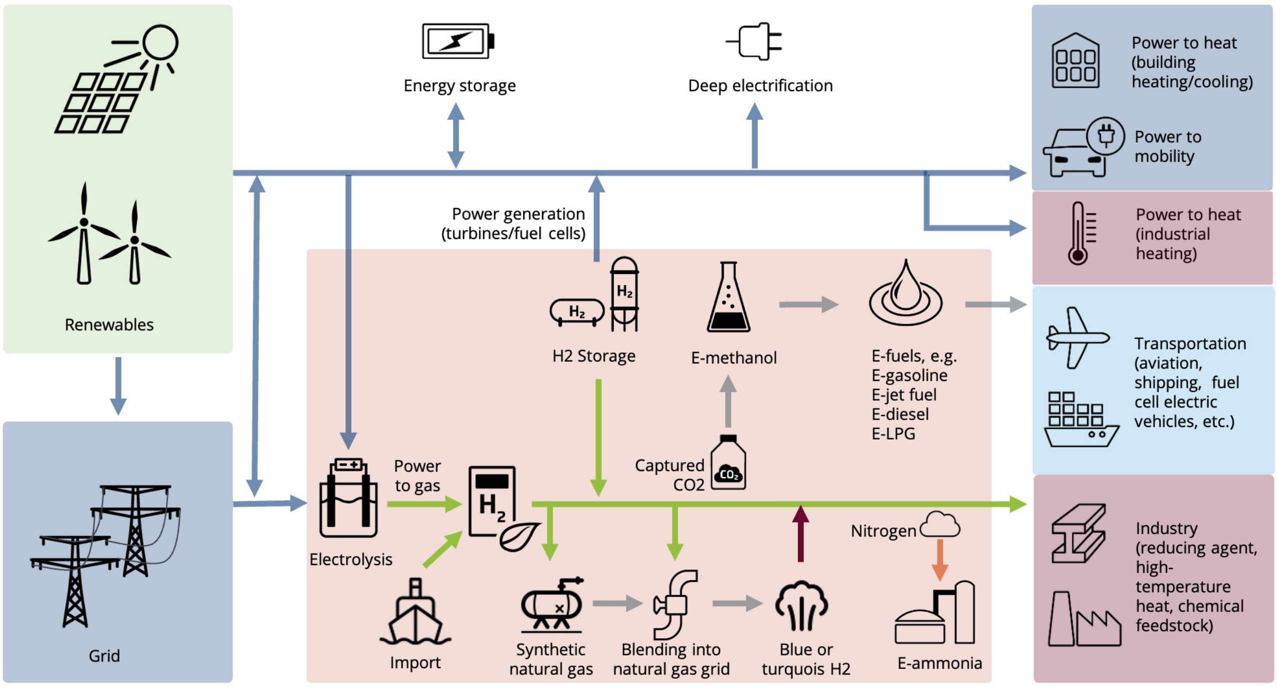
1.3.2 Sector coupling via renewable hydrogen

Sector coupling is defined as the connection of at least two different sectors via substitution of non-renewable activities with renewable alternatives to establish fully renewable energy systems.[5] Some advantages of sector coupling include increased flexibility, enhanced storage, and distribution opportunities to use renewable energy, as well as reliability. In energy transition-related discourse, sector coupling implies making renewable power the default form of energy in energy consuming sectors wherever possible. Because weather-dependant renewables are not always available when energy is needed, and as the market share of wind and solar in global electricity generation growing at double digits,[6] energy storage and power balancing become not only increasingly prominent technical challenges but also business opportunities.

Sector coupling could be especially beneficial in the following scenarios: power could be used to heat large amounts of water (power-to-heat, PtH), electrifying the heating sector. During periods of peak renewable power output, excess electricity could be utilized to produce hydrogen or synthetic gases (power-to-gas,

[3] Source: Aleksandra Małachowska et al. (2022), "Hydrogen Storage in Geological Formations—The Potential of Salt Caverns" Energies 2022, 15: 5038.
[4] Source: John Williams et al., "Theoretical capacity for underground hydrogen storage in UK salt caverns," British Geological Survey, accessed on 10 January 2022 at https://ukccsrc.ac.uk/wp-content/uploads/2020/05/John-Williams_CCS-and-Hydrogen.pdf.
[5] Caledonia T.C.Trapp et al., "Sector coupling and business models towards sustainability: The case of the hydrogen vehicle industry," March 2022.
[6] Reference: Joel Jaeger, "Explaining the Exponential Growth of Renewable Energy," World Resources Institute, September 2021.

Figure 3. Sector coupling via renewable hydrogen



PtG). The gases can then be used directly to produce electricity and heat in times of low renewable output, or as a reducing agent or feedstock for industrial sectors such as steelmaking and ammonia manufacturing. An indirect application of the above gases is to further process them to various types of electro-fuels (e-fuels) for aviation, maritime shipping, and long-haul heavy-duty trucking. Especially in Europe, energy conversion pathways that utilize electricity as the primary input to produce various e-fuels, energy services, and chemicals are often categorized as Power-to-X (PtX), with typical products as below:

- Hydrogen
- E-ammonia
- E-methanol
- E-gasoline
- E-LPG (liquified petroleum gas)
- E-jet fuel
- E-diesel

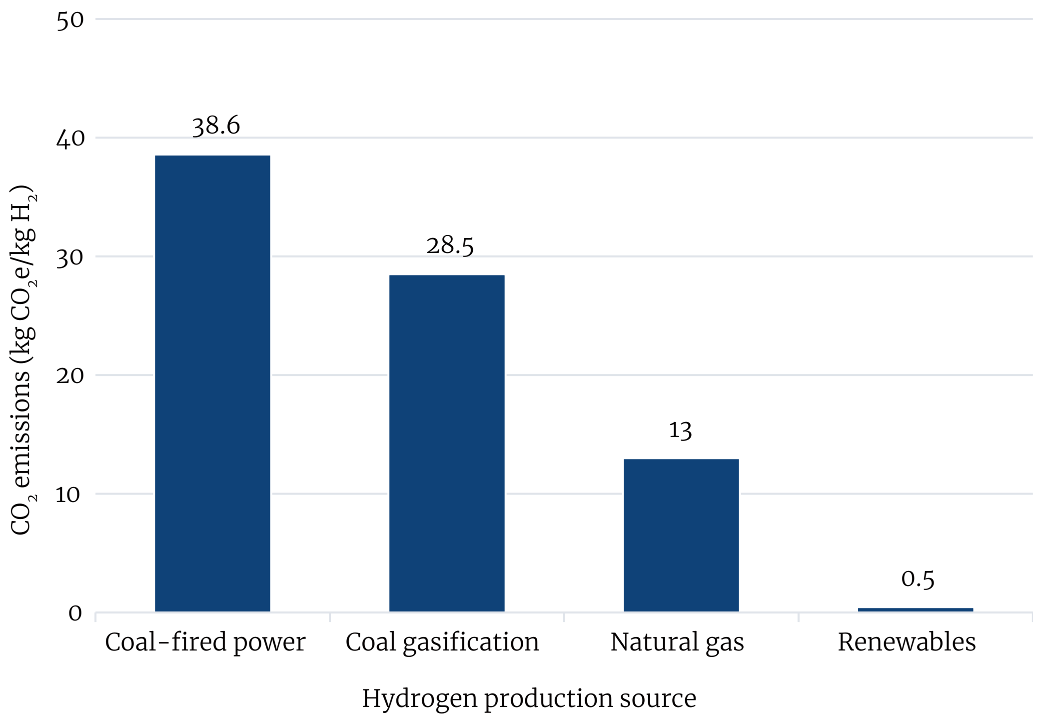
In 2021, renewables account for 30% of China's power generation, and China plans to increase this to 33% by 2025. Though China's 14th FYP targets for renewables are widely considered conservative, the growing share of renewables in China's power mix enables renewable hydrogen serve as an energy carrier to supplementing electricity in sector coupling and net-zero decarbonization, especially in transport and energy-intensive heavy industry.

