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China's hydrogen development: A tale of three cities

CHINA

ENERGY TRANSITION

OIES PAPER: CE5

Dr Arabella Miller-Wang, OIES-Aramco Fellow

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Introduction

China is the world's largest producer and consumer of hydrogen[1] and has adopted a domestic strategy that targets significant growth in hydrogen consumption and production. Given the importance of hydrogen in the low-carbon energy transition, it is critical to understand China's hydrogen policies and their implementation, as well as the extent to which these contribute to the country's low-carbon goals.

A number of recent studies have focused on policies and regulations to support hydrogen development in China, seeking to gain a better understanding of China's current and future hydrogen prospects.[2] They point to the fact that hydrogen development is as much an industrial strategy as a decarbonisation tool and that strong and concerted government support will allow China to forge ahead in developing a green hydrogen industry. That said, these studies also indicate that the various policy support mechanisms, while still embryonic, do not necessarily point to hydrogen-based decarbonisation.

This study aims to conduct more in-depth research and to improve our understanding of how China's hydrogen policies are being implemented by looking at the way in which three cities are adapting the national framework to their own hydrogen strategies. It discusses the motivations for developing hydrogen and the extent to which these align with the national commitment to peak emissions before 2030 and reach carbon neutrality by 2060—known as the 2030–2060 Dual Carbon goals (or 30–60 targets). It points out that cities, while following the central government mandate, are also forging ahead and building momentum, although this may potentially lead to uncoordinated investments and growth.

The paper examines the three cities of Zhangjiakou (in China's renewable-rich Hebei province), Datong (in the country's coal-heartland of Shanxi province), and Chengdu, which is rich in hydropower and natural gas. The paper begins with a brief overview of national hydrogen policies before turning to the cities. Each section then discusses the drivers for hydrogen development in the city, the policy support it receives from the municipality and the province, as well as the challenges to its development. It argues that while local hydrogen policies and plans to date point towards potential future green hydrogen development, they do not lay out the specifics of how green hydrogen can become economic, nor do they provide a pathway for transitioning China's massive hydrogen demand away from fossil fuel-derived sources. Conversely, in some cases, local hydrogen strategies offer a way to expand the market for locally-produced fossil fuel-derived hydrogen. In many cases, hydrogen has little to do with helping to achieve decarbonisation targets.

Indeed, the high costs of producing renewable hydrogen and transporting it suggest that considerable government support remains necessary. The cities analysed in this paper have opted for a combination of subsidized power prices, one-off subsidies as well as preferential tax policies, but the impact so far has been mixed. Nonetheless, given that the cities analysed here view hydrogen as part of their industrial programmes, economic development, and climate strategies, support is likely to remain significant, even as the specific incentive schemes will likely evolve.

Water, land availability, and technology continue to be constraints. While the cities analysed here are seeking to develop home-grown technologies, they currently rely on foreign inputs. Only Chengdu's policy documents, however, actively encourage foreign investments. Indeed, local hydrogen developments diverge between cities and are path-dependent, based on resource endowment, local economic growth priorities, and support or scrutiny from the provincial and central government.

While the three cities analysed in this paper do not cover all regional plans and initiatives, they offer a useful window into local hydrogen policy implementation. They also illustrate the major challenges

[1] NDRC (March 2022). 'Medium and Long-term plan for the development of a hydrogen industry (2021-2035)', p.1, https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123 [in Chinese].

[2] Tu, K.J. (October 2020). 'Prospects of a hydrogen economy with Chinese characteristics', Etudes de l'Ifri, IFRI, https://www.ifri.org/en/publications/etudes-de-lifri/prospects-hydrogen-economy-chinese-characteristics; Tu, K.J. and Wang, I. (2022). 'Prospects of Renewable Hydrogen in China and Its Role in Industrial Decarbonization', Agora Energiewende, https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Agora/Prospects_of_Renewable_Hydrogen.pdf; Brown, A. and Grünberg, N. (June 2022). 'China's nascent green hydrogen sector: How policy, research and business are forging a new industry', MERICS China Monitor No. 77, https://merics.org/sites/default/files/2022-06/MERICS_China_Monitor_No_77_Green-Hydrogen_EN_final.pdf; Gong, X., Quitzow, R. and Boute, A. (January 2023). 'China's Emerging Hydrogen Economy Policies, Institutions, Actors', RIFS Study, https://publications.iass-potsdam.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_6002649.

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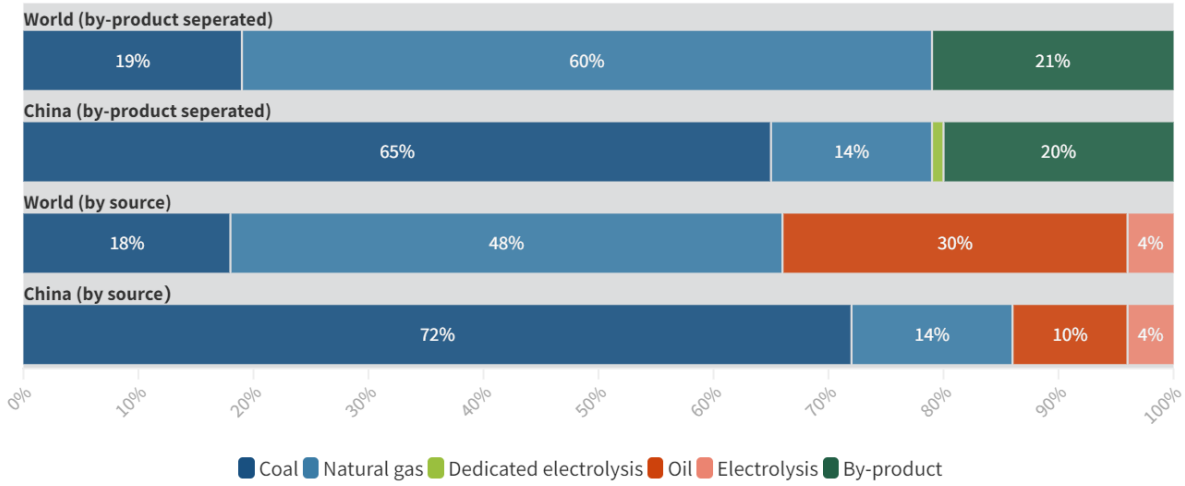
facing green hydrogen as it moves beyond the narrow, highly subsidized field of fuel cell vehicles (FCVs).

The hydrogen policies and road maps reviewed in this paper offer numerous targets—often setting quantitative goals for FCVs, hydrogen refuelling stations, hydrogen supply chain revenue, and new hydrogen technology companies—aligning with the view that hydrogen development is currently more of an industrial policy than a decarbonisation strategy. Indeed, hydrogen's potential to decarbonise sectors such as manufacturing and chemicals is of secondary importance, if mentioned at all. Given this local hydrogen development model, rising demand for hydrogen in China could ultimately increase rather than decrease CO_2 emissions from fossil fuels in the short run. While central government's hydrogen targets (as laid out in its 2022 policy documents) seem relatively conservative, Chinese cities' appetite for new sources of growth and the ability to fund various business models are worth watching.

1. China's hydrogen economy: ambitious plans emerging

China is the world's largest producer of hydrogen, with an annual output estimated at 33 million tonnes (Mt).[3] In China, most hydrogen is produced from coal gasification, known as black or brown hydrogen, whereas natural gas is the main source of hydrogen in most other countries (See Figure 1). Almost all hydrogen in China today is made from coal or natural gas, releasing carbon dioxide (CO_2) to the atmosphere in the process.[4] Roughly 60 per cent of China's hydrogen comes from coal and 15 per cent comes from methane. Most of the remaining hydrogen is a by-product of petrochemical industry processes, and only a small percentage of China's hydrogen comes from electrolysis—using renewable electricity or grid power.[5]

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



Source: Agora Energiewende, 2022[6]

[3] NDRC (March 2022). 'Medium and Long-term plan for the development of a hydrogen industry (2021-2035)', p.1 [in Chinese], https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123.

[4] NDRC (March 2022). 'Medium and Long-term plan for the development of a hydrogen industry (2021-2035)', p.1 [in Chinese], https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123; Statista, Hydrogen consumption worldwide by country, 2020 (accessed 5 August 2022), https://www.statista.com/statistics/1292403/global-hydrogen-consumption-by-country/#:~:text=Global%20hydrogen%20use%202020%2C%20by%20country&text=China%20is%20the%20world's%20largest,tons%20of%20global%20hydrogen%20consumption.

[5] IEA (October 2021). Global Hydrogen Review 2021, p.188 https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf; Tu, K.J. (October 2020). 'Prospects of a Hydrogen Economy with Chinese Characteristics', Etudes de l'Ifri, IFRI https://www.ifri.org/en/publications/etudes-de-lifri/prospects-hydrogen-economy-chinese-characteristics; International PtX Hub. Factsheet on China, the world's largest Hydrogen producer and consumer', https://ptx-hub.org/factsheet-on-china-the-worlds-largest-hydrogen-producer-and-consumer/.

[6] Tu, K.J. and Wang, I. (2022). 'Prospects of Renewable Hydrogen in China and Its Role in Industrial Decarbonization', Agora Energiewende, p.2, https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Agora/Prospects_of_Renewable_Hydrogen.pdf.

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Most of China's hydrogen is used as a chemical feedstock, which includes ammonia synthesis, methanol production, and petroleum refining (See Box 1) In 2019, 10.8 Mt of hydrogen was used for ammonia syntheses, 9.1 Mt for methanol production, and 8.2 Mt for refining and chemical processes. Despite the media and policy attention given to hydrogen vehicles, the transport sector consumed less than 20,000 tonnes of hydrogen in 2019.[7]

Box 1: The hydrogen rainbow

In describing different ways of producing hydrogen, the following terms are commonly used:

- Black or brown hydrogen – hydrogen made from coal
- Grey hydrogen – hydrogen made from natural gas
- Blue hydrogen – hydrogen made from coal or natural gas, with carbon capture and storage
- Green hydrogen – hydrogen made from the electrolysis of water using renewable energy
- Pink or yellow hydrogen – hydrogen made from the electrolysis of water using nuclear energy
- Turquoise hydrogen – hydrogen made from natural gas using pyrolysis or photocatalysis

The hydrogen produced from all these methods is identical (a molecule with two hydrogen atoms – H_2). But different production methods have very different climate change implications: the CO_2 intensity of hydrogen production from coal-fired power in China is estimated at 38.6 kg/kg H2 compared with 28.5 kg CO_2e/kg H2 for coal gasification, 13 kg CO_2e/kg H2 for natural gas and 0.5 kg CO_2e/kg H2 for renewables.

According to International Energy Agency estimates, the use of hydrogen-based fuels could avoid cumulative emissions of close to 16 Gt CO_2 in China by 2060, with the biggest reductions coming from industry, followed by shipping, aviation, and road transport.[8] However for hydrogen to help mitigate climate change and contribute to decarbonisation, it must be produced with low-carbon processes. Additionally, research suggests that limited green hydrogen supplies should be prioritized to abate emissions in sectors that are otherwise difficult or impractical to electrify. For example, Agora Energiewende classifies the cement, steel, ammonia, aviation, maritime shipping, and seasonal energy storage fields as 'no regrets' sectors for decarbonisation via green hydrogen, while classifying heavy-duty vehicles and process heat as having a lower priority.[9]

The International Energy Agency emphasizes the need to set clear targets and incentives for low-carbon hydrogen to replace fossil fuel-derived hydrogen in existing hydrogen-consuming industries as well as in industries that could use hydrogen.[10] Recent scientific literature has also emphasized the role of hydrogen in replacing fossil fuels in industries with limited or no potential for direct electrification,

[7] NDRC (March 2022). 'Medium and Long-term plan for the development of a hydrogen industry (2021-2035)' [in Chinese], https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123; Tu, K.J. (October 2020). 'Prospects of a hydrogen economy with Chinese characteristics', Etudes de l'Ifri, IFRI, https://www.ifri.org/en/publications/etudes-de-lifri/prospects-hydrogen-economy-chinese-characteristics; IEA (October 2021). Global Hydrogen Review 2021, https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf; China Hydrogen Alliance (May 2021). 'The Report of the Development of China Hydrogen Energy and Fuel Cell Industry 2020' (paperback copy, online version not available), p.19.

[8] IEA. 'An energy sector roadmap to carbon neutrality in China', p.175, https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china.

[9] Tu, K.J. and Wang, I. (2022). 'Prospects of Renewable Hydrogen in China and Its Role in Industrial Decarbonization', Agora Energiewende, https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Agora/Prospects_of_Renewable_Hydrogen.pdf.

[10] IEA (2021). Global Hydrogen Review 2021, page 9, https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

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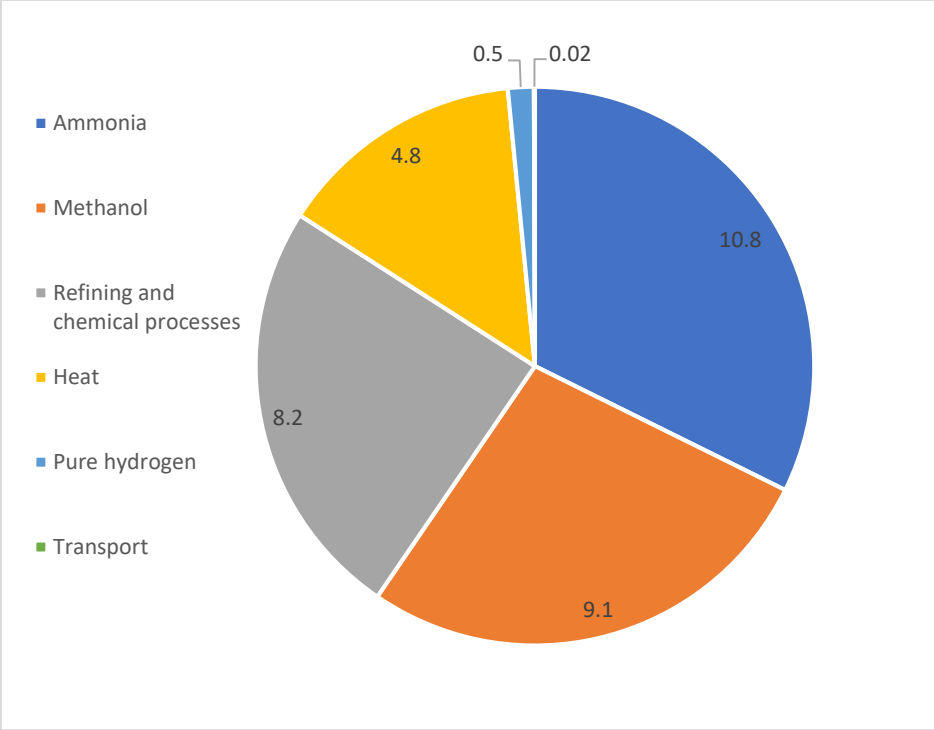
suggesting that sectors such as short-range heavy-duty FCVs (such as buses and local logistics) fall lower in a hypothetical CO_2-abatement cost and efficiency curve.[11]

Figure 2: China's hydrogen consumption by sector, 2019



Source: National Development and Reform Commission (NDRC)

While the Chinese Government has issued various policies dating back to the 2000s aimed at promoting hydrogen development, these were not part of a low-carbon energy transition strategy as they focused on fuel cells powered by hydrogen and did not target any other forms of hydrogen. In this vein, since the late 2010s, cities have announced hydrogen development policies focusing on using local energy resources or industrial by-products.[12]

Following China's September 2020 pledge to peak carbon emissions before 2030 and aim to reach carbon neutrality by 2060 (the 30–60 targets), hydrogen has started figuring more prominently in central and local government policy documents. This is because of its potential to contribute to a low-carbon energy transition, as well as to hydrogen's potential as a strategic industry and field of technology. However, before discussing local implementation, it is useful briefly to take stock of the evolution of China's hydrogen strategy and the broader policy context in which city-level policies have developed.