1.3.3 Carbon intensity of hydrogen to be reduced via renewables-powered water electrolysis

All the carbon abatement benefits related to renewable hydrogen are based on the premise that it is produced via electrolysis with renewables. By comparison, CO2 emissions discharged from China's sizable fossil fuel-based hydrogen production routes are significantly higher (Figure 3). Therefore, replacing fossil fuel-based hydrogen with renewable hydrogen in a timely fashion is crucial to efforts to reduce China's industrial emissions.

To avoid undermining its dual carbon goals and locking in emissions, China needs to ensure that greenfield hydrogen capacity additions are based on renewables. However, China currently lacks concrete supporting policies. Even the chemical sector lacks a requirement that new capacity to be based on low-carbon routes. Though renewable hydrogen has yet to reach cost parity with coal-based hydrogen, its competitiveness is expected to improve over time, especially once China's national carbon emissions trading scheme is enlarged beyond the power sector, with the chemical sector likely among the next sectors to face carbon pricing. For companies along the hydrogen supply chain to avoid stranded assets and locked-in investment, proactive planning and preparation for the forthcoming green transition is necessary.

Figure 4. CO_2 intensity of hydrogen production in China (kg CO_2e/kg H_2)

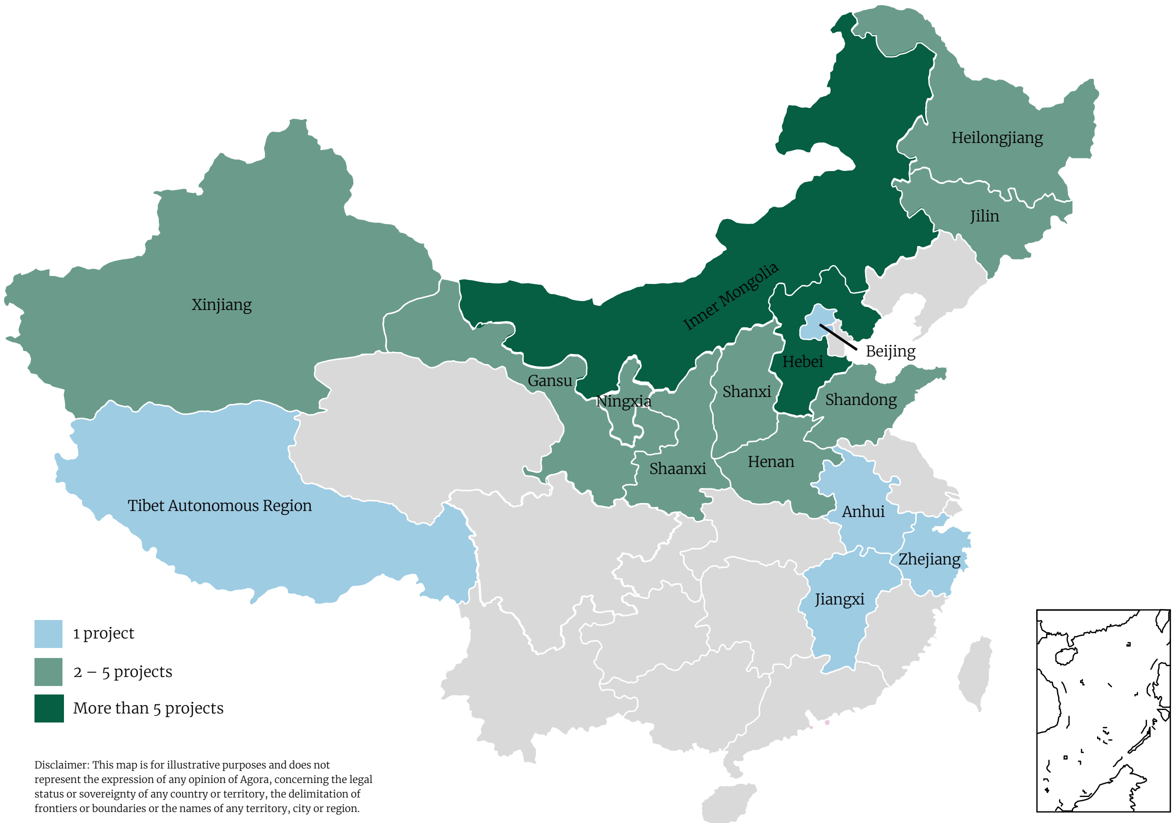


Source: China Hydrogen and Fuel Cell Industry Handbook, 2020

1.4 Renewable hydrogen in China

In September 2021, the China Hydrogen Alliance and the Rocky Mountain Institute (RMI) jointly launched the Renewable Hydrogen 100 Initiative, setting an ambition of building 100 gigawatts (GW) of installed renewable hydrogen production capacity across China by 2030. Supported by policy, state-owned enterprises (SOEs), private Chinese companies, and international companies in China are all expected to take an active part in renewable hydrogen production. However, a major question remains of how the regulatory framework might support this transition.

Figure 5. Distribution of renewable hydrogen projects in China



1.4.1 Renewable hydrogen production concentrates in North China

In terms of geography, as of July 2022, there were 50 renewable hydrogen production projects are underway across China, concentrated mainly in North China. (For further detail, see Annex A: A list of renewable hydrogen projects in China.) Inner Mongolia and Hebei lead other provinces so far, though the drivers in each province differ.

As China's second largest coal producer, and as a province with enormous clean energy resources, Inner Mongolia has long planned to foster a renewable hydrogen supply chain. The province has China's largest installed wind capacity (39.9 GW), and the highest solar energy potential, as well as possessing abundant by-product hydrogen production. Wuhai in Inner Mongolia became the first Chinese municipal government to release a 14th FYP for hydrogen development. Starting from utilizing by-product hydrogen from coal chemicals and chlor-alkali manufacturing, Wuhai aims to establish the first hydrogen-based steel-making zone in China by 2025. In April 2021, its Ordos City published a Three-Year Action Plan for Hydrogen Development, prioritizing deployment of seven renewable hydrogen production projects, with aggregate capacity at 42.3 kt/year.

In July 2021, the provincial energy bureau released a draft hydrogen policy for public consultation, targeting 500 kt/year of renewable hydrogen production capacity and commercialization of hydrogen-based steelmaking and chemical manufacturing by 2025. In March 2022, Inner Mongolia's 14th FYP on Energy and Opinions on Promoting the High-Quality Development of the Hydrogen Industry reiterated the above targets on renewable hydrogen production, by-product hydrogen utilization and hydrogen-based energy storage. In addition to the projects listed in Annex A, 13 other projects are under development.

For Hebei province, all the nine existing projects are located in Zhangjiakou, a city in the northwest of the province where wind energy resources are abundant. 180 kilometres away from Beijing and site of winter sports venues, Zhangjiakou takes advantage of its proximity to Beijing and its position as one of the three competition zones for the 2022 Beijing Winter Olympic Games. Renewable hydrogen contributed to a zero-carbon Olympic Games as the primary fuel for dedicated buses. The preparation of renewable hydrogen projects in Zhangjiakou commenced as early as 2016 with strong support from the local government, state-owned enterprises (SOEs) and multinational companies.

Among China's the renewable hydrogen production demonstration projects, four are operational. The largest is Baofeng Energy's renewable hydrogen project in Ningxia province. With 200 MW solar PV commissioned in April 2021 to feed 30 MW alkaline electrolysers in Phase One, the project has an annual renewable hydrogen output of about 240 million m3 with a utilization rate at 46%. The hydrogen feeds Baofeng's coal chemical facilities for olefin production, reducing coal consumption by about 320 kt per year, or the equivalent of 560 kt of CO_2 emissions abatement on an annual basis. Baofeng's renewable hydrogen project currently relies on the power grid as a backup for its dedicated solar power, it is legitimate to question how green the project really is. To address the above concern, Baofeng plans to expand its renewable hydrogen production capacity by 300 million m3 a year, supplemented with configuration of on-site energy storage.

Sinopec, Asia's biggest petroleum refiner and a major Chinese central government-owned SOE, in November 2021 launched a 20 kt/year solar-to-hydrogen pilot project equipped with hydrogen pipelines and storage facilities. The project is expected to be commissioned in June 2023 and replace an existing natural gas-based hydrogen stream in Sinopec's Tahe Refinery, leading to 485 kt/year of CO_2 emissions reduction on an annual basis.

1.4.2 Mismatch between supply and demand of renewable hydrogen

As shown in Figure 5, sites of renewable hydrogen production are concentrated in China's far west, north and northeast. However, China's economic centres, including most hydrogen consumption, are clustered along the coastal provinces in the east and southeast. Guangdong province, China's largest provincial economy, hosts one of China's hydrogen FCEV city clusters as well as the Baowu's Hydrogen Metallurgy Test Site. While Guangdong has potential for renewable hydrogen consumption, it is nevertheless far from China's most promising sites for renewable hydrogen production. This mismatch resembles the situation with China's coal value chain, where production concentrates in North China and West China, with demand centres in coastal provinces.

Two potential solutions could help address this divergence: First, relocating large end-users closer to production sites, which would also bring economic benefits to less developed projects, in line with the central government's intention to stimulate economic development in inland regions. Second, planning and construction of long-distance power transmission or renewable hydrogen grid infrastructure could help link renewable production with large existing hydrogen consumers. In practice, both pathways are likely applicable, depending on the situation. Given the magnitude of the implied investment, hydrogen producers, consumers, and local government authorities should work together to identify the most appropriate strategy through cost-benefit analysis, considering costs of relocating facilities, freight rates, and construction costs associated with either high voltage transmission lines or long-distance hydrogen pipelines.

2 No-regret: hydrogen's role in China's industrial decarbonization

Direct CO2 emission from the Chinese industrial sectors (iron and steel, cement, petro-chemicals, industrial heating, industrial boilers and building materials) reached 5.2 billion tons (Gt) in 2020, accounting for about half of China's total emissions and outweighing those from the power sector. [7] Steel and cement are the top two carbon emitting industrial sub-sectors, respectively accounting for 1.6 Gt and 1.1 Gt of annual CO2 emissions, or 15% and 11% of the national total. In December 2021, China released its 14th FYP for Raw Material Industries Development, highlighting an integrated development strategy for raw materials sectors including steel, chemicals, and cement. In decarbonizing these carbon-intensive sectors, what roles could hydrogen play and which roles are essential?

2.1 Renewable hydrogen application scenarios

Figure 6. Renewable hydrogen application scenarios in China

Renewable hydrogen application sectors	No-regret	Debatable	Bad idea
Industry	• Reaction agents (DRI steel) • Feedstock (ammonia, chemicals)	• High-temperature heat	• Low-temperature heat
Transport	• Long-haul aviation • Maritime shipping	• Commercial vehicles with ports and industry clusters • Short-haul aviation and shipping • Long-haul heavy-duty trucking • Trains (depending on distance, frequency and energy supply options)	• Passenger cars • Light-duty vehicles
Power	• Renewable energy back-up (seasonal demand)	• Absolute size of need given other flexibility and storage options	
Buildings		• Heating grids	• Building level heating

Source: Adapted from Agora Energiewende (2021)

As an energy carrier, hydrogen suffers from a relatively large efficiency loss during various conversion processes. For example, compared with battery electric vehicles' end-use energy efficiency of around 73%, a similar index of hydrogen FCEVs is only about 22%.[8] Therefore, before investment to ramp up renewable hydrogen supply across China, it is necessary to first identify the most promising areas, known as no-regret options, for hydrogen utilization. As shown in Figure 5, Agora Energiewende (2021) has identified such options, taking into consideration China's unique national circumstances.

[7] Source: " 网易研究局碳中和报告 [NetEase Research Institute Carbon Neutrality Report]," NetEase Research Institute, August 2021.
[8] Source: Transport & Environment, "Cars: battery electric most efficient by far," 2017, accessed on 3 November 2022 at https://insideevs.com/news/332584/efficiency-compared-battery-electric-73-hydrogen-22-ice-13/.

2.2 No-regret utilization of renewable hydrogen in industrial processes

In contrast to deployment of renewable hydrogen in carbon-intensive industrial processes—often considered as a no-regret choice where no better alternative to hydrogen would be available—utilization of hydrogen for heating is debatable. China has sufficient potential for direct electrification in China and a number of power to heat options could be deployed to meet industrial heat demand, whether for low- or high-temperature applications. For low-temperature heating, using renewable hydrogen from electrolysis results in substantial efficiency loss due to multiple energy conversions. For high-temperature heating, solid oxide fuel cell (SOFC) technology has some market potential over the next few decades, though this will depend on technological progress.

Compared with the power and transport sectors, China's industrial sectors, especially iron and steel manufacturing, are much more carbon-intensive. In addition, these sectors have fewer options to mitigate process-related emissions, and thus have significant potential for hydrogen consumption, such as in the case of hydrogen metallurgy. The pilot hydrogen direct-reduction iron (DRI) plant under construction by HBIS is designed with an annual steel capacity of 1.2 Mt, the equivalent of about 64.8 kt/year of renewable hydrogen demand. This single demonstration project alone would consume more than China's total hydrogen output via electrolysis in 2020. Under an optimistic scenario, China's DRI-based crude steel output by renewable hydrogen is projected to reach 124.2 Mt by 2050,[9] or the equivalent of about 6.7 Mt/year of renewable hydrogen demand.