1.1 National policy in the early 2000s: hydrogen in transport

Chinese hydrogen policies date back to the *10th Five-Year Plan (2001–2005)*, with a focus on the transport sector. Hydrogen fuels derived from domestic energy sources were seen as a potential way of reducing China's growing oil import dependence—a source of significant strategic vulnerability due to China's rapidly growing vehicle fleet. Hydrogen FCVs were also seen as potentially helpful in curbing urban air pollution[13] given the significant contribution of heavy-duty vehicles to local air quality issues in China. Hydrogen was first included in China's national technology development plan in 2006.

[11] Ueckerdt, F. et al. (May 2021). 'Potential and risks of hydrogen-based e-fuels in climate change mitigation', *Nature Climate Change*, https://doi.org/10.1038/s41558-021-01032-7.

[12] Sun, X. et al. (30 November, 2022), Textual Quantitative Analysis on China's Local Hydrogen Energy Development Policies (我国地方性氢能发展政策的文本量化分析) [in Chinese], Chemical Industry and Engineering Progress, at Section 1, https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CAPJ&dbname=CAPJLAST&filename=HGJZ20221128009&uniplatform=NZKPT&v=9r1FBu-G_dQnnlDbbdPhJsmPtxjNcWjLv_8GmxuPXS_a8xQlElQRkNheBkglnAaf.

[13] Meidan, M. (May 2021). 'China's emerging hydrogen strategy and the 2060 net zero commitment', Oxford Energy Forum issue 127, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/05/OEF-127.pdf.

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In 2015, the Chinese Government published the *Made in China 2025 initiative*—a ten-year plan to upgrade China's manufacturing industry—citing hydrogen as a key technology to develop in the energy vehicle market.[14] The following year, the first *Hydrogen Fuel Cell Vehicle (FCV) Technology Roadmap* was released aiming for the mass application of hydrogen in the transport sector by 2030.[15] The Hydrogen FCV Roadmap set targets to have 5,000 FCVs and 100 hydrogen refuelling stations (HRS) by 2020, focusing on establishing industrial clusters and demonstration projects in the regions of Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Shandong Peninsula, and the central region.[16]

Purchase subsidies for fuel cell passenger cars were introduced as a linear function of the rated power of the fuel cell system, starting at RMB 4,800/kW and capped at RMB 160,000 per car. For light-duty fuel cell commercial vehicles—buses, coaches, trucks, and other commercial fleet vehicles—the base subsidy is RMB 240,000 per vehicle. For medium to heavy-duty commercial vehicles, the base subsidy is RMB 400,000 per vehicle.[17] By the end of 2021, the FCV targets were surpassed with 10,700 FCVs (mostly buses and trucks) deployed in China and 194 hydrogen fuelling stations in operation.[18] The Hydrogen FCV Roadmap also envisioned having more than 50,000 FCVs in operation and more than 300 HRS in 2025, reaching more than 1 million FCVs by 2030 and more than 1,000 stations by 2030. The plan did not set specific targets for the source of hydrogen fuel, incentivizing production of green hydrogen, or otherwise connecting FCVs with low-carbon energy.

For the first time, the *2019 draft Energy Law* recognized hydrogen as an energy carrier. However, because Chinese regulations classify hydrogen as a hazardous material, its use and transportation require strict management and oversight that limit where and how it can be used. In 2020, the National Development and Reform Commission listed hydrogen as a strategic emerging industry, calling to accelerate 'the development of the new energy industry' including hydrogen.[19]

These documents illustrate that even prior to the government's 2030–2060 dual carbon pledge, policymakers had focused on developing hydrogen FCVs and the hydrogen industry as an economic strategy. In 2018, the National Alliance of Hydrogen and Fuel Cells (or China Hydrogen Alliance) was launched and in 2019, hydrogen was mentioned for the first time in the central government's work report.[20]

The following year, the State Council issued its *New Energy Vehicles Industry Development Plan (2021–2035),*[21] in which it issued targets for the next phase of development for the country's new energy vehicles (NEVs), which refers to battery electric vehicles, plug-in hybrid vehicles, and FCVs. The plan

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[14] 'Made in China 2025', (国务院关于印发《中国制造 2025》的通知) [in Chinese], (8 May 2015), Chapter 3, section 6, point 6, http://www.gov.cn/zhengce/content/2015-05/19/content_9784.htm.

[15] 'Energy Saving and New Energy Vehicle Technology Roadmap', (节能与新能源汽车技术路线图), cited in China Automotive Technology Research Center (September 2017). 'China's fuel cell vehicle development roadmap', (中国燃料电池汽车发展路线图) [in Chinese], p.6, https://www.efchina.org/Attachments/Report/report-20170915-2-zh/report-20170915-2-zh.

[16] 'Energy Saving and New Energy Vehicle Technology Roadmap', (节能与新能源汽车技术路线图), cited in China Automotive Technology Research Center (September 2017), 'China's fuel cell vehicle development roadmap', (中国燃料电池汽车发展路线图) [in Chinese], p.6, https://www.efchina.org/Attachments/Report/report-20170915-2-zh/report-20170915-2-zh.

[17] ICCT Policy update (July 2020). 'China announced 2020–2022 subsidies for new energy vehicles', https://theicct.org/sites/default/files/publications/China%20NEV-policyupdate-jul2020.pdf.

[18] IEA. Global Hydrogen Review 2021, (October 2021) p.188 https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf; '8,198 vehicles! 163 million km! 6,3259 million hours! How are the five pilot city clusters progressing?' (8198 辆！1.63 亿公里！632.59 万小时！五大示范城市群进展如何？) [in Chinese] (1 June 2022) https://news.bjx.com.cn/html/20220601/1229935.shtml; 21st Century Business Herald (2 April 2022). Forecast of the number of hydrogen refuelling stations in China in 2025', (2025 年我国加氢站数量预测) [in Chinese], https://m.21jingji.com/article/20220402/herald/66de383da3e8d8f850dd6d043a6b30e3.html.

[19] NDRC (25 September 2020). '关于扩大战略性新兴产业投资 培育壮大新增长点增长极的指导意见 (Guiding Opinions on Expanding Investment into Strategic Emerging Industries and Fostering New Areas of Growth)', https://www.ndrc.gov.cn/xxgk/zcfb/tz/202009/t20200925_1239582.html?code=&state=123.

[20] Li, K. (5 March 2019), 'Government Work Report 2019 (2019 年政府工作报告)', [in Chinese] http://www.gov.cn/premier/2019-03/16/content_5374314.htm.

[21] See State Council (20 October 2020). '国务院办公厅关于印发新能源汽车产业发展规划'，（2021—2035 年）的通知 [State Council publishes New Energy Vehicle Industry Development Plan 2021–2035] [in Chinese], http://www.gov.cn/zhengce/content/2020-11/02/content_5556716.htm.

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introduced various supporting policies and incentives to meet the FCV roll-out targets.[22] It ended the FCV purchase subsidies but the subsequent *Notice on the Demonstration of Fuel Cell Vehicles*[23] established a four-year pilot programme in which cities were selected to carry out research, development, and demonstrations of FCVs, supporting the entire value chain from vehicle production to infrastructure development and end-use.

The scheme rewards clusters of cities based on a series of parameters, including the deployment of more than 1,000 FCVs that meet certain technical standards, achieving a maximum delivered hydrogen price of RMB 35.00/kg (~USD 5.00/kg), at least 15 operational HRSs and a favourable policy environment for FCV development.[24] Cities can apply to be included in the pilot programme with funding attributed according to a points system.[25] Notably, the points system does not explicitly include quantitative targets for hydrogen production from renewables, or explicitly connect FCV policy with the low-carbon energy transition. Following the notice, several provincial governments issued their own subsidy programmes,[26] in addition to central government support.

At the time of writing, the central government has approved five clusters of cities, led by Daxing district, Beijing; Shanghai; Foshan, Guangdong; Zhengzhou, Henan; and Zhangjiakou, Hebei province. Over the four years of demonstration, the five clusters of cities aim to deploy 33,010 FCVs,[27] together with expanded hydrogen refuelling station networks. Clusters of cities led by Daxing district, Shanghai city and Foshan city will deploy 322 HRSs. These local plans therefore support the targets set out in the *National Hydrogen Plan* for 50,000 FCVs deployed by 2025, which include medium and heavy trucks, buses, and other vocational vehicles.

1.2. Policies on hydrogen beyond FCVs

While the main policy thrust for hydrogen was in the transport sector, policy papers have also offered guidance on other hydrogen-related technologies. The *National Innovation-Driven Development Strategy and the Action Plan for Innovation in the Energy Technology Revolution (2016–2030)*[28] as well

[22] 'Notice on optimizing fiscal subsidies for promoting new energy vehicles', (关于完善新能源汽车推广应用财政补贴政策的通知) [in Chinese], (April 2020), http://www.gov.cn/zhengce/zhengceku/2020-04/23/content_5505502.htm.

[23] Ministry of Finance, Ministry of Industry, Information and Technology, Ministry of Science and Technology, NDRC, NEA (September 2020). 'Notice on the Demonstration of Fuel Cell Vehicles' [in Chinese], http://www.gov.cn/zhengce/zhengceku/2020-10/22/content_5553246.htm.

[24] Ministry of Finance et al. (September 2020). Notice on the Demonstration of Fuel Cell Vehicles (关于开展燃料电池汽车示范应用的通知) [in Chinese], in Fuel Cell Vehicle Demonstration City Cluster Declaration Guide, http://www.gov.cn/zhengce/zhengceku/2020-10/22/content_5553246.htm.

[25] Cui, H. and He, H. (13 July 2020). 'China announced 2020–2022 subsidies for new energy vehicles', ICCT Policy update, https://theicct.org/publication/china-announced-2020-2022-subsidies-for-new-energy-vehicles/.

[26] For a brief overview of Shanghai's subsidies: China Association of Automobile Manufacturers, (November 2021). 'Shanghai: subsidies for fuel cell vehicle industry' (上海：对燃料电池汽车产业给予补贴) [in Chinese], http://www.caam.org.cn/chn/38/cate_430/con_5234935.html.

[27] Mi, Y., Beijing (January 2022). 'Tianjin and Hebei Fuel Cell Vehicle Demonstration City Cluster Launched' (京津冀燃料电池汽车示范城市群启动) [in Chinese], http://www.xiongan.gov.cn/2022-01/27/c_1211544334.htm; Chen A. et al. (June 2021). 'Shanghai city cluster fuel cell vehicle demonstration project launched' (上海城市群燃料电池汽车示范项目启动) [in Chinese], http://m.xinhuanet.com/sh/2021-06/11/c_1310002032.htm; Guangdong DRC et al. (August 2022). 'Plan for Accelerating the Construction of a Demonstrative Cluster for Fuel Cell Vehicles (2022-2025)' (广东省加快建设燃料电池汽车示范城市群行动计划（2022-2025 年) [in Chinese], http://drc.gd.gov.cn/ywtz/content/post_3993253.html; Henan Province Government (August 2022). 'Medium and Long-term Plan for the Development of Hydrogen Energy Industry in Henan Province' (河南省氢能产业发展中长期规划) [in Chinese], https://fgw.henan.gov.cn/2022/09-08/2603392.html; Zhangjiakou News (January 2022). 'Hebei Province Fuel Cell Vehicle Demonstration and Application City Cluster led by Zhangjiakou City Approved' (张家口市牵头的河北省燃料电池汽车示范应用城市群获批) [in Chinese], http://www.zjknews.com/news/202201/24/354941.html.

[28] 'National Innovation-Driven Development Strategy and the Action Plan for Innovation in the Energy Technology Revolution (2016-2030)' (中共中央 国务院印发《国家创新驱动发展战略纲要》) [in Chinese] (May 2016), Chapter 4, section 1, point 10 http://www.gov.cn/zhengce/2016-05/19/content_5074812.htm.

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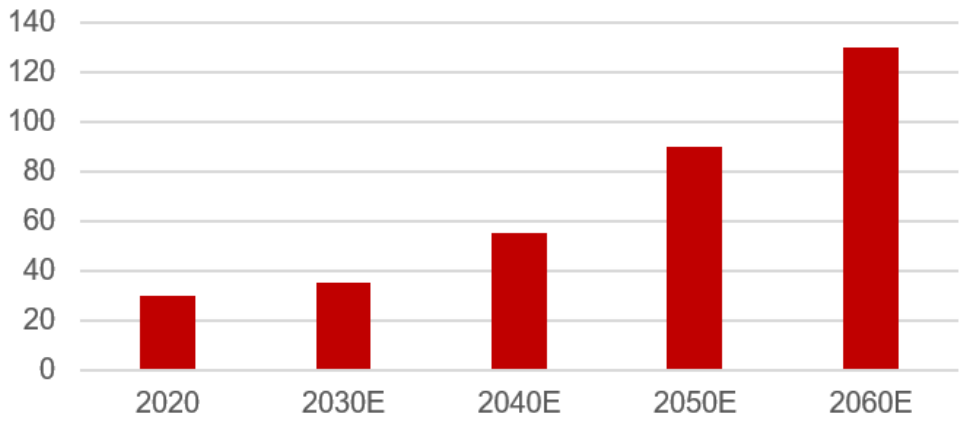
as the *13th Five-Year Plan for Strategic Development in Emerging Industries*[29] promote research and industrial development of hydrogen, hydrogen storage systems, and fuel cell technology.

Since the announcement in September 2020 of China's dual carbon targets, hydrogen has gained growing importance given its potential contribution to the country's decarbonization targets and its ability—from a local perspective—to create new industries while supporting existing industries and resource production, including fossil fuels.

In an April 2021 report, the China Hydrogen Alliance (CHA) predicted that hydrogen production from renewable energy in China would reach 100 Mt by 2060, with total hydrogen use of 130 Mt accounting for 20 per cent of China's final energy consumption.[30] According to the Alliance, around 60 per cent of hydrogen demand will come from industry, with most of the rest coming from transport.[31] These views were considerably more optimistic than the outlook in the CHA's first report in 2019, when it first expected hydrogen demand to reach 35 Mt in 2030 (at least 5 per cent of the Chinese energy supply) and 60 Mt in 2050 (10 per cent, see Figure 3). This amount of hydrogen would require roughly 1,000 GW of wind or 2,000 GW of solar capacity.[32]

Figure 3: China's hydrogen demand, million tonnes[33]



Source: China Hydrogen Alliance

In 2021, the *14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035* highlighted the hydrogen industry and encouraged R&D in the field of hydrogen energy.[34] The *14th Five-Year Plan of Energy Technology Innovation* included the active promotion of innovation in hydrogen technology while the framing document for achieving China's 30–60 targets, the *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy,*[35] stated that developing hydrogen value chains will help to achieve the goal of establishing a 'clean, efficient, low-carbon and safe energy system' and

[29] '13th Five-Year Plan for Strategic Development in Emerging Industries' (国务院关于印发"十三五"国家战略性新兴产业发展规划的通知) [in Chinese] (November 2016), Chapter 5, Section 1 http://www.gov.cn/zhengce/content/2016-12/19/content_5150090.htm.

[30] China Hydrogen Alliance (May 2021). 'The Report of the Development of China Hydrogen Energy and Fuel Cell Industry 2020' (paperback copy, online version not available) (2020 中国氢能源及燃料电池产业白皮书), p.19.

[31] 'Experts predict: For China's net zero pledge, hydrogen will account for around 20% of China's final energy consumption' (专家预测：在碳中和情景下 氢能在我国终端能源消费中占比将达 20%左右) [in Chinese], CNR, (22 April 2021) http://finance.cnr.cn/txcj/20210422/t20210422_525467869.shtml.

[32] Based on Collins, L. (19 March 2020). 'A wake-up call on green hydrogen: the amount of wind and solar needed is immense,' RECharge.

[33] CHA's report published in 2021 produced Forecast 1. Its report published in 2019 produced Forecast 2, which merely projected year 2030 and 2050.

[34] State Council. 'China's 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035' [in Chinese], http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.

[35] State Council (October 2021). 'Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy' [in Chinese], http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm.

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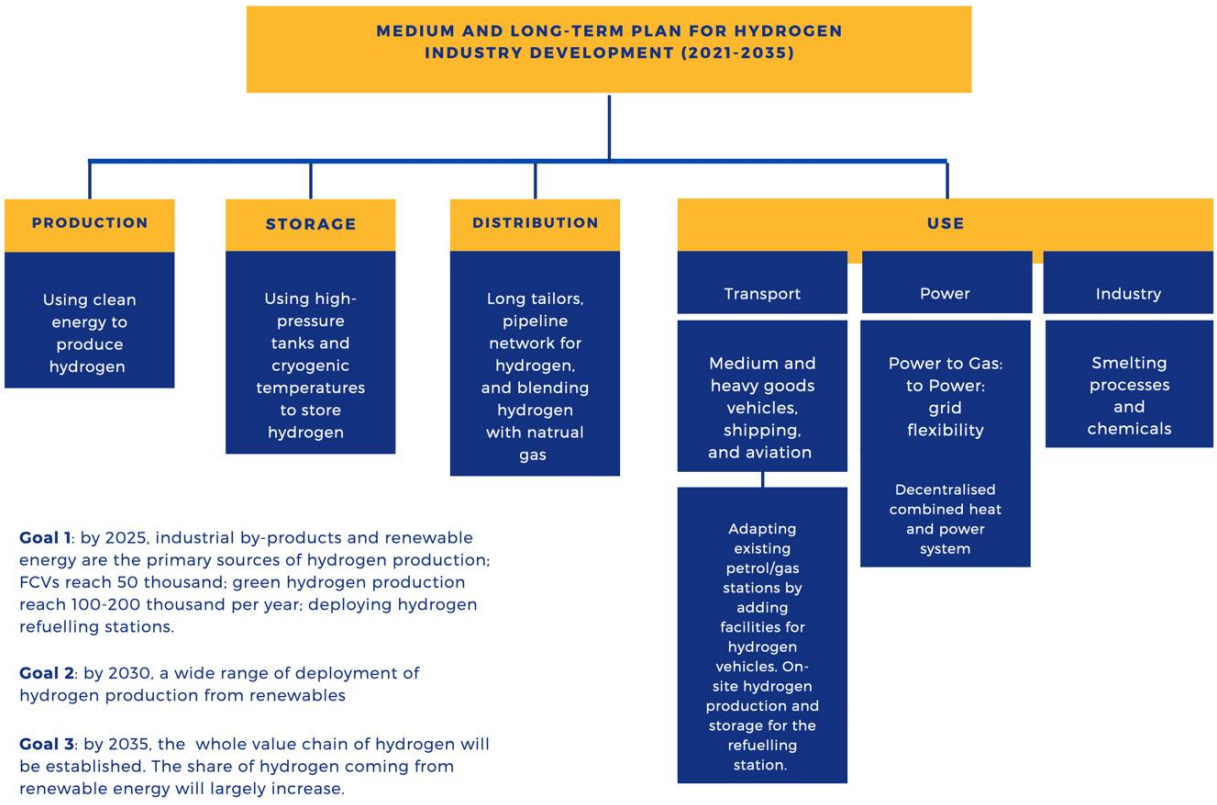
will increase the supply of non-fossil fuels. In the *Action Plan for Carbon Dioxide Peaking Before 2030,*[36] the State Council announced its goal of trialling hydrogen in the chemical, metallurgy, transport, and construction industries to reduce carbon emissions.

In March 2022, the National Development and Reform Commission (NDRC) published its *Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035),*[37] the first official document to lay out a long-term vision for China's hydrogen economy. It highlights the importance of hydrogen for developing a safe and climate-neutral energy supply and its potential contribution to economic development. The Plan highlights hydrogen's importance in decarbonizing hard-to-abate sectors, including the steel, transport, and chemical industries. Meanwhile, the plan also notes the technological barriers in the hydrogen value chain and stresses the importance of developing safety standards.

The Plan effectively consolidates existing hydrogen policy initiatives into a single document and reiterates some goals set out in previous plans, including the deployment of 50,000 FCVs by 2025.[38] It also calls for the production of 100,000–200,000 tonnes of green hydrogen per year by 2025 (roughly 0.3 per cent to 0.6 per cent of current hydrogen production). According to the NDRC, this will lead to CO_2 emissions reductions of 1–2 Mt per year by 2025.

The 'Medium and long-term plan for hydrogen industry development' sets out the direction and guiding principles for China's efforts to develop a hydrogen economy (see Figure 4).

Figure 4: China's Medium and long-term plan for the Development of the Hydrogen Energy Industry



In the near term, the NDRC's *Hydrogen Plan* calls for establishing hydrogen markets close to current production sites, including where hydrogen is recovered as an industrial by-product from alkaline production, propane dehydrogenation (PDH) plants, and renewable electrolysis power-to-gas. The

[36] State Council (October 2021). 'Action Plan for Carbon Dioxide Peaking Before 2030' [in Chinese], http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.htm.

[37] National Development and Reform Commissions (23 March 2022). 'Medium- and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035)', (氢能产业发展中长期规划（2021-2035 年）) [in Chinese], https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123.

[38] The Hydrogen Plan does not set a target for HRSs, although the New Energy Vehicle Industry Development Plan includes a target for HRSs to grow from 72 units in mid-2020 to 2,000 units by 2035.

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principles set out in the main hydrogen plan were then reiterated and fine-tuned in subsequent papers. For example, in April 2022, the government issued the *Guidelines on Promoting the High-quality Development of Petrochemical and Chemical Industries during the 14th Five-Year Plan*, with plans to decarbonize refining and chemicals using green hydrogen.

The Plan also calls on the industry to pilot more advanced technologies, including seawater electrolysis and nuclear hydrogen production. The Plan reiterates the importance of hydrogen fuels for transport in the near term but emphasizes that, in the future, hydrogen should be used for energy storage, power generation, industry, and other sectors beyond transportation. Indeed, hydrogen as a means of dealing with intermittency of renewables in power generation was addressed in January 2022, when the National Development and Reform Commission (NDRC) and the National Energy Agency (NEA) issued *The New Energy Storage Development Implementation Plan During The 14th Five-Year Plan,*[39] noting that hydrogen (ideally from renewable energy) will be used for electricity storage in demonstration projects. There are currently a few trial projects looking at grid flexibility, which have proven to be technologically viable, but there has been limited progress to date as the technologies are still very expensive.

The Plan also encourages financing to support the industry's development, using central government funding initially with the aim of encouraging financial institutions to offer additional support for hydrogen development.[40] Subnational governments can also raise funds through special bonds for developing hydrogen and other strategic projects, with central government first setting local government allocations for these special bonds. Local governments can then use the raised capital to invest in new industries such as hydrogen.[41]

In addition, a number of funds have been set up for investments. Industry funds, for example, combine public and private investments, including state-owned companies, research institutions, and universities (such as Tongji University, China University of Geoscience), local governments (such as Dalian, Wuhan), commercial institutions, and private companies. For example, in June 2019, Dongfang Electric Group signed an agreement with Three Gorges Capital and Chengdu Innovation Ventures to initiate a hydrogen industry fund of RMB 500 million (about USD 73 million). At the same time, bank loans and bonds are also increasingly used: in September, Chengdu municipal government issued bonds of RMB 224 million (about USD 30 million) for a hydrogen industrial park, with an interest rate of 3.94 per cent and maturity of 20 years.[42]

While there have been a growing number of policy documents and efforts to support the industry, the national plans remain quite vague. What is more, policy papers do not define 'hydrogen' or 'green hydrogen', although discussions of hydrogen as a way of storing renewable energy clearly aim to support renewables-based hydrogen. However, China's hydrogen policy does not discuss or regulate the carbon footprint of different hydrogen applications.[43] Beijing is aiming for a complete and diversified ecosystem of green hydrogen applications covering transportation, energy storage, and industry by 2035, (see Figure 5); however, the pathways will depend on additional support packages, as well as on local implementation.

A number of provinces and cities have already set up pilot zones and issued their own hydrogen plans. As a result, some observers argue that China will easily meet the targets laid out in its hydrogen plan.[44]

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[39] NDRC, NEA (January 2022). 'The New Energy Storage Development Implementation Plan During The 14th Five-Year Plan' (《"十四五"新型储能发展实施方案》) [in Chinese], https://www.ndrc.gov.cn/xwdt/tzgg/202203/P020220321550104020921.pdf.

[40] National Development and Reform Commissions (23 March 2022). 'Medium- and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035)', (氢能产业发展中长期规划（2021-2035 年)) [in Chinese], p.13, https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123.

[41] Wen, L. and Wang, R. (October 2022). The Forecast and Review of China's Fiscal Investment and Financing System Reform (我国财政投融资管理体制改革回顾与展望) [in Chinese], p.48. See also Gong, X., Quitzow, R., and Boute, A. (January 2023). 'China's Emerging Hydrogen Economy Policies, Institutions, Actors', RIFS Study, pp. 50–52, https://publications.iass-potsdam.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_6002649.

[42] Yue, M. and Wang, C.N. (27 September 2020). 'Hydrogen: China's Progress and Opportunities for a Green Belt and Road Initiative', https://greenfdc.org/hydrogen-chinas-progress-and-opportunities-for-a-green-belt-and-road-initiative/?cookie-state-change=1641223946498.

[43] Gong, X., Quitzow, R., and Boute, A. (January 2023). 'China's Emerging Hydrogen Economy Policies, Institutions, Actors', RIFS Study, https://publications.iass-potsdam.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_6002649.

[44] Brown, A. and Grünberg, N. (June 2022). 'China's nascent green hydrogen sector: How policy, research and business are forging a new industry', MERICS China Monitor no 77, https://merics.org/sites/default/files/2022-06/MERICS_China_Monitor_No_77_Green-Hydrogen_EN_final.pdf.

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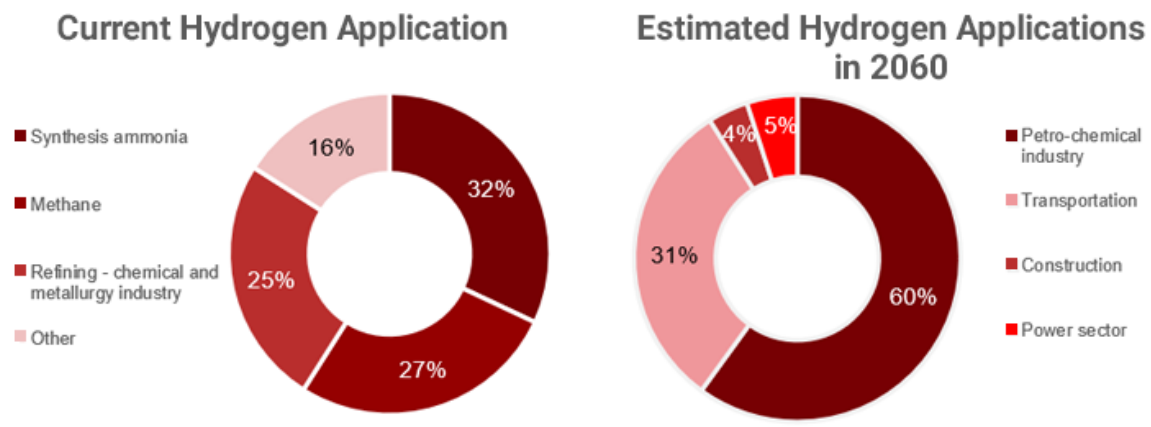
Already in 2020, China accounted for 8 per cent of the global stock of electrolysers and 35 per cent of the global manufacturing capacity of electrolyser equipment and components.[45] The China Hydrogen Alliance (CHA) estimates China could add 100 GW of electrolyser capacity by 2030 to produce green hydrogen.[46] Yet China's green hydrogen production is currently estimated at roughly 25 thousand tonnes.[47] In fact, the actual number might be less than that as not all production facilities are running due to high costs. This suggests that reaching the CHA's 2025 projection, let alone its 2060 projection of 100 million tonnes, is uncertain and would require either substantial cost reductions or subsidies for green hydrogen.

Figure 5: Current and future hydrogen applications in China



Source: China Hydrogen Alliance

The Hydrogen Plan represents an important signal from central government about the role of hydrogen in reaching the dual carbon goals and potentially shifting the policy focus at the local level from a narrow pursuit of FCV manufacturing and deployment towards a broader vision of hydrogen as an enabler of the energy transition. Indeed, the Plan implicitly notes the risk of overcapacity in vehicle manufacturing due to the promotion of FCVs, especially in areas with existing auto manufacturing bases. The Plan was therefore likely in part aimed to streamline local development, pushing provinces and cities to apply hydrogen to other end uses. Yet the Plan also recognizes local developments and notes that provinces should choose their hydrogen production routes according to local conditions (including resource endowments and industrial structure), giving provinces considerable leeway in their hydrogen strategies.

The flexibility of the present policy could promote innovation as provinces experiment with different approaches for scaling up hydrogen infrastructure, but it could also lead to overcapacity as provinces develop strategies without coordination. If technologies to deploy green hydrogen do not come down in cost, green hydrogen will either need substantial subsidies or China's hydrogen development will continue to rely on fossil fuels. Given the uncertainties around the economics of carbon capture, utilization, and storage (CCUS), this raises questions about the role of hydrogen in supporting the country's 2030–2060 goals.

[45] Nakano, J. (3 February 2022). 'China's Hydrogen Industrial Strategy', CSIS Commentary, https://www.csis.org/analysis/chinas-hydrogen-industrial-strategy.

[46] 'Experts predict: For China's net zero pledge, hydrogen will account for around 20% of China's final energy consumption', (专家预测：在碳中和情景下 氢能在我国终端能源消费中占比将达 20%左右) [in Chinese], CNR, (22 April 2021) http://finance.cnr.cn/txcj/20210422/t20210422_525467869.shtml; 氢启未来网 (2021). '中国氢能联盟发布《"可再生氢 100"行动倡议》(China Hydrogen Alliance Issues 'Renewable Hydrogen 100 Initiative')' [in Chinese], 23 September, https://h2weilai.com/cms/index/shows/%20catid/32/id/3290.html.

[47] Author interview with a researcher in a Beijing-based hydrogen think-tank.

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2. Cities adapt the national level targets

Provincial governments and local officials can play both a supportive and inhibiting role in implementing the country's energy policies.[48] From the early days of the Reform and Opening up in 1978, provinces had incentives to encourage the start of new companies in selected industries which would often receive subsidized land, tax incentives, or other preferential treatment. The result is known as 'local state corporatism'. This, in turn, has enabled a rapid growth of new companies in sectors targeted for development, but also in duplication and segmentation along provincial and regional lines. At various times, including in recent years, provinces have pursued policies that resulted in excess production capacity and over-investment in coal, steel, and renewable energy production. At the same time, provinces and localities have also fostered new energy industries and new technology strategies as they have experimented with new policies and business models, applying to host pilot programmes or experimental clusters. For hydrogen, it is useful to examine the various local and city-level initiatives to assess the sector's trajectory.

For local officials, hydrogen development stems from two main policy imperatives. First, hydrogen development offers economic development potential, both in developing new projects in industries that central government has designated as strategic, and supported with high levels of subsidies, and as a customer for local resource-producing industries with hydrogen by-products. Many Chinese cities rely on natural resource extraction and processing as an economic base. Though hydrogen may eventually be a potential solution for industrial decarbonisation, in the near term it represents a source of investment funds, revenue from existing by-products, and a source of jobs and tax revenues.