Last but not least, industrial sectors normally require consistent and stable supply of hydrogen to ensure smooth manufacturing operations. If the stock of fossil fuel-based hydrogen is to be replaced with its green counterpart, an additional challenge is to compensate for the variability of renewables with either energy storage or grid power. Thus, planners of renewable hydrogen projects have to evaluate the cost-effectiveness of storage and the environmental sustainability of the grid.

[9] Source: Ji Chen et al.,"Pursuing Zero Carbon Steel in China," RMI.

3 Germany’s national hydrogen strategy and implications for China

Government policies play a vital role in supporting any emerging industry. As more countries set mid-century net-zero commitments, several advanced economies have issued national hydrogen strategies, with the twin goals of decarbonizing carbon-intensive sectors while also capturing industrial development opportunities in the new hydrogen supply chain. In June 2020, Germany released its National Hydrogen Strategy with a coherent framework supported by 38 specific measures to ramp up renewable hydrogen in areas of production, consumption, transport, infrastructure, and research. In addition, the strategy incorporates €9 billion in government funding to leverage private investment and nurture a future renewable hydrogen value chain.

3.1 German hydrogen policy tools and dedicated governance

Figure 7. German national hydrogen strategy summary

Source: The National Hydrogen Strategy (Germany)

According to the National Hydrogen Strategy, Germany aims to tap hydrogen's significant potential in achieving its ambitious climate targets, create new value chains and foster international energy cooperation. Its goals include establishing renewable hydrogen as an energy carrier and as a sustainable feedstock material for the industrial sector, improving the competitiveness of renewable hydrogen, developing the market for hydrogen technology, enhancing the hydrogen transportation and distribution infrastructure, and promoting international markets and cooperation on hydrogen. To realize the above goals, Germany focuses its efforts on four strategic areas: hydrogen production, industrial consumption, transportation, and heating. (Germany's supporting measures are shown in Figure 7.)

3.1.1 Structured governance and the policy environment

The German federal government has created a State Secretaries' Committee on Hydrogen, National Hydrogen Council, and Hydrogen Coordination Office to monitor the implementation of the strategy and its improvements. Each of the three bodies has its own roles and reports to different authorities in ensuring the implementation of the national hydrogen strategy. The State Secretaries' Committee on Hydrogen is composed of relevant ministries and conducts strategic management by setting targets and objectives, and developing an action plan. To ensure the strategy aligns with market trends and delivers on its overall targets, the Committee will work with the Federal Cabinet to adapt the action plan to new requirements, and in case of implementation delays or a failure to meet the targets.

The National Hydrogen Council is a group of 26 high-level experts appointed by the government. Unlike the Committee, Council members are selected from business, science, and civil society for their expertise in production, research and innovation, industry decarbonisation, transport and building/heating, infrastructure, international partnerships, as well as climate and sustainability. The Council advises the State Secretaries' Committee and makes recommendations for action, providing specialist support as needed.

The Hydrogen Coordination Office assists the implementing of the Strategy, drafts recommendations for action, monitors the National Hydrogen Strategy and provides a flexible project management structure. This office delivers an annual monitoring report that summarizes the overall progress on the hydrogen economy, alerts policy makers to unexpected challenges and identifies necessary next steps. It is jointly operated by the German Energy Agency (Deutsche Energie-Agentur GmbH, dena), Programme Hydrogen and Fuel Cell Technology (NIP) at NOW GmbH, a project management agency called Project Management Jülich (PtJ), and a federally-owned company called Zukunft–Umwelt–Gesellschaft (ZUG) gGmbH, which manages funding projects on behalf of Federal Environment Ministry.

3.1.2 Making renewable hydrogen economically viable

In early 2022, the cost of renewable hydrogen was more than three times that of fossil fuel-based hydrogen due to the cost of renewable electricity, low electrolyser utilization when paired with renewables, and electrolyzer system costs.[10] To bring the cost of renewable hydrogen down, Germany has introduced the following measures:

- exempting Renewable Energy Sources Act (EEG) surcharges from its electricity consumption;
- introducing additional CO2 pricing for fossil fuels;
- funded investments into electrolyzers to encourage the switchover to renewable hydrogen in the industrial sector;
- exploring new business and cooperation models for electrolyzer and grid/gas network operators; and
- designating additional areas for offshore production of renewable hydrogen or its derivatives.

Moreover, the German federal government acknowledges that domestic supply is unlikely to meet its future renewable hydrogen demand for energy transition. Apart from boosting domestic production, the government is taking proactive measures to foster international cooperation and economic partnerships on renewable hydrogen. Germany plans to develop a sustainable import of hydrogen-based fuels and nurture markets for German hydrogen technologies based on its existing energy partnerships. Against the backdrop of the ongoing Russian-Ukrainian War, the EU is planning to produce 10 Mt of renewable hydrogen within its administrative boundary and import another 10 Mt by 2030, which is expected to further boost the momentum of renewable hydrogen development in Germany.

3.1.3 Promoting hydrogen applications in key downstream sectors

As indicated in Figure 6, Germany's National Hydrogen Strategy prioritizes downstream hydrogen utilization, as reliable demand and widespread use of hydrogen could drive the hydrogen market towards economies of scale. To promote the application of renewable hydrogen in industry, the German government is considering a demand quota for climate-friendly material inputs, including green steel, to encourage a broader market for climate-neutral and recycled products. The German Immediate Climate Action Programme for 2022 set out product quotas for carbon-efficient products and funding to cover the additional costs to create green lead markets.

To ensure industrial competitiveness abroad, Germany has decided against measures to pass the full cost of investment in zero-carbon technologies to the customer. Instead, Germany plans to reward the substitution of fossil fuel-based technologies via novel industrial processes that use renewable hydrogen as either fuel or feedstock. The steel and chemical industries are especially important in this regard. The German government provides funds for "Decarbonising the Industrial Sector" and the programmes for "Hydrogen Use in Industrial Production (2020-2024)" and "Avoiding and Using CO2 in Industries Relying on Base Substances." Moreover, the government has launched a pilot programme entitled "Carbon Contracts for Difference (CCfD)" under the EU framework, primarily targeting process-related emissions in steel and chemical manufacturing. Through CCfDs, governments can compensate for costs for projects related to deploying low-carbon technologies if they are not fully compensated by EU ETS. The purpose is to nurture a

[10] Source: Agora, 2021 (Matthias Deutsch)

reliable investment environment for renewable hydrogen application and scale up breakthrough hydrogen technologies.

To promote hydrogen as an alternative fuel for transport, especially for long-haul heavy-duty vehicles, one of the main measures taken by the German federal government is granting €3.4 billion to build out refuelling and charging infrastructure. In addition, the funding for highly-efficient fuel-cell heating systems is to be expanded: by 2024, up to €700 million from German's Energy Efficiency Incentive Programme and the future Federal Compensation Act have been planned for funding fuel-cell heating systems.

3.1.4 Implications of EU Carbon Boarder Adjustment Mechanism (CBAM) and Climate Club

As an EU member state, Germany acts in accordance with the overall EU climate goals and is an important contributor to EU climate agenda including the EU emission trading system (ETS). Established in 2005, the EU ETS is the world's first international emissions trading system. Since then, it has resulted in 37% emissions reduction by 2021 in sectors including power and heat generation, energy-intensive industries, and aviation within Europe.[11] The EU ETS has established greenhouse gas (GHG) emission allowances (EU allowances, EUA) issued to companies, a market mechanism for trading the allowances and a cap on the total emission for each calendar year. It gives CO2 a price and thus incentivises emission abatement.