Second, since the 2030–2060 goals were announced in 2020, hydrogen has become a way for local governments to demonstrate progress towards the dual control targets, which have now been integrated into the Chinese Government's management and promotion systems. Local governments must meet their emissions reduction targets on a five-year basis. Evaluations depend on central government setting an overall target for the whole of the country over five years and then provincial governments breaking down the five-year targets into annual targets for their cities.[49] The cities divide the targets into seasonal or even monthly targets for their districts. In the end, the targeted companies in the districts implement the policy and seek to reduce their emissions to meet the goals.[50] Alongside economic growth, welfare provision, and other performance targets, the ability of local governments to meet these dual control targets has become an important indicator for central government to assess the local officials' performance.

While both these motivations can explain the local push for hydrogen, each city's focus varies depending on its local situation, as well as resource endowments and industrial focus. Since the country is currently using fossil fuels, industrial by-products, and renewables, this paper examines three cities that are representative of these three hydrogen sources: Zhangjiakou, Datong, and Chengdu. As we shall see, the cities of Datong and Zhangjiakou have focused on producing hydrogen using their abundant coal and renewables resource bases. Chengdu has focused on developing FCV manufacturing to align with its existing automobile manufacturing base. However, Datong and Zhangjiakou have also focused on FCVs, including establishing vehicle manufacturing bases, apparently to capitalize on lucrative subsidies and policy attention on FCVs as a strategic sector.

[48] For further discussion of this see Hove, A., Meidan, M., and Andrews-Speed, P. (December 2021). 'Software versus hardware: how China's institutional setting helps and hinders the clean energy transition', OIES Paper CE2, December 2021, https://www.oxfordenergy.org/publications/software-versus-hardware-how-chinas-institutional-setting-helps-and-hinders-the-clean-energy-transition/.

[49] NDRC (September 2021). Improving the Dual Control Scheme for Energy Consumption Intensity and Total Volume (完善能源消费强度和总量双控制度方案) [in Chinese] (September 2021) p.3, https://www.ndrc.gov.cn/xwdt/tzgg/202109/P020210916534072411763.pdf.

[50] Xiaowei, X. (March 2022). From "the Amount and Intensity Control of Energy Consumption" to "the Amount and Intensity Control of Carbon Emission": Challenge and Strategy ("能耗双控" 到 "碳双控": 挑战与对策), p.48.

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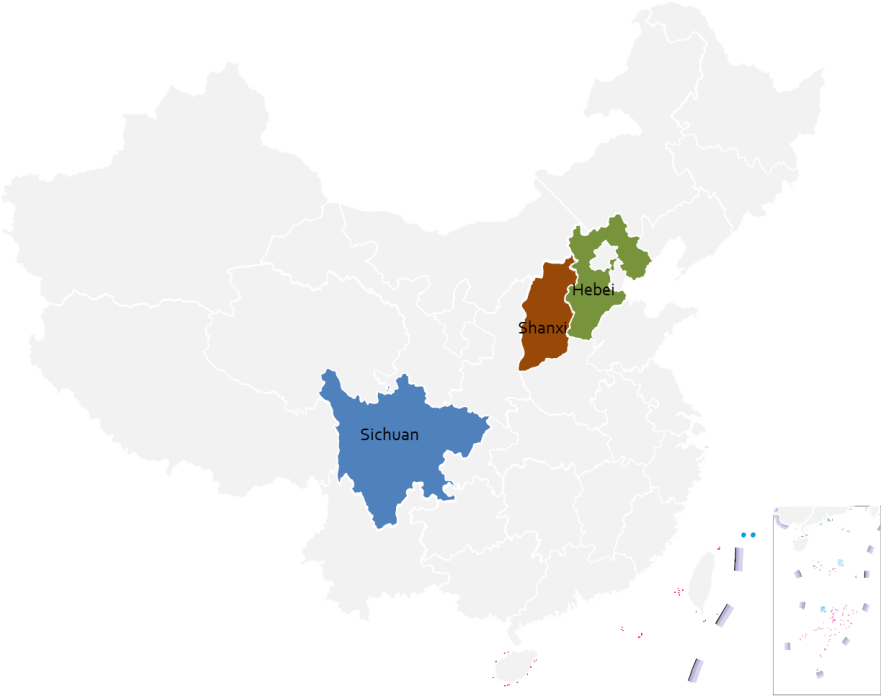
Figure 6: Map of China and provinces in which the three cities are located



Note: This map is for illustrative purposes and does not represent the expression of any opinion concerning the legal status or sovereignty of any country or territory, the delimitation of frontiers or boundaries or the names of any territory, city or region.

Source: OIES

3. Zhangjiakou city, Hebei province

Zhangjiakou city lies in the north-western Hebei province, just 150 km from Beijing. The city's area is 36,800 square kilometres and the population is about 4.1 million. The city benefits from its close proximity to Beijing and from the province's diversified economic structure. The province also has the second largest installed capacity of both wind and solar in China,[51] towards which Zhangjiakou contributed 42 per cent in 2021.[52] China's State Council designated the city as a Renewable Energy Demonstration Area (REDA) in 2015, which also marked the beginning of its hydrogen sector development. Given its abundant renewable energy resources and excellent skiing conditions, the city was selected to co-host the low-carbon 2022 Winter Olympic Games in Beijing, which further accelerated its hydrogen development.

3.1. The drivers for developing a hydrogen economy in Zhangjiakou city

Zhangjiakou city is one of the five demonstration clusters in China's FCV programme (discussed above) and currently leads in FCV bus deployment in China. The city has capitalized on its vast wind resources for its hydrogen development. Already at the end of 2014, the city had installed wind and solar capacity of 7 GW[53] that was also grid-connected. But for several years the Zhangjiakou region suffered from severe curtailment, despite its location near Beijing and other major cities. Between 2012 and 2013, wind power curtailment in the county increased from 20 per cent to 30 per cent.[54] In 2014, hydrogen

[51] At the end of 2021, Hebei province had 25 GW of installed wind power and 29 GW of installed solar. Based on Sandalow, D. et al., Guide to Chinese Climate Policies 2022, https://chineseclimatepolicy.oxfordenergy.org/book-content/domestic-policies/renewable-power/solar-power/.
[52] Calculated with publicly available data.
[53] NDRC (28 July 2015). Development Plan for Renewable Energy Demonstration Area in Zhangjiakou City, Hebei Province Plan (河北省张家口市可再生能源示范区发展规划) [in Chinese], p.5, http://www.gov.cn/xinwen/site1/20150729/87251438169616905.pdf.
[54] IRENA (2019). 'Zhangjiakou Energy Transformation Strategy 2050', p.32, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Zhangjiakou_2050_roadmap_2050.pdf.

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was seen as a way to absorb Zhangjiakou's wind and solar output, although formal policy support documents for creating a hydrogen industry were first issued in 2019 (see below).

Direct support from central government boosted the city's wind and solar installed capacity, especially following its designation by central government as a Renewable Energy Demonstration Area. This designation by the NDRC[55] (Zhangjiakou is currently the only city in China to have been awarded this status) in 2015 led to continued central government interest in Zhangjiakou's development given that the REDA pilot project sought to test applications of advanced and innovative renewable energy technologies, as well as power sector reform with a view to accelerating the nationwide scale-up of renewable electricity generation and use.

By 2017, the total installed wind generation capacity reached 8.72 GW and solar PV generation capacity reached nearly 3 GW, with cumulative renewable generation capacity of 13.45 GW accounting for 73 per cent of the total installed capacity that year and producing around 45 per cent of the total electricity output.[56] In the same year, the first wind-to-hydrogen project in China was launched in Zhangjiakou. In 2018, the NDRC set up a special scheme for industrial innovation and development for the Zhangjiakou REDA which, by the end of 2020, had received RMB 550 million, investing in its 16 projects, including wind manufacturing, hydrogen from wind, fuel cell manufacturing, and lithium-ion battery manufacturing.[57] While the curtailment issues in China's eastern provinces have eased since 2019, ongoing government support promoted the development of Zhangjiakou's hydrogen industry.[58]

In 2019, Zhangjiakou published its *Three-Year Action Plan for Hydrogen Energy Construction (2019–2021),*[59] which formed the basis for its *Hydrogen Energy Development Plan (2019–2035)*[60] that was also published in 2019. Following President Xi Jinping's 2020 carbon peaking and carbon neutrality pledge, and given greater central government focus both on renewables and hydrogen, the city has also included hydrogen industry-related targets in its 14th Five-Year Plan (FYP) documents as well as in a number of hydrogen-specific supporting policies.[61]

3.2. Policy documents and targets: a mixed bag

These policy documents emphasize all aspects of the hydrogen supply chain: from research to development of energy storage, transportation and infrastructure networks, FCVs, and standard systems. But they include a few numeric targets:

- Reaching hydrogen production capacity of 21,000 tonnes by 2021 and 50,000 tonnes in 2035 (local hydrogen output in 2020 was expected to be 11,000 tonnes[62] and the targets are not specifically for low-carbon hydrogen).

[55] NDRC (28 July 2015). 'Development Plan for Renewable Energy Demonstration Area in Zhangjiakou City, Hebei Province Plan (河北省张家口市可再生能源示范区发展规划)', (28, July 2015) [in Chinese], p.5, http://www.gov.cn/xinwen/site1/20150729/87251438169616905.pdf.

[56] IRENA (2019). 'Zhangjiakou Energy Transformation Strategy 2050', p. 32, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Zhangjiakou_2050_roadmap_2050.pdf.

[57] ThePaper (26 October 2020). Zhangjiakou City accelerates the development of new energy industry documentary (张家口市加快新型能源产业发展纪实) [in Chinese], https://www.thepaper.cn/newsDetail_forward_9717556.

[58] Hove, A. et al. (2021), 'China Energy Transition Status Report 2021,' GIZ, page 38, at https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2021/China_Energy_Transition_Status_Report_2021.pdf.

[59] 'Three-Year Action Plan for Hydrogen Energy Construction (2019–2021)' (张家口氢能建设三年行动计划（2019-2021 年)).

[60] 'Hydrogen Energy Development Plan (2019–2035)' (氢能张家口建设规划(2019-2035 年)).

[61] 'The 14th Five-Year Plan for the economic and social development of Zhangjiakou City', (中共张家口市委关于制定国民经济和社会发展第十四个五年规划和二〇三五年远景目标的建议) [in Chinese], 13 January 2021, https://www.zjkzx.gov.cn/article/20210113/zjkzx-2021-13458.html, which mentions hydrogen 9 times; 'The Layout Planning for Hydrogen Refuelling Stations in the Main Urban Area of Zhangjiakou City (2019-2035)' (张家口市主城区加氢站布局规划（2019-2035 年)); Ten Measures for Supporting Zhangjiakou's Hydrogen Energy Industry for Development; Zhangjiakou New Energy Industry Planning (2021-2025).

[62] Zhangjiakou city (15 May 2019). 'Suggestions on accelerating the development of hydrogen energy industry to build a low-carbon Olympic city' (关于加快推进氢能产业发展打造低碳奥运城市的建议) [in Chinese], https://www.zjkzx.gov.cn/article/2019-05-15/zjkzx-2020-13319.html.

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- The cumulative output value of the city's hydrogen industry will reach RMB 6 billion (US$872 million), RMB 26 billion ($3.8 billion), RMB 85 billion ($12 billion), and RMB 170 billion ($25 billion) by 2021, 2025, 2030, and 2035 respectively (although one report estimated its value at RMB 9 billion in 2020 ($131 million)[63]).
- Build a hydrogen fuel cell engine production base with an annual output of 2,000 units and HRS capable of refuelling 50 fuel cell buses a day.

Importantly, in July 2019, the Zhangjiakou city government introduced *10 measures to support the development of the hydrogen industry*,[64] which included funding for research institutions and corporate technology centres in the city working on hydrogen; subsidizing and supporting work related to standard development; a mandate to include hydrogen industrial clusters in government procurement plans and give priority access to government services, including land sales (as well as lower land costs); and providing access to preferential loans and funding. The document also set out a 'reasonable' but undefined subsidy to fuel cell transport.

Significantly, the local government also introduced subsidized electricity costs capped at RMB 0.36/kWh (around US$ 0.05/kWh) for hydrogen produced from water electrolysis. In the same vein, in its 2022 Hydrogen Development Plan central government highlighted preferential electricity prices, although they left it to localities to determine if and at what levels to offer these.

In 2020, the municipal government also began to offer subsidies for the construction of HRS, offering refuelling stations with a daily capacity of more than 500 kg a one-off subsidy of RMB 8 million ($1.2 billion) while stations with a daily refuelling capacity of (200–500kg) receive RMB 4 million ($582,000).

Local and provincial authorities had a strong incentive to develop and showcase their low-carbon credentials and accelerate the deployment of hydrogen for the Winter Olympics. This meant that local government bodies worked together to ease approval processes while also collaborating with various state-owned enterprises (SOEs), including China Energy Investment Group Co., Hebei Construction and Investment Group Co., and Sinopec, to accelerate the construction of hydrogen refuelling infrastructure.

By the end of 2021, Zhangjiakou had installed renewable capacity of 23.5 GW, including 16.4 GW of wind and 6.95 GW of solar PV, along with 15 MW of solar thermal, and 65 MW of biomass, the largest non-hydro renewable capacity in China.[65] In mid-2021, it had six hydrogen production plants with an estimated production capacity of 25 tonnes per day and six HRS.[66] In addition, there were three stations under construction with a refuelling capacity of 7.7 tonnes/12 hours.[67] For the Winter Olympics in 2022, Zhangjiakou had put 710 fuel cell buses on the road but in early 2023, 444 fuel cell buses were reportedly in operation.[68] Zhangjiakou leads all other Chinese cities in FCV bus deployment.[69]

Still, at the time of writing, the main hydrogen consumers in the city include the fertilizer industry, methanol production, and polypropylene production, with hydrogen use in transport steadily increasing. While Zhangjiakou's policies have focused on developing a green hydrogen supply base and on FCV deployment, in large part for the Winter Olympics, reality seems to have fallen somewhat short of ambition. Building on its status as a demonstration cluster alongside four other cities, Zhangjiakou is

[63] Zhangjiakou city (15 May 2019). 'Suggestions on accelerating the development of hydrogen energy industry to build a low-carbon Olympic city' (关于加快推进氢能产业发展打造低碳奥运城市的建议) [in Chinese], https://www.zjkzx.gov.cn/article/2019-05-15/zjkzx-2020-13319.html.

[64] 支持张家口市氢能产业发展的十条措施, discussed in 'Zhangjiakou's ten measures to support the development of a hydrogen energy industry' (张家口十措施支持氢能产业发展) [in Chinese], 7 August 2019 http://heb.hebei.com.cn/system/2019/07/26/019718246.shtml.

[65] Hebnews, Zhangjiakou Become Number One in Renewable Generation (12 April 2022). 张家口市非水可再生能源规模位居全国第一 [in Chinese] https://baijiahao.baidu.com/s?id=1729878923272772463&wfr=spider&for=pc.

[66] Bjd, Zhangjiakou to become the largest green hydrogen production base in China (August 2021) [in Chinese], https://baijiahao.baidu.com/s?id=1708751909107561390&wfr=spider&for=pc.

[67] Bjd, Zhangjiakou to become the largest green hydrogen production base in China, (August 2021) [in Chinese], https://baijiahao.baidu.com/s?id=1708751909107561390&wfr=spider&for=pc.

[68] Xinhua (9 January 2023). 'Hydrogen-powered buses now on roads of Beijing Winter Olympics co-host city', https://english.news.cn/20230109/5e9a9e7fefe8462f84e52248efab15c6/c.html.

[69] Qin, J. (January 2023). 'Hebei Zhangjiakou takes the lead in the era of hydrogen public transport by leveraging the Winter Olympics', Economic Information Daily.

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part of an effort to promote and trial 7,710 FCVs within the Hebei FCV Demonstration Cluster from 2022 to 2025, making it the second largest such cluster nationally. In 2020, however, Hebei province issued the *Three-year Plan for Hydrogen Industry Cluster of Supply Chain Development,*[70] which set a 2022 target for Zhangjiakou to have more than 2,500 FCVs (including buses and logistics vehicles) out of 4,000 in Hebei province. Zhangjiakou's own plans were slightly less ambitious: in its *New Energy Industry Plan*,[71] the city aims to deploy more than 2,500 FCVs by 2025 (rather than by 2022).[72] Hebei province's *14th Five-Year Plan for Hydrogen*[73] released in 2021 also reduced Zhangjiakou's FCV goal to 1,500. The reason for the discrepancy in these targets is unclear but may reflect the fact that local officials prefer to overachieve a lower goal than underwhelm, and they were likely not on track to meet the initial target.

These revisions do not seem to have reduced the municipality's appetite for hydrogen development: Zhangjiakou still plans to adopt FCVs for logistics and goods vehicles, government vehicles, refuse trucks, and sprinkler trucks. To support FCV deployment, the city plans to build 18 HRS by 2025.[74] The municipality continues to promote a hydrogen industry as it is supported (and cited) in both provincial level targets and plans, and in national level documents, implying financial as well as policy support. Indeed, Hebei's provincial hydrogen plans name Zhangjiakou and Chengde as hydrogen industry clusters, supporting the development of renewable hydrogen through direct subsidies as well as tax incentives for companies in the hydrogen industry, particularly technology companies and small enterprises.

As set out in the city's plans, the government will experiment with hydrogen for energy storage, as well as in combined heat and power systems, and for minerals smelting. From 2021 to 2025, Zhangjiakou city will trial demonstration projects of combined heat and power systems powered by renewable energy and fuel cells in small residential compounds. By 2025, the city aims to demonstrate hydrogen projects for distributed combined heat and power systems. That said, there is no open source data on current hydrogen production and consumption in the city, and it is unclear how much hydrogen is used in industry versus FCVs or how much is derived from renewables. Additionally, hydrogen energy storage projects are still seeking financial capital investment.

The city's ambition and ability to attract new projects also seems to be growing, despite falling short of FCV targets. Zhangjiakou is home to China's first industrial application of wind power-to-gas in China. Launched in 2020, the Hebei Jiantou Guyuan Hydrogen Production Station Phase I[75] is a 200 MW onshore wind farm (connected to the grid since 2016) and a hydrogen production system by electrolysis with 10 MW capacity. The project's capacity at the end of 2021 was 1.7 tonne/day, alongside 4 tonnes/day renewable production from phase I of Zhangjiakou Haiboer (Harper).[76]

Zhangjiakou currently produces hydrogen from wind for new sectors such as FCVs rather than replacing industrial hydrogen derived from coal or industrial by-products from chemical processes such as the production of fertilizers, synthetic methanol, and polypropylene. The local government has not yet issued green hydrogen production targets and its plans have more broadly focused on creating new industrial champions and revenue streams. Indeed, by developing a hydrogen industrial supply chain, the city hopes to benefit from RMB 10.2 billion in tax revenues, see the creation of 35,000 jobs, and reduce CO_2 emissions by 166,000 tonnes per year (by 2035).[77]

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[70] The Hebei provincial government, Hebei Province Three-year Plan for Hydrogen Industry Cluster of Supply Chain Development, 河北省氢能产业链集群化发展三年行动计划（2020-2022 年）July 2020.

[71] Zhangjiakou Government, 'New Energy Industrial Plan' 新型能源产业规划(2021-2025 年).

[72] Zhangjiakou Government, 'New Energy Industrial Plan' 新型能源产业规划(2021-2025 年), January 2021.

[73] The Hebei provincial government, Hebei Province's Hydrogen Plan for Fourteenth Five-year, 河北省氢能产业发展"十四五"规划, July 2021, p. 26

[74] The Hebei provincial government, Hebei Province's 14th Five-Year Plan for Hydrogen, July 2021.

[75] 'New progress on the first domestic wind power hydrogen production project' (国内首个风电制氢项目新进展) [in Chinese], December 2020, https://www.gg-fc.com/art-40993.html.

[76] 'New progress on the first domestic wind power hydrogen production project' (国内首个风电制氢项目新进展) [in Chinese], December 2020, https://www.gg-fc.com/art-40993.html.

[77] Zhangjiakou's hydrogen development plan (2019–2035) has been published, (《氢能张家口建设规划(2019-2035 年)》发布) [in Chinese], http://www.china-nengyuan.com/news/china-nengyuan_news_140598.pdf.

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3.3. Lessons from Zhangjiakou's policies to develop its hydrogen industry

Subsidized electricity prices have supported industrial development, but are part of a broader policy environment. Subsidized electricity prices have sought to keep the price of hydrogen below RMB 30/kg ($4.4/kg), as electricity prices account for 70–80 per cent of the cost of hydrogen made by water electrolysis. Hydrogen production from wind projects in Zhangjiakou can also use electricity directly without sending power to the grid, avoiding costs such as capacity payments, power dispatch charges, and cross-subsidies. Zhangjiakou Haiboer (Harper) receives subsidized electricity, while also trading with wind power plants and using curtailed wind power, but its hydrogen production cost is still estimated at RMB 40/kg ($5.8/kg).[78] Accordingly, if power prices fall to an estimated RMB 0.2/kWh ($0.03/kWh), renewable hydrogen will be more cost-competitive than coal-based hydrogen. As such, the extent to which preferential electricity prices have driven investments in Zhangjiakou remains unclear, given that other factors have likely been appealing, including the availability of renewable power, central government support, as well as a developed industrial base. Indeed, government support remains strong: The municipal government hopes to cut the cost of renewable hydrogen production from RMB 30/kg ($4.4/kg) to RMB 14/kg ($2.04/kg) within four years through (as yet unspecified) policy support and technological upgrades.[79]

Transporting hydrogen remains a challenge. Given that hydrogen is classified as a hazardous material, and the cost of developing dedicated hydrogen pipelines is high, hydrogen production is confined to industrial parks under centralized management and is then distributed by truck to refuelling stations, which is not cost-effective for hydrogen outside of industrial applications. Zhangjiakou has created a regulatory exception that allows wind farms to build hydrogen production facilities on-site so they can use the power generated from wind to produce green hydrogen, though the distribution problem remains if hydrogen must be sent elsewhere for consumption. Even if surplus hydrogen output could be sent to other cities, the distribution of hydrogen in Zhangjiakou by long trailers is an additional constraint as it is costly and inefficient.

In general, the transportation costs of industrial by-product hydrogen production and natural gas hydrogen production are estimated in China at RMB 1.4–1.8/m3 ($0.20–0.26/m3) and RMB 0.9–1.9/m3 ($0.14–0.28/m3) respectively, compared with production costs of RMB 2–4/m3 ($0.30–0.58/m3) for electrolysis (considering that the hydrogen density is about 0.09kg/m3) and RMB 1–1.5/m3 ($0.15–0.22/m3) for industrial by-products. In Zhangjiakou, the cost of producing green hydrogen is estimated at RMB 1.8/m3 ($0.26/m3) after subsidies[80] suggesting that Zhangjiakou's green hydrogen is relatively cost-competitive compared with elsewhere in China.

This natural gas pipeline infrastructure can mix hydrogen, though the benefits of doing so to achieve carbon neutrality goals are modest. The International Energy Agency (IEA) estimates 15 per cent green H2 blending reduces natural gas direct CO_2 emissions by 6 per cent.[81] Zhangjiakou has not yet started to use existing natural gas pipelines to distribute hydrogen, although in 2020, Hebei province launched a demonstration project for blending hydrogen from wind power into the natural gas pipelines.[82]

Land use rules constrain Zhangjiakou's ability to produce and scale up green hydrogen. Like other Chinese cities, Zhangjiakou's land use for deploying (new) energy infrastructures is constrained by ecological red lines set by central government. Zhangjiakou local authorities in 2012 capped land use for economic development at 1.54 billion square metres for 2020.[83] However, the actual amount of land used reached 1.58 billion square metres in 2014, already exceeding the 2020 cap.[84] This implies that the city has developed cropland or environmentally protected lands.[85] The city's ecological red lines

[78] Tang, W. et al. (2022). 'Current situation analysis of electrohydrogen production under the background of "Carbon Neutralization"', IOP Conference Series: Earth and Environmental Science, https://iopscience.iop.org/article/10.1088/1755-1315/983/1/012035/pdf.
[79] Tang, W. et al. (2022). 'Current situation analysis of electrohydrogen production under the background of "Carbon Neutralization"', IOP Conference Series: Earth and Environmental Science, https://iopscience.iop.org/article/10.1088/1755-1315/983/1/012035/pdf.
[80] China Energy Research Society, Natural Gas Hydrogen Doping Verification Application Technology, April 2022.
[81] IEA (October 2021). 'Net Zero by 2050: A Roadmap for the Global Energy Sector', p. 76, https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.
[82] Gong, X., Quitzow, R., and Boute, A. (January 2023). 'China's Emerging Hydrogen Economy Policies, Institutions, Actors', RIFS Study, https://publications.iass-potsdam.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_6002649.
[83] The Zhangjiakou Government, Zhangjiakou City General Land Use Plan (2006–2020) (updated in 2017), June 2017.
[84] The Zhangjiakou Government, Zhangjiakou City General Land Use Plan (2006–2020) (updated in 2017), June 2017.
[85] The Zhangjiakou Government, Zhangjiakou City General Land Use Plan (2006–2020) (updated in 2017), June 2017.

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account for 24.98 per cent of the whole of the city's land, and demand for land use is set to rise in the coming decade as it plans to install 30 GW of wind power and solar PV. Zhangjiakou's green hydrogen development could borrow agricultural land, but this would not be a sustainable solution as the city doesn't have much agricultural land to give up. Excluding the area for protecting food security, only 0.56 billion square metres can be used for other purposes, accounting for 1.5 per cent of the overall land in the city. These remaining sites include grassland, inland tidal flats, saline-alkali land, swamp land, sandy land, bare land, and mining land. Within these constraints, Zhangjiakou will have to contend with the competing needs of land use for urban construction, other economic development and for wind farm deployment.

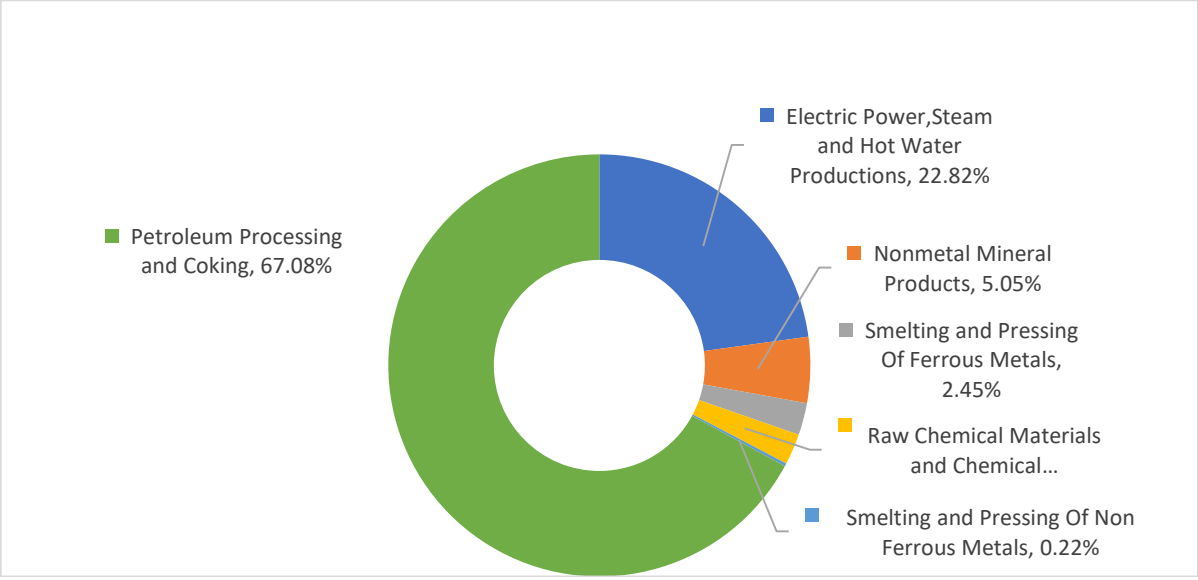
In sum, Zhangjiakou has made strides towards achieving its numeric targets of FCV deployment and of renewable hydrogen production but, with limited data, it is unclear to what extent the city is on track to meet its production targets. Its FCV deployment goals already seem to have been revised down.

Although green hydrogen in Zhangjiakou faces numerous obstacles, such as land constraints, distribution costs and questions around reliance on subsidized power costs, given the political support and the proximity to Beijing, the city will likely continue to develop both its renewables base and its hydrogen applications. Of the cities studied here, Zhangjiakou has the most favourable combination of policy support and resource endowment to develop green hydrogen.

4. Datong, Shanxi province

Datong is a radically different example to Zhangjiakou. It is a coal-based economy looking to hydrogen as an industrial development strategy, albeit one that will allow it to use its existing fossil fuel resources. Importantly, Datong is a coal-dependent city, and the second largest city in Shanxi province, one of China's largest coal-producing provinces. It has a population of 3.1 million and accounts for 9.1 per cent of the province's land area. In 2020, its GDP ranked seventh in the province. Coal accounts for about one third of Datong's GDP and coal consumption is mainly concentrated in the power and chemical industries. These industries, in turn, account for about 85 per cent of the total industrial value-added in Datong.

Figure 7: Value added of the (top) six energy intensive industries in Datong city, 2019



Source: Datong Statistical Yearbook 2020

Even though coal plays a dominant role in the city's economy, under the pressure of air pollution control and carbon emission reductions, Datong has sought to limit coal production and consumption. As a result, Datong's air quality largely meets the city's targets for annual concentration levels of Pm2.5, NO2, SO2, and carbon monoxide, as well as the city's eight-hour standard for ground-level ozone.[86]

In 2021, Datong city's coal output reached nearly 150 million tonnes (see Table 1), but Datong's 14th Five-Year Plan sets a target to reduce the capacity of coal mines to about 130 million tonnes by 2025,

[86] Datong 14th Five-Year Plan of Ecological and Environmental Protection, December 2021.

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with coal output of around 120 million tonnes. These targets highlight the pressure of carbon emission reduction plans on this resource-based city.

Table 1: Datong Coal Output from 2015 to 2021

Year	Output (million tonnes)	Annual growth rate
2021	149.9	12.80%
2020	132.1	6.70%
2019	122.5	9.80%
2018	111.6	2.20%
2017	108.6	10.40%
2016	95.6	-23.70%
2015	122.5	7.40%

Source: Datong Statistical Report of National Economic and Social Development

Datong's coal sector consists mainly of state-owned enterprises that have experienced weak economic performance in recent years. In 2020, 63 enterprises were engaged in coal mining and washing, of which 31 were unprofitable. The sector's asset-liability ratio had reached 107 per cent.[87] Datong's concerns about the economic and environmental sustainability of its coal industry motivated the government to find other drivers of economic growth.

Given Datong's heavy reliance on coal, stimulating economic growth for this city is challenging. Since 2001, the industrial value-added of the coal industry in Datong has been declining with the industry experiencing negative economic growth. This, in turn, has affected the city's social and economic outlook, given rising unemployment. In 2016, for example, China's elimination of old coal mines and cuts in coal consumption—as part of government efforts to reduce overcapacity in the coal industry[88]—weighed on the industrial value added. The local government has therefore been under pressure to manage its unemployed coal workforce, in part by transferring workers to other related industries.[89] Lastly, high-intensity coal mining has also led to resource exhaustion in the region, with some mining areas in Shanxi province entirely depleted.