Since its inception, a major challenge for the EU ETS has been how to combine meaningful incentives for emissions reductions via sufficiently high carbon prices while avoiding the risk of companies shifting production and emissions offshore, known as "carbon leakage." To avoid carbon leakage and encourage industry outside the EU to take parallel steps on carbon abatement, on 14 July 2021 the EU Commission presented the proposal for a Carbon Border Adjustment Mechanism (CBAM), targeting direct emissions from imports of carbon-intensive products including electricity, iron and steel, cement, aluminium, and fertilisers, with the objective to equalise the prices between EU products and imports.

On 22 June 2022, the European Parliament adopted the carbon legislation package including the new CBAM and the revision of the EU ETS. The new version of CBAM will be extended to cover indirect emissions and a wider range of products (organic chemicals, plastics, hydrogen, and ammonia) but postpones the phase-in to 2027. To emphasise the coherence between the EU ETS and CBAM and avoid double protection for domestic industry, starting from 2032 when the CBAM is fully implemented, free emission allowances granted to the industries covered by the EU ETS should also be fully phased out.

As the world's largest exporting country, China is naturally concerned about any unilateral move by its trading partner that may negatively affect the economic competitiveness of Chinese products and services in the international market. China exports more manufactured goods and services to the EU than any other country.[12] The unilateral introduction of the EU CBAM has thus raised concerns among Chinese policy makers.

In addition to the CBAM, the EU aims for greater international cooperation with third countries and seeks to establish a climate club for the discussion and promotion of carbon pricing policies. In June 2022, the Group of Seven (G7) under the German Presidency released the G7 Statement on Climate Club, announcing a plan to establish an intergovernmental forum in 2022 to enhance the effective implementation of the Paris Agreement while complying with international rules.

The Climate Club's goals are threefold: 1) advancing ambitious and transparent climate mitigation policies, strengthening emissions measurement and reporting mechanisms, and countering carbon leakage at the international level; 2) transforming industries jointly to accelerate decarbonization, with a focus on carbon leakage risks for emission intensive industrial goods; and 3) boosting international climate ambition through partnerships and cooperation, leveraging Just Energy Transition Partnerships (JETPs) to support the decarbonization in developing countries. While the G7 Climate Club anticipates participation beyond the group, China is unlikely to become a member of the club.

[11] Source: "Total greenhouse gas emission trends and projections in Europe," European Environment Agency, accessed on 5 October 2022 at https://www.eea.europa.eu/ims/total-greenhouse-gas-emission-trends.

[12] Source: Kevin Tu, Oliver Sartor, Run Zhang-Class (2021): EU-China Roundtable on Carbon Border Adjustment Mechanism. Briefing of the first dialogue on 26 May 2021. Agora Energiewende: Berlin.

On 16 July 2021, China established its national ETS starting from the power sector. The nascent market in China results in an average carbon price that is about one tenth of the price level of EU ETS so far. The possible inclusion of indirect emissions in CBAM disadvantages Chinese exporters operating in a coal power-dominated economy, and pressures export-oriented Chinese manufacturers to take action, which could ultimately benefit development of renewable hydrogen. For example, China's annual steel direct export is around 64 Mt while indirect export is roughly 96 Mt.[13] The China Iron and Steel Association (CISA) shares the growing concerns of Chinese steel makers and jointly launched the Environmental Product Declaration (EPD) platform for steel together with Baowu on 19 May 2022. The EPD aims at adopting international carbon footprint standards for Chinese steel products based on life-cycle assessments (LCA).

3.2 China's national strategy for hydrogen

In March 2022, China released its long-awaited national hydrogen policy, the Medium- and Long-term Development Plan for Hydrogen (2021-2035), setting the tone for central government support of the hydrogen industry. This policy document represents China's national strategy for hydrogen, and it positions hydrogen as an important energy carrier that could contribute to optimization of China's energy mix, such as by serving as seasonal storage. It identifies hydrogen as a useful way to move the energy transition agenda forward, and also as a driver for economic development.

Compared with its German counterpart, China's hydrogen strategy lacks specific measures and only has a few quantitative indicators regarding targets, except for reaching 100-200 kt/year of renewable hydrogen production and a FCEV stock of 50,000 by 2025. However, as of today, the aggregate production capacity of 32 out of the 50 planned renewable hydrogen pilot projects across China exceeds 297 kt/year. The regional development policy of Inner Mongolia, China's second-largest coal-producing province in 2021, targets for renewable hydrogen production capacity to grow to 480 kt/year by 2025.

The conservative goals of China's national hydrogen strategy reflect the central government's lack of confidence in developing a self-reliant and cost-competitive renewable hydrogen value chain in the coming decade. In a more detailed policy document entitled the Implementation Plan for the Development of New Energy Storage in the 14th FYP period, the central government calls for technology breakthroughs and equipment upgrading in hydrogen- and ammonia-related energy storage.

Based on a comparison of the Chinese and German hydrogen strategies, we suggest that China consider the following options for improving its regulatory environment in support of renewable hydrogen development.

3.2.1 Improved coordination of hydrogen value chain governance

At the Chinese central government level, hydrogen governance is fragmented among different authorities. For example, though the National Energy Administration (NEA) under the National Development and Reform Commission (NDRC) regulates hydrogen in the energy sector, hydrogen-related standardization is largely the responsibility of State Administration for Market Regulation. Meanwhile, as renewable hydrogen consumption in industrial sectors takes off, Ministry of Industry and Information Technology (MIIT) is expected to have more say in its governance. In addition, while climate change is currently covered by China's Ministry of Ecology and Environment (MEE) and the Ministry of Science and Technology (MOST) is in charge of sponsoring technological research, these two ministries are also key stakeholders. For further detail, please refer to Annex B: List of selected key stakeholders for hydrogen governance in China.

While coordination among government agencies is a common challenge in any country, the German hydro-

[13] Source: "World Steel in Figures 2022," World Steel Association, 2022.

gen governance mechanism serves as a good reference for comparison. Establishing a hydrogen council (or a working group) under the State Council of China would represent a sensible approach to create synergies among relevant ministries, with great potential to establish an integrated regulatory framework in support of hydrogen development in China.

3.2.2 Detailed supporting policies yet to be promulgated

The Chinese style of policy making often consists of a flagship policy document outlining main targets without much elaboration on how they will be achieved. Specific supporting policy documents with detailed measures thus need to be issued to implement these flagship documents at the sectoral or regional levels. The 1+N policy framework for carbon peaking and carbon neutrality mentioned in Chapter 1 is a good example in this regard. China's national hydrogen strategy still waiting for additional supporting policies.

How fast the detailed supporting policies are released depends on its economic or political relevance with either a specific sector or region. Shortly after China's national hydrogen strategy was published in March 2022, Daxing District of Beijing updated its Promotion Plan for the Hydrogen Industry, with emphasis on hydrogen utilization in transport. The update offers subsidies in areas of fuel cell parts manufacturing, technology innovations, and FCEV procurement.