4.1. Datong's brown hydrogen economy

Under these circumstances, hydrogen is increasingly regarded by the Datong Government as an important means for transforming the city's economic structure, mainly utilizing local fossil fuel resources. Hydrogen in Datong is currently produced from coalbed methane by coal-mining companies, using waste gas generated during the operation of coal chemical enterprises including methanol production. While there are a few demonstration projects for water electrolysis in Datong, none have reached a commercial scale. In 2020, these projects included Datang Yungang Thermal Power's 60 MW wind-solar electrolysis water hydrogen production system, and China Datang's 6 MW PV hydrogen production project.

Datong's abundant coal resources provide a cost advantage for producing hydrogen from coal locally. The municipality is looking to build a coal-to-hydrogen project with an annual output of 110,000 tonnes

[87] Datong Statistical Yearbook 2021.

[88] McGarrity, J. (January 2016). Roundtable: What are the benefits of China's ban on new coal mines? China Dialogue, https://chinadialogue.net/en/energy/8546-roundtable-what-are-the-benefits-of-china-s-ban-on-new-coal-mines/; Datong Coal Industry Co., Ltd. 2016 Annual Report [in Chinese], http://file.finance.sina.com.cn/211.154.219.97:9494/MRGG/CNSESH_STOCK/2017/2017-4/2017-04-28/3355436.PDF. This company merged along with the other two companies into Jingneng Holding Group in 2020; The State Council (February, 2016), Guidance on Resolving Overcapacity in the Coal Industry and Realizing Development Out of Difficulties [in Chinese], http://www.gov.cn/zhengce/content/2016-02/05/content_5039686.htm.

[89] For more on this, see Andrews-Speed, P. and Xu, Y. (August 2022). 'Managing the social consequences of the transition away from coal: the case of job losses in Shanxi Province, China', OIES Energy Insight 121, https://www.oxfordenergy.org/publications/managing-the-social-consequences-of-the-transition-away-from-coal-the-case-of-clean-heating-in-shanxi-province-china/.

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with an estimated cost of RMB 0.8/m3 ($0.12/m3),[90] or RMB 9/kg ($1.35/kg), much lower than the at least RMB 1.45/m3 ($0.21/m3) cost of natural gas hydrogen production, or RMB 16/kg ($2.35 /kg).[91]

Currently, hydrogen in Datong is mainly used for heavy-duty buses and vehicles as well as passenger cars. Datong is also investing heavily in industries related to hydrogen for transportation, such as hydrogen fuel cells and vehicle equipment manufacturing, and developing policies for hydrogen FCVs and HRS. During the 13th Five-Year Plan period (2016–2020), Datong put into operation 100 hydrogen fuel cell buses and 22 hydrogen fuel cell logistics vehicles. It also built the first 1 tonne/day hydrogen production and refuelling integrated station in Shanxi province.

In 2019, the Datong municipal government named Datong as a hydrogen city, and in 2020 issued the *Datong Hydrogen Energy Industry Development Plan for 2020–2030*,[92] followed in 2021 by prominent mentions of hydrogen in both the city's *14th Five-Year Plan for National Economic and Social Development*[93] and its *14th Five-Year Plan for Ecological Environmental Protection*.[94] These two plans discuss developing Datong as a model hydrogen energy city with a complete hydrogen energy industry supply chain, including hydrogen production and storage, construction of industrial links, and promotion of hydrogen FCVs.

While coal is widely seen as the basis of Datong's hydrogen development plans, the city is also adding renewable power which, according to government plans, could enable green hydrogen production in the future. At the end of 2019, the total installed capacity of renewable energy power generation in Datong city was 4.66 GW, accounting for 35 per cent of the city's installed power capacity. Wind power accounted for 1.88 GW, and grid-connected wind power generation accounted for 20 per cent of the province's installed capacity. Solar power generation reached 2.68 GW, and grid-connected power generation accounted for one third of the province's installed capacity.[95]

The need to improve local air quality is another factor in Datong's low-carbon transition and its desire to develop a hydrogen economy (see Table 2).

Table 2: Datong's emissions control targets

	2015	2020	2025 Target
Annual average PM2.5 concentration	34	31	Lower than 30μg/m3
Annual average O_3 concentration	127	150	Lower than 145μg/m3
Annual average SO_2 concentration	40	29	Lower than 20μg/m3
Annual average NO_2 concentration	25	32	Lower than 30μg/m3
Annual average CO concentration	2.6	2.8	Lower than 2.2mg/m3
Annual average PM_{10} concentration	74	70	Lower than 70μg/m3

Source: Datong's Fourteenth Five-Year Plan for Ecological and Environmental Conservation[96]

Datong's hydrogen development plan contains several quantitative targets for hydrogen, although these focus predominantly on the number of companies and revenue as well as on FCV and HRS deployment.

[90] The Datong Government (November 2020). As a coal city, Datong's Practice of Hydrogen Development, [in Chinese] https://www.dt.gov.cn/dtszf/szcjd/202011/3f20baf8bf134a77aeab3b8461762a57.shtml.

[91] Producing one cubic metre of hydrogen consumes 0.49 cubic metres of natural gas. At a gas cost of RMB 2.97/m3, the fuel cost of hydrogen production from natural gas alone is about RMB 1.45/m3.

[92] Datong Government, 'Datong Hydrogen Industry Development Plan (2020–2030)' (大同市氢能产业发展规划（2020－2030年）[in Chinese], http://www.dt.gov.cn/dtzww/szfwj1/202009/855ca69cf94b4d588a846f06d11af579.shtml.

[93] Datong Government, 'Datong City's 14th Five-Year Plan for National Economic and Social Development' (大同市国民经济和社会发展第十四个五年规划和 2035 年远景目标) [in Chinese], http://www.dt.gov.cn/2021zt/sswghgy/sswghindex.shtml.

[94] Datong Government, 'Datong City's 14th Five-Year Plan for Ecological Environmental Protection' (大同市"十四五"生态环境保护规划) [in Chinese], http://www.dt.gov.cn/dtzww/zcjddmtjd/202112/4298779be2cb41869c38c35b2b184eeb.shtml.

[95] Datong Government, 'Datong City's 14th Five-Year Plan for Ecological Environmental Protection', (大同市"十四五"生态环境保护规划) [in Chinese], http://www.dt.gov.cn/dtzww/zcjddmtjd/202112/4298779be2cb41869c38c35b2b184eeb.shtml.

[96] 大同市"十四五"生态环境保护规划的通知 [in Chinese], 12 December 2021, http://www.dt.gov.cn/dtzww/szfwj1/202112/08278ae479e94453a982fe214c014b79.shtml.

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Datong aims to deploy more than 1,000 FCVs by 2023, alongside 17 HRS, more than 6,300 FCVs by 2025, with 50 HRS, and dramatically increase its FCV fleet to 57,000 by 2030, deploying 100 HRS.

The Plan discusses the entire supply chain and includes broad goals for innovation. While it also includes an aspiration to develop green hydrogen, the Plan recognizes the importance of coal and therefore of CCUS development as well.

The Datong Government has issued a number of policies to underpin the local development of hydrogen industry. They include:

- improving government buying standards for procuring FCVs,[97] and providing strong support to demonstration projects;
- increasing government staffing in order to facilitate the process of land use application and hydrogen project approval, and offering incentives including tax rebates and local subsidies, although most of the preferential funding available for FCVs and hydrogen comes from provincial support mechanism or national funds (rather than municipal support);
- facilitating the process of putting key hydrogen projects in place, which include hydrogen's production, storage, transport, and refuelling;
- updating fiscal and taxation policies to promote the development of the hydrogen energy industry, such as exempting FCVs from purchase taxes, matching the national FCV purchase subsidy, reducing corporate taxes to 15 per cent for hydrogen technology companies, and subsidizing insurance for developing new hydrogen-related materials and equipment such as membranes.

In terms of technologies, Datong's Plan emphasizes CCUS as the most critical technology, given the importance of coal in the city's energy mix. Already in 2020, the Datong municipal government highlighted CCUS as a key technology with demonstration projects to capture 50,000 tonnes of CO_2 and convert them into carbon nanotubes.[98] But CCUS remains costly and, with few incentives from central government, scaling up remains a challenge.[99] The Datong Plan then highlights hydrogen pressure swing absorption (PSA) and new, low-cost membrane separation materials. Thirdly, it highlights the need to develop low-cost electrolysis technology and the need to research high-voltage compact alkaline liquid electrolyte electrolysis water technology (AE), develop new electrode and diaphragm materials, develop proton exchange membrane (PEM) using non-precious metal catalysts, and, finally, low-temperature, high-efficiency, low-cost, and good thermal stability methanol cracking catalysts. Finally, the Plan discusses the need to improve and develop key equipment and processes for methanol cracking hydrogen production. Various demonstration projects are earmarked for some of these technologies.[100]

The Plan expects Datong's hydrogen production to reach 20,000 tonnes per year in 2020–2023, increasing tenfold to 200,000 tonnes per year in 2023–2025, a much more rapid and ambitious growth target than the one set out in Zhangjiakou. In addition, the Plan expects that by 2025, roughly 100,000 tonnes will be derived from renewables-based hydrogen. Finally, between 2026–2030, the Plan expects hydrogen production in Datong to reach 1 million tonnes per year and the industrial output value to exceed RMB 40 billion ($5.8 million).

Given that coal remains the most significant source of hydrogen, the Plan estimates that by 2023, hydrogen production through flexible peak-shaving water electrolysis in thermal power plants will reach 2,500 tonnes per year and, by 2025, coal gasification + CCUS-based hydrogen production will reach more than 40,000 tonnes/year.

[97] This would include sanitation vehicles, waste collection vehicles.

[98] Shanxi Government (19 November 2021). 'Perspectives on promoting high quality development: Turning carbon into a treasure' (【全方位推动高质量发展透视】变"碳"为宝 大有可为（下)) [in Chinese], http://www.dt.gov.cn/dtzww/sxyw/202111/5a59f1e0cb024739ae37239ac64cf248.shtml.

[99] Shanxi Government (19 November 2021). 'Perspectives on promoting high quality development: Turning carbon into a treasure' (【全方位推动高质量发展透视】变"碳"为宝 大有可为（下)) [in Chinese], http://www.dt.gov.cn/dtzww/sxyw/202111/5a59f1e0cb024739ae37239ac64cf248.shtml.

[100] Datong Government, 'Datong City's 14th Five-Year Plan for Ecological Environmental Protection', (大同市"十四五"生态环境保护规划) [in Chinese], http://www.dt.gov.cn/dtzww/zcjddmtjd/202112/4298779be2cb41869c38c35b2b184eeb.shtml.

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To date, many of Datong's hydrogen policies are geared towards the manufacture of hydrogen FCVs and the development of fuel cells with pilot projects. Since 2019, several of Datong's hydrogen projects have been selected as key projects in Shanxi province,[101] providing them with financing and policy support. According to Datong's hydrogen industry development plan,[102] Datong's buses, logistics vehicles, special vehicles, and heavy trucks will gradually be replaced by hydrogen FCVs. Given that China's hydrogen policy was overwhelmingly geared towards FCVs prior to the 'dual carbon goal' announcement, Datong has also focused on the transport sector. A number of its key hydrogen projects listed in its 14th FYP for Strategic Emerging Industries are therefore focused on the transport sector (see Table 3).

Table 3: Datong's key FCV projects for its 14th Five-Year Plan (2021–2025)

Project	Details
Datong HydraV Yun Ding-Fuel Cell System	• Manufacturing 50,000 electric stacks, engine systems, and engine auxiliary systems a year by 2025. • In 2021, the production capacity will reach 5,000 sets, and the output value will reach RMB 500 million.
Datong Innoreagen-Hydrogen and Fuel Cells Projects	• Construction of office buildings, testing and experimental buildings, warehouses, system integration workshops, processing workshops, power transformation and transmission rooms, and outdoor supporting facilities. • The annual output of hydrogen fuel cell stacks aims to be 10,000 sets, with 1,000 sets in the first phase.
Refire Datong North Headquarter Project	• The project consists of three phases: the first phase in 2021 includes a production capacity of 30,000 sets of fuel cell engine systems, and an estimated output value of RMB 700 million.
CRRC Datong	• Hydrogen fuel cell engine system project (500 sets/year) and hybrid traction locomotive construction project (500 sets/year).
Zevauto – R&D and Manufacturing Base	• Planned annual production capacity of 3,000 units of hydrogen and electric buses, special-use vehicles, and logistics vehicles in phase 1. • Phase 2 includes an annual production capacity of 12,000 units/year, including the production capacity of hydrogen fuelled passenger vehicles (2,000 units/year).

Source: Datong's 14th Five-Year Plan for Strategically Important Emerging Industries (2022)

Merely replacing these vehicles with hydrogen FCVs seems to ignore the role that hydrogen can play in other areas as these vehicles account for a relatively low proportion of Datong's transportation industry. In 2020, the city had 31,000 passenger vehicles and about 45,000 medium and heavy-duty trucks, which together accounted for less than 10 per cent of the vehicle fleet.

Datong's support for its hydrogen economy relies on the central and provincial governments' subsidies schemes, as well as on low-cost coal produced locally. Much like in Zhangjiakou, the municipality's policy measures to date seem to focus on creating a hydrogen industry rather than on controlling emissions through the deployment of hydrogen. However, unlike Zhangjiakou, Datong's renewables-based targets may be highly aspirational.[103] Moreover, Datong's plans, unlike Zhangjiakou, rely heavily on Shanxi provincial support as well as on central government packages to encourage hydrogen

[101] These include a number of large engineering projects and parks such as Datong Hydrogen Xiongyunding Hydrogen Energy Technology Co., Ltd, Xiongtao Hydrogen Energy Datong Industrial Park established in 2019, the hydrogen energy and fuel cell industry project of Datong Xinyan Hydrogen Energy Technology Co., Ltd established in 2020, and Visionox Hydrogen Energy Datong Industrial Park Project established in 2021.

[102] The Datong Government (September 2020). Datong's Plan for Hydrogen Industry Development (2020-2030), [in Chinese] http://www.dt.gov.cn/dtzww/szfwj1/202009/855ca69cf94b4d588a846f06d11af579.shtml.

[103] By 2025, Datong's 14th Five-Year Plan sets out to install 10 GW of renewable energy generation, an increase from 4.66 GW in 2019.

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development. Moreover, with seemingly more modest support schemes than Zhangjiakou, Datong's green hydrogen ambitions are arguably over ambitious.

At the same time, Datong's industrial plans are also creating opportunities for other hydrogen applications and projects, with some initiatives including:

- Jingneng Holding Group (Guangfa Petrochemical Company) – hydrogen production via methanol purge gas. This project aims to build the hydrogen production capacity of 5,000 tonnes/year using pressure swing absorption.
- Tianjin Nichia – solid-state hydrogen storage materials for hydrogen production from wind and solar power. The project aims to develop wind-based hydrogen and solid-state hydrogen storage materials.
- SDTG – Hydrogen Project – Datong Industrial Park. An industrial park aimed at developing the entire value chain from hydrogen production to hydrogen storage, hydrogen fuel cells, HRS, and special equipment. The project aims to provide RMB 600 million in tax revenues and create 500 jobs.
- Datong Yugang – integrated energy utilization project: the construction of 2 million KW of photovoltaic power generation; electrochemical energy storage (100MWh); hydrogen energy storage (70MWh).

Even though Datong's *Hydrogen Energy Plan* mentions the development of hydrogen iron and steelmaking, there are no specific policies or operational projects yet. Its slow pace may be because of the sector's less notable contribution to Datong's GDP, which arguably makes it less urgent to grapple with. In 2019, the industrial value-added of ferrous and non-ferrous metal smelting and rolling processing industry was about RMB 0.2 billion, accounting for 5.54 per cent of the total industrial value-added.[104]

Indeed, although hydrogen has been mentioned in many of Datong's policy papers, the subsequent supporting measures seem limited. Most of the current fiscal and tax measures in Datong are aimed at the hydrogen FCV industry and include one-off subsidies. There is no specific support mechanism for CCUS development and deployment in the policy documents. While there are no preferential power prices, coal-based hydrogen is cost-competitive. In addition, the Datong Datang Yungang photovoltaic hydrogen production project for instance starts up its hydrogen equipment after 10 p.m. when power prices are lower, thereby allowing it to keep its power costs manageable.[105]

4.2. Outlook and challenges

Datong has been developing its hydrogen industry driven by factors such as policy pressure, mainly to reduce coal use, and a need to find new sources of economic development. However, despite the high share of renewable generation capacity in the province, Datong still primarily produces hydrogen from coal taking advantage of its low cost and ample supplies. The city's Hydrogen Energy Plan and 14th Five-Year Plan mention green energy but they offer few specific policies to encourage the development of green hydrogen. Indeed, other than numeric targets for hydrogen production and FCV deployment, the subsidy and incentive schemes are mainly focused on FCV infrastructure and, without subsidized power prices, coal-based hydrogen remains more competitive than renewables-based hydrogen.

In 2019, Datong's wind and solar capacity accounted for 42 per cent of installed capacity. It plans to increase it to more than 50 per cent during the 14th Five-Year Plan period and to promote the industrial demonstration of hydrogen production from renewable energy. Over time, renewables-based hydrogen could begin to compete with coal. Wind and solar electricity in the province are currently estimated to be as low as RMB 0.2/kWh but the low use of dedicated electrolysis plants still carries a significant cost penalty compared to coal-based hydrogen. Given that Datang, one of China's Big Five State-owned conglomerates, is dominant in Datong, it will likely impact the future development of hydrogen in the city. To date, the company has invested heavily in coal and is considered a laggard in renewables and cleantech. Much will also depend on the city's and the province's financial situation: with coal production and consumption rising in China, their ability to invest and fund new projects could increase.

[104] Datong Statistical Yearbook 2020.

[105] Tang, W. et al. (2022). 'Current situation analysis of electrohydrogen production under the background of "Carbon Neutralization"', IOP Conference Series: Earth and Environmental Science, https://iopscience.iop.org/article/10.1088/1755-1315/983/1/012035/pdf.

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It is noteworthy that hydrogen is repeated in a variety of policy documents, including the 14th FYP, the environmental protection plans as well as in new industry development targets, suggesting that hydrogen development meets a number of policy priorities for the city. Yet it lacks the policy focus and central government support that Zhangjiakou seems to enjoy, making its targets (both for hydrogen production and FCV roll-out) seem extremely ambitious. Without CCUS deployment, Datong could become a leader in coal-based hydrogen at the expense of its environmental targets.

Water scarcity might also restrict the development of green hydrogen in Datong. In 2020, Datong had a total water resource of 1.218 billion cubic metres, 816 million cubic metres of which was usable, equivalent to 297 cubic metres per capita, which is 14 per cent of the national average. In addition, the groundwater source that Datong's urban life and industry mainly rely on has been severely overexploited. The precipitation in the urban area is relatively low, and it will take years to restore the groundwater level. In 2019, water extraction exceeded 80 per cent of the local economy's needs. Also, coal mining in Datong has destroyed the groundwater aquifer. The impurities contained in the polluted water will reduce the service life of the electrolytic cell, so may not be suitable for hydrogen production by electrolysis. That said, research highlights that electrolysis uses less water[106] than coal mining or coal power. Datong's choice of hydrogen production (whether coal- or renewable-based hydrogen) will also have implications for water use.

5. Chengdu city, Sichuan province

Chengdu, the capital of hydro- and natural gas-rich Sichuan province in Southwest China, is the most populous of the three case studies, with more than 20 million inhabitants. The city, which has a mixed economy that includes IT, electronics, finance, and car-making, has accelerated its efforts to develop a hydrogen sector since 2019, after previous policies focused on FCV deployment. In its 2022 *Government Work Report*, Chengdu stated that it will develop the whole value chain of hydrogen, including production, distribution, storage, and consumption and build the country's 'green hydrogen capital'.[107] For Chengdu, hydrogen development is motivated by its desire to develop and lead in strategic emerging industries, given the city's large auto manufacturing base and extensive R&D facilities.

5.1. A gas-based hydrogen industry

The province's abundant gas resources—with a cumulative proven recoverable reserve of 35.4 billion cubic metres—currently account for the city's main hydrogen feedstock.

Hydrogen use is therefore concentrated in refining and synthetic ammonia. In 2020, nearly 60,000 tonnes of purchased hydrogen was used in manufacturing processes.[108] Over the course of the 13th Five-Year Plan (2016–2020), Chengdu's hydrogen policies, like many other parts of China, focused on the transport sector and FCVs, driven in part by industrial opportunity but also because of the city's large vehicle stock, and the pollution from tail-pipe emissions. In 2018, the city reportedly commissioned its first 10 hydrogen buses, after Dongfang Electric—one of the world's largest manufacturers of steam turbines and a Dongfang-based state-owned company—had started developing fuel cells in 2010.[109] Although like many other cities, it only published dedicated hydrogen policy papers in 2019, the city's 13th Five-Year Plan included targets for FCV and hydrogen refuelling station manufacturing and construction, with financial incentives and subsidies rolled out in support. As a result, in 2020, at the end of the 13th FYP, Chengdu city had 370 hydrogen buses and trucks, as well as two HRS[110] (with capacity for 1,500 kg/day each).

[106] Beswick, R.R., Oliveira, A.M., and Yan, Y. (August 2021). 'Does the Green Hydrogen Economy Have a Water Problem?', ACS Energy Lett. 2021, 6, 9, 3167–3169, https://doi.org/10.1021/acsenergylett.1c01375.

[107] '2022 Chengdu Government Work Report', 2022 年成都市政府工作报告 [in Chinese] (30 January 2023), http://gk.chengdu.gov.cn/govInfo/detail.action?id=135786&tn=6.

[108] 《成都统计年鉴 2021》*Chengdu Statistical Yearbook 2021*.

[109] China Daily (19 July 2019). 'The Leading Green Development in Chengdu of China', https://www.world-energy.org/article/790.html.

[110] The Chengdu Municipal Bureau of Economic and Information Technology (May 2022). Chengdu's Fourteenth Five-year Plan for Energy [in Chinese], http://cdjx.chengdu.gov.cn/cdsjxw/c132875/2022-05/24/content_dfc4301b05924fc1b7f3ab86ebdb997d.shtml.

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5.2. Policy support

In 2019, the city issued its *Hydrogen Energy Industry Development Plan (2019–2023)*[111] which, interestingly, was issued by the Chengdu Hydrogen Energy and New Energy Vehicle Industry Promotion Leading Group.[112] Typically, Leading Groups are ad hoc groups charged with decision-making on major functional issues. They are high-level steering committees that operate as inter-agency executive committees, cutting across government and party bureaucracies. Their existence highlights areas of importance in which coordination is deemed critical. Much like in Zhangjiakou, where the desire to develop a hydrogen economy led to cross-ministerial coordination (often a challenge in the Chinese bureaucracy), Chengdu institutionalized these efforts, highlighting the importance it attaches to hydrogen.

The 2019 Plan emphasized Chengdu's ambition in developing a hydrogen economy. Like many other cities, it outlined a goal related to industrial value (hoping for the industry to reach a value of more than RMB 50 billion by 2023 or $7.3 billion) and an ambition to promote more than 2,000 FCVs and 30 HRS by 2023. Much like in Datong, Chengdu's Plan covers manufacturing, infrastructure, logistics, and technological development, although it focuses on the use of hydropower as its hydrogen source.

The following year, the Chengdu municipal government issued further support policies to promote hydrogen development in the *Opinions on Promoting the High-quality Development of the Hydrogen Energy Industry.*[113] These include:

- Preferential electricity costs for electrolysis (at RMB 0.3/kWh or $0.04/kWh) alongside preferential gas supplies (although the policy documents 'encourage[s] natural gas suppliers to support qualified hydrogen producers' suggesting that the government relies on producers and distributors to implement this but cannot guarantee steady or low-cost supplies).
- Companies specializing in high-pressure hydrogen/liquid hydrogen storage are eligible for a one-off subsidy of up to RMB 5 million ($727,000) following an initial 20 per cent investment. According to the actual annual cumulative hydrogen transportation volume, companies specializing in hydrogen transportation will be given RMG 1.5/kg and a maximum operating subsidy of RMB 1.5 million.
- HRS are eligible for a one-off subsidy of up to RMB 5 million in addition to an operating subsidy of up to RMB 5 million.
- Manufacturers of key parts and components are awarded subsidies of up to RMB 10 million.
- Demonstration projects for distributed energy, cogeneration systems, hydrogen mixing, and hydrogen pipeline network construction can apply for subsidies of up to RMB 5 million, based on 10 per cent of the actual investment (excluding land cost).

Despite these support mechanisms, FCV deployment still requires considerable subsides. According to an interview conducted with an official from Dongfang Electric[114] in February 2022, the price to deliver hydrogen to refuelling stations in Chengdu was about RMB 35/kg ($5/kg). When adding hydrogen refuelling station fees, the retail price of hydrogen is estimated at more than RMB 60/kg ($8.7/kg). Yet in order to be competitive with diesel trucks, it is estimated that the cost would need to remain under RMB 35/kg.[115]

The impetus to develop hydrogen has further been accelerated by Xi Jinping's 'dual carbon' goals, with a number of Chengdu's 14th Five-Year Plans highlighting hydrogen (including Chengdu's *14th FYP for*

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[111] Chengdu Hydrogen Energy Industry Development Plan (2019-2023) (成都市氢能产业发展规划（2019—2023 年)) [in Chinese], July 2019, http://gk.chengdu.gov.cn/govInfoPub/detail.action?id=2398916&tn=2.

[112] 'Focus on breakthroughs in key links of the industrial chain and work together to promote the healthy and rapid development of the hydrogen energy and new energy vehicle industries' (聚焦产业链关键环节攻坚突破 合力推动氢能及新能源汽车产业健康快速发展) [in Chinese], Chengdu Daily, 15 April 2019, http://www.zgcdds.cn/detail.asp?id=50678.

[113] Chengdu Municipal Government (10 August 2020). 'Opinions of the General Office of the Chengdu Municipal Government on Promoting the High-Quality Development of the Hydrogen Energy Industry' (成都市人民政府办公厅关于促进氢能产业高质量发展的若干意见) [in Chinese], http://gk.chengdu.gov.cn/govInfo/detail.action?id=119605&tn=6

[114] Author interviews with official from Dongfang Electric, Chengdu, February 2022.

[115] The cost competitive price of hydrogen varies across different regions in China. Most industrial professionals would say between RMB 10 and 30/kg.

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Economic Development, its *Environmental Protection Plan* as well as its *14th FYP for energy development*[116]). In addition, hydrogen is promoted in regional integration policies, namely the Shuangcheng Economic Circle, which encompasses the Chengdu–Chongqing area.

The city's subsequent plans, issued in 2021, reiterated existing targets through 2023 while also looking to broaden hydrogen applications. Some of the targets[117] include:

- completing the construction of 40 HRS by the end of 2025;
- applying for national pilot FCV cluster status;
- promoting hydrogen in public transport, sanitation vehicles, forklifts, drones, and emergency supply;
- promoting and developing the entire hydrogen value chain and promoting sectoral standards;
- exploring the application of hydrogen storage;
- planning hydrogen tram lines;
- delivering green hydrogen to the city.

As the capital city of Sichuan, and with a better developed economy than many other cities in the province, Chengdu has a relatively favourable environment for promoting FCVs. In provincial government plans, Sichuan expects to roll out 6,000 FCVs across the province by 2025, with Chengdu leading the roll-out with at least 5,000 FCVs,[118] a lofty target compared with the other cities studied here and requiring a rapid roll-out.

In its *14th Five-Year Plan*, the city aims to increase its hydrogen production capacity to 110 thousand tonnes per year by 2025—accounting for a large chunk of the national goal—although there is no target for green hydrogen, and very limited data on current output or capacity. Since 2021, however, the municipality has published various plans and regulations in support of its efforts to become a green hydrogen city. These policies focus on FCVs, HRSs, and electrolysis facilities. The local government has reduced its preferential power prices—to RMB 0.15–0.2/kWh ($0.02-0.03/kWh)—and added subsidies for hydrogen stations and hydrogen storage. Chengdu's subsidy scheme offers numerous one-off incentives to companies and developers, unlike Zhangjiakou, for instance, that offers various preferential policies such as expedited approval processes, land use, and tax rebates. Chengdu also seeks to encourage foreign investors as part of its hydrogen bid,[119] while Zhangjiakou is hoping to become a global leader in the 2030s. All cities currently highlight the need for technology and rely on foreign inputs, but Chengdu's policy documents offer the clearest support for foreign investments.

5.3. A challenging hydro outlook

Yet for developing renewables-based hydrogen, Chengdu will need to rely on hydropower. Hydropower accounted for 77.39 per cent of the province's total generating capacity of 114 gigawatts (GW) in late 2021, or 88.87 GW, followed by 18.25 GW of thermal power. Wind and solar new energy accounted for just 7.23 GW due to unfavourable climatic conditions. The city's ability to produce green hydrogen therefore relies heavily on its hydro resources which in turn, are subject to rainfall. Even though Sichuan curtails hydropower each year, this tends to happen between June and October. Whereas in the winter and spring (from December to April), when water flow decreases, the province has to purchase power from other provinces in order to meet local demand. As such, producing hydro-based hydrogen during the dry season will be challenging.

[116] Chengdu Ecological Environmental Protection Plan (2021–2035); Chengdu's 14th Five-Year Plan for Energy Development; Chengdu's 14th Five-Year Plan for New Economic Development.

[117] The Chengdu Municipal Bureau of Economic and Information Technology (May 2022). Chengdu's Fourteenth Five-year Plan for Energy [in Chinese], http://cdjx.chengdu.gov.cn/cdsjxw/c132875/2022-05/24/content_dfc4301b05924fc1b7f3ab86ebdb997d.shtml.

[118] Sichuan Provincial Department of Economy and Information Technology (September 2020). 'Sichuan Province Hydrogen Energy Development Plan 2021-2025' [in Chinese], https://jxt.sc.gov.cn/scjxt/wjfb/2020/9/21/12979ab0d1cf41b18489d7d9559e4abf.shtml.

[119] Chengdu Municipal Government (10 August 2020). 'Opinions of the General Office of the Chengdu Municipal Government on Promoting the High-Quality Development of the Hydrogen Energy Industry' (成都市人民政府办公厅关于促进氢能产业高质量发展的若干意见) [in Chinese], http://gk.chengdu.gov.cn/govInfo/detail.action?id=119605&tn=6.

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In addition, despite hydropower curtailment, Chengdu is one of China's water-scarce cities, due to its location in the Chengdu Plain. Its per capita water resources are only one quarter of the national level.[120] Water supply to Chengdu mostly comes from the Min River and Dujiangyan, which have been heavily extracted. The intensity of water extraction has gone up to 80 per cent.[121] This is beyond international red lines for water resource development, which should be below 40 per cent. Some small rivers have even dried up or stopped flowing from time to time. The dry season is increasingly testing Chengdu's water supplies.

Sichuan's hydropower output is also subject to quotas: hydropower facilities are invested and operated by centrally-owned power companies, with electricity output allocated by central government through long-term contracts. Every year, the province is allocated a certain volume of hydropower for local use and transmits roughly one third of its hydropower to other provinces.[122] So, when hydro resources abound, Chengdu can use the surplus for hydrogen production. In 2019, for example, 9.2 billion kWh of hydropower[123] was curtailed. Yet the quotas governing Sichuan's local use of hydroelectricity do not take into account hydrogen production. In order to increase Chengdu's green hydrogen capability, central government needs to lift the city's quota on hydropower but given the long-term contracts in place any such revision may be challenging.