The inclusion of hydrogen demonstration in supporting policy documents has helped investment flow into government-targeted pilot projects, but the above ad hoc approach is insufficient to nurture a well-functioning renewable hydrogen value chain at scale. China should urgently advance its hydrogen development agenda with an integrated and coordinated supporting policy package at both the sectoral and regional levels.

3.2.3 The need to emphasize hydrogen's role in industrial decarbonization

Through sector coupling or PtX, renewable hydrogen makes deep decarbonization possible even in the most carbon-intensive industrial sectors. Both SOEs and private companies in China have started pilot projects that integrate upstream renewable hydrogen production from renewables with downstream hydrogen utilization. For example, both state-owned Sinopec and Baofeng (a private company) have pilot projects that cover the entire renewable hydrogen value chain from production, transport, storage to end use. However, these two cases are not necessarily replicable, given the deep pockets of these two companies and their senior management's high motivation to improve their corporate image.

To foster the hydrogen economy, the Chinese government should introduce a mechanism that coordinates upstream production, downstream consumption and mid-stream transport when necessary. For example, the Chinese government could play an important role in encouraging renewable hydrogen production from excess renewable output and also in building no-regrets infrastructure for hydrogen transport.[14]

According to China Hydrogen Alliance, 60% of China's national hydrogen demand in 2060 is projected to be consumed by the industrial sector, followed by 31% in transport, and less than 1% by the power sector. In contrast, current policy incentives in transport and power currently exceed those for industrial use. Given the introduction of the EU CBAM, hydrogen's role in industrial decarbonization should be promoted and supported with concrete policy and monetary instruments. To nurture early hydrogen application in the industrial sector, China could learn from German practices, especially policies related to green steel, CCfD, and demand quotas for climate-friendly base materials.

[14] Source: Agora Energiewende (2021) No-regret hydrogen: Charting early steps for H2 infrastructure in Europe.

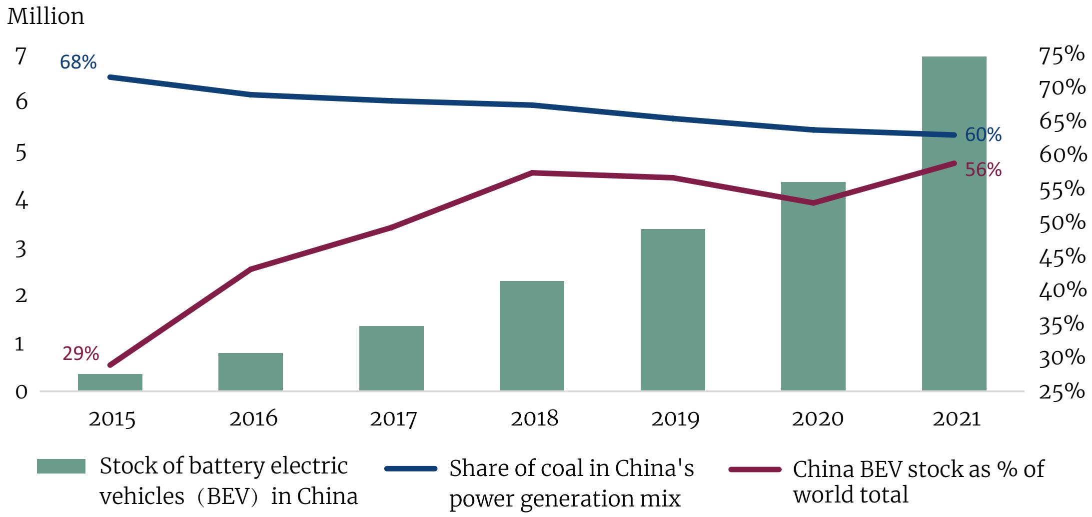
4 Experience and lessons of China’s EV program

China could also benefit from drawing on lessons from EV policy to boost the infant renewable hydrogen economy. EVs were first introduced in the 2000s to reduce China's heavy reliance on oil import and alleviate widespread air pollution. This policy faced criticism, given the role of coal in China's power mix, but policy makers persistently pursued EVs as an economic development strategy and as an alternative to fossil fuel-burning internal-combustion engine vehicles.

Today, EVs have become an important pillar in transport decarbonization and China has grown into the world's largest EV market with 3.4 million sold in 2021 alone, accounting for more than half of global total. [15] According to China Association of Automobile Manufacturers, China's cumulative EV sales reached 5.28 million during the first 10 months of 2022, with annual sales projected to double the 2021 level.

4.1 Separation of upstream power production and downstream EV deployment

Figure 8. Share of coal power in China's power mix and rising deployment of battery EVs in China, 2015-2021



Source: IEA and Chinese Ministry of Public Security

After MOST released the 12th Five-Year-Plan (2011-2015) for Developing EV Technologies in 2012, it took five years before China's cumulative EV stock exceeded one million. Nevertheless, China became the largest EV market in the world as early as 2014 and retained this title ever since. China has also become the largest clean energy market in the world, and coal power's share in China's national power mix keeps declining, leading to synergies with rapidly rising EV deployment. Since 2015, coal power's share in national power mix has declined by almost eight percentage points, making EVs more effective in lowering emissions. Since China introduced the dual carbon goals in September 2020, not only has EV deployment received a major policy boost, but decarbonization of the Chinese power sector has gained political momentum.

In retrospect, separating downstream EV deployment from upstream power decarbonization during the infant stage of the EV industry turned out to be a reasonable political decision. Likewise, decarbonizing China's present carbon-intensive hydrogen production should not constrain hydrogen deployment in downstream sectors at the present, early stages of large-scale hydrogen application. Given the phased approach of the dual carbon goals, scaling up renewable hydrogen production in China should go hand-in-hand with fostering downstream utilization, aiming at creating synergy that resembles the development of the Chinese EV industry.

[15] Source: "Global EV Outlook," IEA, 2022.

4.2 Avoiding fraud and promoting fair competition

Since 2009, China's support for developing the EV industry came with generous subsidies provided by both central and local governments, leading to some 500 EV manufacturers across the country. In 2016, an investigation into 93 carmakers revealed that 33 were involved in subsidy fraud totalling ¥9.2 billion. Consequently, the Chinese Ministry of Finance tightened the rules governing EV subsidies, introducing new minimum range and efficiency requirements and rules for post-payment monitoring. Another lesson from the early stages of EV subsidies is that local governments in major regional car markets sought to create protected markets for local manufacturers, preventing the establishment of nationally- or globally-competitive players with attractive products that could scale to become a truly national EV market. Without fair competition to stimulate innovation, for years Chinese EV manufacturers lagged behind international counterparts in terms of technology and quality, despite China becoming the largest EV market in the world. Winnowing the number of EV players and reforming subsidies largely resolved this problem.

Following the release of China's hydrogen strategy, some local governments in pilot regions have announced monetary incentives for hydrogen technology R&D, technology transfer, and fuel cell equipment procurement. For example, the Daxing District Promotion Plan for the Hydrogen Industry includes a clause for monitoring and supervision, specifying that entities violating the rules must return the subsidies and be disqualified for the following three years. However, details on how the monitoring will be carried out are still unclear. If the central government decides to subsidize renewable hydrogen at scale, policy package should be carefully designed from the beginning, with effective supervision measures to avoid widespread fraud, foster a competitive national market with a level playing field, and encourage technological innovation.