Chengdu has set out ambitious claims to become a green hydrogen city, in part to support China's goal to achieve carbon neutrality. However, the city has not defined the term 'green hydrogen', and existing policies do not provide a clear picture of Chengdu's vision for green hydrogen. As with Datong and Zhangjiakou, while municipal policies offer targets for hydrogen in transport, helping the city capture FCV subsidies from central government and developing new industries related to FCVs, they offer few details about green hydrogen in major industrial sectors that are far larger consumers of hydrogen.

Chengdu's hard-to-abate sectors contributed to 83 per cent of Chengdu's energy consumption in 2020.[124] Those sectors include power generation, heat generation and supply, raw chemical materials, and chemical product manufacturing, among others. As these sectors contribute to around half of Chengdu's value-added tax,[125] the government, at least in the near term, will prioritize affordable and reliable energy to these industries. Promoting their decarbonization through hydrogen applications will likely require considerable technological progress and sharp cost reductions to ensure their economic viability.

Given the economics of green hydrogen, it remains uncompetitive with local fossil fuel-derived hydrogen. Chengdu currently produces hydrogen mostly from natural gas, which is used in industrial sectors such as oil refining. There are a small number of trial projects to produce green hydrogen but few of them seem capable of supplying the government's targeted 5,000 FCVs by 2025. Furthermore, as there is currently no green hydrogen production in the city, and if the water electrolysis demonstration projects are not deployed at scale, Chengdu will struggle to become a green hydrogen city. Meanwhile, there are few plans looking to develop carbon capture, utilization and storage (CCUS) or policy proposals to repurpose the provincial gas networks to use gas for hydrogen production.

Pricing and cost competitiveness remain a major issue. FCV costs are higher than diesel for freight and have required subsidies to make them more competitive. Meanwhile, electricity prices are generally regarded as the main obstacle to hydrogen cost reduction, given that it accounts for 70–80 per cent of the cost structure. According to grid electricity price estimates by hydrogen sector, in China, green hydrogen will become cost-competitive with gas-derived hydrogen at prices below RMB 0.3/kWh ($0.04/kWh) and, according to some, at RMB 0.2/kWh or $0.03/kWh). Electricity for industrial use is now traded in the power market in Chengdu, but prices vary over the year, ranging from RMB 0.12–0.4/kWh ($0.019–$0.06/kWh) in 2021. While the Chengdu Government can subsidize electricity

[120] Chengdu Water Authority (October 2018). The 13th Five-Year Plan for Chengdu Water Development [in Chinese], http://cdwater.chengdu.gov.cn/cdsswj/c109465/2018-10/22/content_156177dd7b914d4c8fd974f31e827a7d.shtml.
[121] Chengdu Water Authority (October 2018). The 13th Five-Year Plan for Chengdu Water Development [in Chinese], http://cdwater.chengdu.gov.cn/cdsswj/c109465/2018-10/22/content_156177dd7b914d4c8fd974f31e827a7d.shtml.
[122] Xia, Z. (August 2022). China's power system needs to modernise, China Dialogue, https://chinadialogue.net/en/energy/chinas-power-system-needs-to-modernise/.
[123] Li, X. (January 2020). Last year, Our province abandoned 9.2 billion kwh of water, the lowest in six years [in Chinese], SCDaily, https://www.sc.gov.cn/10462/10464/10797/2020/1/4/74a684da782240b0b943ae6d157d20b9.shtml
[124] Chengdu Bureau of Statistics, Chengdu Statistical Yearbook 2021 [account required to sign in] https://tinyurl.com/yc6szhuv.
[125] Chengdu Bureau of Statistics, Chengdu Statistical Yearbook 2021 [account required to sign in] https://tinyurl.com/u7p26ee6.

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prices[126] to hold them below RMB 0.3/kWh for favoured industries, the high cost to the local government might be prohibitive. And such subsidies, despite their positive impact on cost reductions, would also work against central government efforts to promote the market pricing of electricity for greater economic efficiency.

Meanwhile, there is limited public data on the cost of Chengdu's current hydrogen production—from the industrial by-products of chemical processes powered by natural gas—but the cost in the country of using industrial by-products to produce hydrogen is RMB 5–6/kg ($0.73–0.87/kg).[127]

In sum, starting in 2019, Chengdu began to promote hydrogen, focusing on its nascent FCV industry, which builds on both the city's existing auto industry as well as on its high-tech and R&D capabilities. While the city's policies suggest an effort to eventually use natural gas infrastructure for hydrogen, transport will remain dependent on trucks in the near term. And even though green hydrogen from curtailed hydropower remains a prominent part of the city's vision for becoming a green hydrogen city, this concept faces limitations in practice given hydropower seasonality, water shortages in some years, and the need to comply with national and provincial renewable energy quotas. As with Zhangjiakou and Datong, Chengdu's concrete targets and incentives have focused on industrial strategy, especially related to the small FCV sector, and there is a lack of transparency or long-term targets for green hydrogen to substitute for fossil fuel-derived hydrogen in the main hydrogen-consuming industries. This likely reflects both uncertainty over whether the economics of green hydrogen will become competitive for such applications and the lack of clear policy support for such substitution at central government level.

Conclusion: insights from three hydrogen city case studies

While the three cities analysed in this paper do not cover all regional plans and initiatives, they offer a useful window into local hydrogen policy implementation and how cities are translating and adapting China's national hydrogen ambitions to local needs and priorities. They also illustrate the major challenges facing green hydrogen as it moves beyond the narrow, highly subsidized field of FCVs.

All three cities studied here had already begun investing in FCVs in the transport sector given central government's support for it. Zhangjiakou was an early leader in renewable energy deployment and hydrogen development. Beijing's air pollution reduction plans introduced in 2013—encompassing the Beijing-Tianjin and Hebei area—had already forced greater efforts to reduce air pollution in the province and the city, while the designation to co-host the low-carbon Winter Olympics with Beijing offered both motivation and funding.

Zhangjiakou gained considerable support from the central and provincial governments to ensure it would meet its targets for the Winter Olympics, while also supporting Beijing's energy transition. Importantly, the city has been designated as a demonstration city in the country's FCV pilot scheme and has issued preferential power prices to hydrogen producers. The combination of supportive infrastructure and the availability of competitively-priced renewable electricity suggest Zhangjiakou is well-positioned to develop its hydrogen economy both from an FCV manufacturing perspective and an emissions reduction point of view. That said, even with these favourable conditions, it seems to have lagged behind its FCV deployment targets, while land availability and hydrogen transportation costs and logistics remain open questions. Moreover, even though the city has plans to broaden hydrogen applications beyond the transport sector, additional sectoral plans are as yet unclear.

Datong presents a stark contrast with Zhangjiakou. The coal-rich city is gradually looking to diversify its economy away from coal, due to the 2030–2060 targets and the gradual depletion of its local coal resources, and it has looked to hydrogen as a means of diversification. Developing new hydrogen-consuming industries such as FCVs has also provided an additional customer for existing fossil fuel-derived hydrogen. But for now, Datong has few local policy incentives in addition to central government support mechanisms. In terms of reducing carbon emissions, even though the city emphasizes the need for CCUS, which would help decarbonize existing hydrogen production, there are few specific incentives to accelerate this. While it also hopes to promote green hydrogen at scale from the region's growing wind and solar capacity, the current policies would suggest that coal-based hydrogen in transport will

[126] 'The Measures for Optimizing Energy Structure and Promoting Green and Low Carbon Development in Chengdu' (July 2022) [in Chinese] set out that the government is providing power price subsidy of RMB 0.15–0.2/kWh for green hydrogen production, http://gk.chengdu.gov.cn/govInfoPub/detail.action?id=138846&tn=6.

[127] Jun, M. and Weijun, G. (December 2020). *The Production Methods of Hydrogen and their economical feasibilities*, *Energy Chemical Industry*, Vol. 41 No. 6.

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remain Datong's immediate focus. The city's targets seem extremely ambitious given the policy support and financing available to it. Given the dominance of state-owned power giants in the city and their need to find new avenues to promote their own low-carbon transition, Datong is likely to keep developing its hydrogen economy. However, whether it will pursue a renewables-based path or a coal-based hydrogen economy remains to be seen. The city also suffers from questions around water use and, as with other cities, the cost and ease of transportation.

Chengdu, meanwhile, plans to develop its hydrogen economy on the basis of both gas and hydropower resources, capitalizing on its auto infrastructure and position as R&D hub in China. While its hydrogen production currently relies on gas, Chengdu has focused its hydrogen policies on FCVs, emphasizing manufacturing, innovation, and supply chains. The 14th Five-Year Plan has added promotion of green hydrogen and suggested broader applications for hydrogen, with the local government introducing preferential power prices to encourage hydrogen from electrolysis. But Chengdu's hydropower resources may be ill-suited to provide the foundations of a green hydrogen economy, and the regulated power sector leaves limited excess capacity for hydrogen use. At the same time, there are few plans currently to use gas with CCUS. As in the other cases studied here, Chengdu is looking at hydrogen as an industrial and innovation strategy, with few details on how the city would plan to use hydrogen as a decarbonisation strategy.

Overall, all three city cases illustrate how hydrogen policy at the local level has mainly been implemented as an industrial policy, aimed at capturing central government subsidies to develop a new industry related to FCVs, as well as utilizing existing local energy resources to meet the incremental demand created by supporting FCVs and building HRSs. While FCVs are promoted and subsidized by central government, without subsidies it is unclear whether FCVs and HRSs will become a sustainable economic development pathway for cities. And even with these one-off subsidy schemes, existing stations are not yet profitable. Hydrogen distribution costs of up to RMB 30/kg—almost equal to the cost of making green hydrogen—have also prevented hydrogen from becoming competitive with diesel for heavy-duty vehicles, despite the recent surge in diesel prices.

Local governments are less focused on solving the problem of green hydrogen economics, for now. While hydrogen appears to offer promise for decarbonizing hard-to-abate industrial emissions in heavy industry, none of the city cases provide clear plans for substituting green hydrogen or fossil hydrogen with CCUS in their large, local industrial sectors—likely due to the high present cost and unclear pathway to reaching competitive prices with coal- and gas-derived hydrogen. The Chinese average production cost of green hydrogen varies widely from RMB 28–85/kg (US$ 4–12/kg) based on varying renewable electricity prices and types of electrolysers, whereas in Datong coal-based hydrogen averages RMB 16/kg (US$2.30/kg).[128]

While carbon prices could someday incentivize a shift away from fossil hydrogen, until central government expands carbon markets beyond an intensity-based system for coal power, the economics of green hydrogen or hydrogen with CCUS remain at a disadvantage and dependent on wider cost reductions in renewable electricity and electrolysis equipment, or on generous subsidies from municipalities, local governments, and central government.

The transportation and distribution of hydrogen remains a barrier with no clear solution. The designation of hydrogen as a hazardous good restricts the use of green hydrogen to local industry parks or small nearby facilities that can be served by truck, such as HRSs. Trucks can only carry small volumes of hydrogen, and there is an efficiency penalty. While natural gas blending is one potential option, only a small portion of China's gas grid currently performs such blending,[129] and there are administrative barriers to blending hydrogen in the important and transregional pipelines. Natural gas blending also does not offer a clear pathway towards decarbonizing hard-to-abate industries.

Local hydrogen policies lack clear, quantitative connections with carbon peaking and carbon neutrality. For now, hydrogen production relies on the cheapest industrial by-products and locally-available resources to supply the nascent markets. While the implicit strategy, including that of the China Hydrogen Alliance projections, is first to scale up hydrogen utilization, and then decarbonize hydrogen production once the economics improve, this poses a number of problems.

[128] Wang, Y., Zhou, S., Zhou, X., and Ou, X. (2021). *The Analysis of the Cost of Hydrogen Production from Different Sources in China*, Energy of China, Vol. 5.
[129] NDRC (23 March 2022). The Press Release of *The Interpretation of the Medium and Long-term Plan for Hydrogen Industry Development* [in Chinese], https://www.ndrc.gov.cn/xwdt/wszb/qncy/?code=&state=123.

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First, as the city cases illustrate, even in regions with high local production of hydropower (Chengdu), or wind and solar (Datong and Zhangjiakou), the variable renewable energy output and limited times when renewable energy curtailment occurs would severely reduce utilization of green hydrogen production equipment and thus the economic viability of hydrogen. While the seasonal storage of hydrogen is presented as a solution for integrating renewable energy, this would not resolve the utilization problem for electrolysis equipment. Second, there are also questions around the availability of land for additional hydrogen-dedicated renewables, concerns about water availability for hydro, and concerns about water scarcity for electrolysis in arid regions. Third, focusing only on boosting hydrogen demand, partly to utilize existing fossil resources, risks locking in capital infrastructure around existing fossil industries, rather than reallocating investment towards clean energy or emissions reductions strategies. Path dependence could be a serious dilemma for each of the three cities, where present investment could close off or hinder an eventual transition to green hydrogen or hydrogen from CCUS.

Quantitative targets for green hydrogen utilization in industry are currently lacking. Taken together, this list of interlocking economic and policy challenges cannot be resolved entirely either by central or local governments. However, the three case studies do point to one potential near-term policy solution that could push local governments to channel more effort and support towards green hydrogen and its utilization in hard-to-abate industries that presently rely on fossil hydrogen. Namely, central and local officials could require publication of hydrogen industry statistics and set annual and five-year planning targets to increase the share of low-carbon hydrogen. In the coal power sector, central government mandates an annual improvement in grams of carbon emissions per kWh of production. In the electricity sector as a whole, the government has set both capacity and percentage targets for renewable energy and non-hydro renewables, with annual quotas for the provinces and industry. Publication of annual statistics of hydrogen production by energy source would represent a first step. In addition, central government could use quantitative indicators to evaluate the success of local hydrogen policies, ensuring that coal-based Datong gets credit for incremental progress even if it cannot match the green hydrogen production of cities such as Chengdu or Zhangjiakou. National statistics would also prevent cities or companies from simply shifting carbon-intensive hydrogen production beyond their boundaries, or claiming titles such as green hydrogen city without substantive achievements.

For now, it is clear that most Chinese cities prioritize hydrogen to drive the growth of local economies, opportunistically capturing central government subsidies to facilitate the development of whole FCV supply chains. Hydrogen's potential to decarbonize sectors such as manufacturing and chemicals so far plays an insignificant role in local strategic planning. Notwithstanding the importance to local officials of showing progress towards the national 2030–2060 carbon peaking and carbon neutrality goals, hydrogen policy at the local level currently seems less geared towards decarbonizing heavy industry or the economy as a whole. In this vein, China's pursuit of hydrogen as an industrial strategy, especially if cities such as Datong scale up coal-based hydrogen without CCUS, could undermine its longer-term decarbonisation goals.

At the same time, the support mechanisms and financing available for FCV projects could lead to rapid deployment of this technology, somewhat reminiscent of China's EV roll-out. Ultimately, much like with PV and batteries, a number of frontrunners could emerge. Unlike PV and batteries, which are modular and manufacturing-intensive, the hydrogen sector as a whole is more of a complex product system. The focus on FCVs could contribute to the scale-up of fuel cell manufacturing, and eventually to fuel cells falling sufficiently in cost in hard-to-abate sectors such as shipping, aviation, or long-distance trucking. However, scaling up green hydrogen or a low-carbon hydrogen economy as a whole will require more than just a scale-up of fuel cell manufacturing, and instead demands a more thorough and long-term set of policy measures and incentives that the city pilots currently lack.

Much as in the early days of EV development, Chinese cities and pilot projects are pursuing their own design and standards, with little centralized oversight. Indeed, while the central government hydrogen plan seems somewhat conservative in its output target (100,000–200,000 tonnes/year of green hydrogen by 2025), the cities are decidedly more ambitious. Central government is signalling caution, likely hoping to avoid some of the overinvestments in early-stage solar PV and battery markets, which led to inefficient use of national subsidies and safety risks. As cities issue numeric targets for value added from the industry or number of companies, there is a risk of wasteful investments and duplication. As these case studies show, China's hydrogen market will need to reconcile bullish local targets and more cautious central mandates.

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