5 Policy recommendations

With the goal of achieving climate neutrality by 2045, and in the context of heightened energy security concerns caused by the ongoing Russian-Ukrainian War, Germany is accelerating its renewable hydrogen policies to advance the ongoing energy transition. This is illustrated by Germany's announcement at COP27 of plans to invest more than €4 billion into the government-funded foundation H2Global—an amount that dwarfs even the EU initiative. By comparison, following the September 2021 power crunch in China coupled with the subsequent European energy crisis, China is also seeking to better balance the short-term challenge of energy supply security and longer-term climate ambition, shown by the delayed release China's 14th FYP for the power sector.

Both Germany and China have a rich history of coal mining and steel manufacturing, and they are also global manufacturing powerhouses that face common but differentiated challenges in decarbonizing heavy industry especially iron and steel, chemicals and cement. In this regard, whether these two countries can work together on the clean energy transition will have policy ramifications beyond their respective national borders.

As Germany is a leading economy with ambitious climate agenda, the country's experience and lessons related to renewable hydrogen economy can benefit China in fostering its infant hydrogen supply chain. With this in mind, we have drafted the following policy suggestions for China:

1. **China should not only take advantage of its sizable fossil fuel-based hydrogen production facilities to establish an industrial-scale hydrogen supply chain, but also incentivise new renewable hydrogen capacity additions**. As with the country's largely successful EV program, downstream utilization of hydrogen should be separated from cleaning up carbon-intensive upstream production before the value chain is established. Meanwhile, given the rapid expansion of coal-fired power capacity during the past decade, China should strive to avoid further growing its already sizable fossil fuel-based hydrogen capacity. Scaling up renewable hydrogen production may go hand-in-hand with fostering hydrogen end uses, thus creating synergy between upstream and downstream segments of the hydrogen value chain.
2. **Hydrogen should be increasingly regulated as an energy carrier**. Currently, hydrogen is still labelled and regulated as a hazardous chemical in China without consideration of its energy utilization potential. This unique policy poses severe challenges for siting production facilities, road transportation, qualification of new entrants, end-use application as well as standardization. A rapid adjustment of the above label requirements is a prerequisite to scaling up hydrogen deployment in China.
3. **Renewable hydrogen's role in deep industrial decarbonization should be prioritized, especially in iron and steel, petrochemical, and coal chemical manufacturing**. Given the enormous potential of renewable hydrogen utilization in heavy industries, industrial decarbonization should become the focus of scaling up the renewable hydrogen supply chain in China. Apart from covering industrial sectors into the national carbon emissions trading system, innovative policy and financial policy instruments with European/German characteristics, especially green steel procurement, CCfD and demand quota for climate-friendly raw materials, should be considered in the Chinese context.
4. **A high-level inter-department coordination mechanism should be established to move China's hydrogen development agenda forward, ideally under the State Council**. Otherwise, continuous fragmentation of hydrogen governance among various authorities is likely to hinder hydrogen development in China. An investigation into the necessity and planning of no-regret cross-province hydrogen grid infrastructure could be carried out by the proposed governance body, with potential to tackle the geographical mismatch between hydrogen production and consumption in China.
5. **Hydrogen-related subsidies by both central and local governments should be carefully designed and monitored to avoid fraud and promote fair competition**. Based on lessons learned in past subsidy programs, especially those in the EV field, checks and balances should be incorporated as an intrinsic feature of China's hydrogen regulatory framework.
6. To close the gap with advanced economies on key hydrogen technologies, **China should consider how to foster a level playing field for all market players, including both international and Chinese companies**. If China could strengthen IP protection and eliminate market barriers, the country would be better positioned to deepen its international cooperation on the hydrogen economy with advanced economies, with potential to attract EU especially German companies for win-win technological collaboration and business investment.

Annex A A list of renewable hydrogen projects in China

	Project name	Ownership/Partnership	City	Province	Estimated H_2 Production Capacity (tons/year)*	Renewable Energy Source	Time of commissioning *
1	Bolken Energy 100MW Solar PV Hydrogen Production Project	Beijing Bolken Energy Technology, Suixi Government	Suixi	Anhui	10786	Solar	N/A
2	Yanqing Renewable Energy Hydrogen Production Project	State Power Investment Corporation (SPIC)	Beijing	Beijing	980	Wind, Solar and Hydro	Feb-2022
3	Liquid Solar Fuel Synthesis Demonstration Project	China National Chemical Engineering Group Corporation, Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, Lanzhou New Area Petrochemical Industry Investment	Lanzhou	Gansu	126	Solar	Oct-2020
4	Yumen Oilfield 160 MW Renewables Hydrogen Production Demonstration Project	China National Petroleum Corporation (CNPC) Yumen Oil Province	Jiuquan	Gansu	7000	Solar	2023
5	Zhangjiakou Green Hydrogen Energy Integration Demonstration Base Project	Shell, Zhangjiakou City Transportation Construction Investment Holding Group	Zhangjiakou	Hebei	2800	Wind	Jan-2022
6	HCIG Guyuan Wind Power Hydrogen Production Demonstration Project	Hebei Construction and Investment Group (HCIG)	Zhangjiakou	Hebei	2517	Wind	Before 2021
7	Zhonghuan Zhangjiakou Integrated Wind and Solar Hydrogen Production Demonstration Project	Zhonghuan Energy (Inner Mongolia), Hebei Qixin Investment and Management	Zhangjiakou	Hebei	N/A	Wind and Solar	Jun-2016
8	Zhangjiakou Shangyi Integrated Wind and Solar Hydrogen Production Technology Demonstration Project	Guodian Power Hebei New Energy Development	Zhangjiakou	Hebei	2696	Wind and Solar	N/A
9	HCIG Wind to Hydrogen Project (Chongli)	HCIG	Zhangjiakou	Hebei	313	Wind	Early 2022
10	Guohua Hebei Chicheng Wind-Hydrogen-Storage Multi-energy Complementary Demonstration Project (Hydrogen Production Phase I)	CEIC Guohua Chicheng Wind Power	Zhangjiakou	Hebei	14381	Wind	N/A
11	Zhongzhi Tiangong Wind and Solar Power Generation and Utilization (Hydrogen Production) Demonstration Project	Zhongzhi Tiangong	Zhangjiakou	Hebei	8000	Both Wind and Solar	Dec-2022
12	Large-scale Wind/Solar Complementary Hydrogen Production Key Technology Research Project	China Energy Investment Corporation (CEIC)	Zhangjiakou	Hebei	N/A	Both Wind and Solar	2021

13	Zhangjiakou Harper Hydrogen Production and Refilling Project	Shandong Binhua Hydrogen, Beijing Sinohytec, Air Products China	Zhangjiakou	Hebei	1400	Wind	Sep-2020
14	Wind, Solar and Hydrogen Storage Clean Energy Base	Longmay Mining Group, Beijing Enterprises Clean Energy Group	(Multiple cities)	Heilongjiang	N/A	Wind and Solar	N/A
15	Wind, Solar and Hydrogen Storage Integrated Project	CEIC, Tongjian Government	Tongjiang	Heilongjiang	N/A	Wind and Solar	N/A
16	Huaneng Daqing Wind, Solar and Hydrogen Energy Storage Demonstration Project	Huaneng East Inner Mongolia, Daqing Government	Daqing	Heilongjiang	N/A	Wind and Solar	N/A
17	Zhongyuan Oilfield Incremental Power Distribution Network Wind to Hydrogen Demonstration Project	Puyang Xinxing Clean Energy	Puyang	Henan	3667	Wind	Dec-2022
18	Henan Pingmei Shenma Group Kaifeng Dongda Chemical 16 MW Solar to Hydrogen Demonstration Project	China Pingmei Shenma Group Kaifeng Dongda Chemical	Kaifeng	Henan	2157	Solar	Jun-2023
19	Huajiu Rooftop Solar PV Power to Hydrogen Project	Huajiu Hydrogen Energy (Henan)	Luoyang	Henan	153	Solar	Nov-2023
20	Hongnijing Million Kilowatt Clean Energy Base Project	CEIC Guodian Inner Mongolia New Energy, Baotou Government	Baotou	Inner Mongolia	N/A	Wind and Solar	N/A
21	Beijing Energy 5000MW Wind and Hydrogen Storage Integrated Project	Beijing Energy Holding	Ordos	Inner Mongolia	N/A	Wind and Solar	2021
22	Sinopec Ordos Green Power Hydrogen Production Project	Sinopec	Ordos	Inner Mongolia	10000	Wind and Solar	Jun-2023
23	Narisong Solar to Hydrogen Industrial Demonstration Project	Hanxia New Energy	Ordos	Inner Mongolia	10000	Solar	Jun-2023
24	Solar-Storage-Hydrogen-Vehicles Zero-Carbon Ecological Chain Demonstration Project	China Hydrogen	Ordos	Inner Mongolia	9300	Solar	Jun-2023
25	250 MW Solar PV Power Station and Hydrogen Comprehensive Utilisation Demonstration Project	Beijing Energy Holding	Ordos	Inner Mongolia	6000	Solar	Jun-2023
26	Shanghaimiao Economic Development Zone Solar PV Hydrogen Production Project	Shenzhen Energy Northern Energy	Ordos	Inner Mongolia	6000	Solar	Jun-2023
27	Shengyuan Zhengneng Solar PV Hydrogen Production Integrated Project Phase 1	Shengyuan Energy; Inner Mongolia ZhengNeng Chemical Industry Group	Ordos	Inner Mongolia	500	Solar	Sep-2022
28	Shengyuan Energy Solar PV Hydrogen Production Integrated Project Phase 1	Shengyuan Energy	Ordos	Inner Mongolia	500	Solar	Sep-2022

29	Taihe County Nanxi Distributed Wind Power Project	SPIC Jiangxi Jian New Energy	Jian	Jiangxi	N/A	Wind	N/A
30	Baicheng City Wind and Solar Integrated Hydrogen Production and Refilling Demonstration Project	SPIC Jilin Electric Power, Xinjiang Goldwind Science Technology, China State Shipbuilding Corporation, Baicheng Government	Baicheng	Jilin	3883	Both Wind and Solar	Oct-2021
31	Yushu Government and Sungrow Wind Power and Hydrogen Production Integrated Demonstration Project	Sungrow Power Supply, Yushu Government	Yushu	Jilin	6667	Wind	N/A
32	Sungrow 1GW Wind and Solar Hydrogen Production and Storage Project	Sungrow Power Supply, Baicheng Government	Baicheng	Jilin	133340	Wind and Solar	N/A
33	Northern Hydrogen Valley Landscape Hydrogen Production Pilot Project	Sungrow Power Supply, Baicheng Government	Baicheng	Jilin	5000	Wind and Solar	N/A
34	Jilin Changling Longfenghu 200 MW Hydrogen Production Demonstration Project	Changling County Changrun Wind Power	Songyuan	Jilin	5393	Wind	2022
35	Beijing Energy Ningdong Power Generation Hydrogen Production, Storage and Refilling Project	Beijing Energy Holding, China Allumium Ningxia Energy Group	Yinchuan	Ningxia	183	Solar	N/A
36	National Comprehensive Demonstration Project for Hydrogen Production by Solar Water Electrolysis by Baofeng Energy	Baofeng Energy	Yinchuan	Ningxia	21571	Solar	Apr-2021
37	SPIC Ningdong Renewable Energy Hydrogen Production Project	SPIC	Ningdong Industrial Zone	Ningxia	536	Solar	Jun-2021
38	Wind, Solar, Hydrogen and Energy Storage Integrated Project	China Three Gorges Renewables, Fugu County Government	Yulin	Shaanxi	N/A	Wind and Solar	N/A
39	Rooftop Solar and Hydrogen Storage Comprehensive Application Project	CEIC Shaanxi Power, Qindu District Government	Xianyang	Shaanxi	N/A	Solar	N/A
40	Weifang Binhai 100MW Solar PV Hydrogen Production Project	Huadian Weifang, Shenzhen Kohodo	Weifang	Shandong	N/A	Solar	Jun-2022
41	Yellow Sea Project	Qingdao Blue Valley Industrial Development Zone, Shandong Zhongneng Integration Offshore Wind Turbine, PowerChina Northwest Engineering Corporation	Qingdao	Shandong	N/A	Wind	N/A
42	Shanxi Yushe County 300MW Photovoltaic and 50MW Hydrogen Production Demonstration Project	Sungrow Power Supply, Yushe County Government	Jinzhong	Shanxi	N/A	Solar	N/A

43	Shanxi Changzhi Liutun District 500MW Photovoltaic Hydrogen Production Project	Sungrow Power Supply	Changzhi	Shanxi	N/A	Solar	Sep-2020
44	Shanxi Hydrogen Storage and Energy Complementary Project	Datong Youyun, China Datang Corporation	Datong	Shanxi	1750	Wind and Solar	N/A
45	China Datang 6MW Hydrogen Production Technology Demonstration Project	China Datang Corporation	Datong	Shanxi	N/A	Solar	N/A
46	Sungrow Yuncheng Photovoltaic Hydrogen Production Project	Sungrow Power Supply	Yuncheng	Shanxi	N/A	Solar	N/A
47	Shuifa Group 50MW Integrated Solar PV and Energy Storage Demonstration Project	Shuifa Group	Rikaze	Tibet	N/A	Solar	Dec-2020
48	Sinopec Xinjiang Kuche Green Hydrogen Demonstration Project	Sinopec	Kuche	Xinjiang	20000	Solar	Jun-2023
49	Panda Green New Energy Integrated Demonstration Project	Beijing Energy International, Manasi County Government	Changji	Xinjiang	N/A	Solar	N/A
50	Demonstration of Hydrogen Power Coupled DC Microgrid	State Grid of China	Ningbo	Zhejiang	35	Wind and Solar	Jun-2022

** Capacity and time of commissioning only refer to Phase 1 in case of multi-phased project.*

Annex B A list of selected key stakeholders for hydrogen governance in China

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 central 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, universi-ties, and etc.

Source: Kevin TU, "Prospects of A Hydrogen Economy with Chinese Characteristics," Ifri, accessed on 18 September 2021 at https://www.ifri.org/en/publications/etudes-de-lifri/prospects-hydrogen-economy-chinese-characteristics.

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