WHITE PAPER

OCTOBER 2022

LIFE-CYCLE ANALYSIS OF GREENHOUSE GAS EMISSIONS OF HYDROGEN, AND RECOMMENDATIONS FOR CHINA

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ACKNOWLEDGMENTS

We are especially grateful for the contributions of Yongwei Zhang, Jianhua Chen, Chunxiao Hao, Bing Liu, Daizong Liu, and Hewu Wang of the expert advisory group; Naiqian Miao, Zhiting Yun, Leilei Zhang, Xicheng Li, Jiabin Zhang, and Qishen Sun of the research group; the China Automotive Technology & Research Center Co. Ltd, the Shanghai Fuel Cell Vehicle Commercialization Promotion Center, and the Foshan Institute of Environmental and Energy Technology; and Chelsea Baldino, Hui He, Tianlin Niu, Nikita Pavlenko, and Felipe Rodríguez of the ICCT. The authors also appreciate the contributions of Ruosu Wang. The views in this article represent the opinion and position of the authors only. Information regarding pilot cities comes from open sources such as published pilot targets and implementation plans. Any differences between the study's data and those of official programs may result from statistical differences or timing issues. We welcome comments.

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EXECUTIVE SUMMARY

Transportation contributes significantly to China's greenhouse gas (GHG) emissions and the national governments in China are promoting the use of fuel cell vehicles (FCVs) and low-carbon hydrogen to help decarbonize the transportation sector. Five agencies of China's national government in 2020 together launched a pilot city program to demonstrate FCVs and the use of hydrogen in cities. Between 2021 and 2022, 5 city clusters were selected for the pilot program, and the lead cities of the clusters are Beijing, Shanghai, Foshan, Zhangjiakou, and Zhengzhou. Under this program, each city cluster can receive up to 1.87 billion RMB (0.3 billion USD), based on its performance against certain evaluation criteria, to support the development of the FCV and hydrogen markets.

One of the evaluation criteria is the carbon intensity (CI) of hydrogen. To qualify for a grant, pilot cities need to use hydrogen with a CI lower than 15 kilograms (kg) of carbon dioxide (CO_2) emissions per kg of hydrogen, equivalent to 125 grams of CO_2 per megajoule (MJ) of hydrogen. Beyond that, cities can receive extra grant funding by using clean hydrogen, i.e., where CI is less than 5 kg CO_2 per kg hydrogen (or 41.7 gCO_2 per MJ hydrogen). While the purpose of this rule is to incentivize the production and use of low-carbon hydrogen, the current design carries risks. First, it lacks detail and guidance on emissions methodology. In particular, the official published document does not define the system boundary of emissions, while officials confirm that this CI applies only to CO_2 emissions during hydrogen production, meaning that the upstream and downstream emissions are not considered; nor are other GHG emissions. It is also not clear who could certify and verify the CI estimates, nor what methods they would use. Finally, whether the two CI thresholds are strong enough for developing a low-carbon hydrogen economy in China is an open question.

In this study, we estimate the CIs of eleven hydrogen pathways in China and compare them to the two thresholds under the pilot city program. We estimate CO_2 emissions from hydrogen production that are compatible with the pilot city program requirement, as well as the life-cycle well-to-wheel GHG emissions that enable a more comprehensive understanding of the climate impacts from hydrogen. Results from this study are shown in Figure ES1. Among the eleven hydrogen pathways, only hydrogen made from coal gasification has emissions of more than 15 kg CO_2 per kg hydrogen during hydrogen production and is therefore not eligible to be used under the pilot program. Four hydrogen pathways meet the additional subsidy threshold, which are hydrogen made from natural gas combined with carbon capture and storage (CCS), hydrogen made from landfill gas (LFG), and electrolysis hydrogen using 100% renewable electricity or grid-average electricity. However, from a life-cycle GHG emissions perspective, hydrogen made using grid-average electricity has the highest emissions among the eleven pathways, and its GHG emissions are even higher than fossil petroleum by a significant amount. This result indicates that the current program design, which covers only CO_2 emissions and excludes upstream and downstream emissions, is insufficient and can mislead the hydrogen industry into producing high-emitting hydrogen.

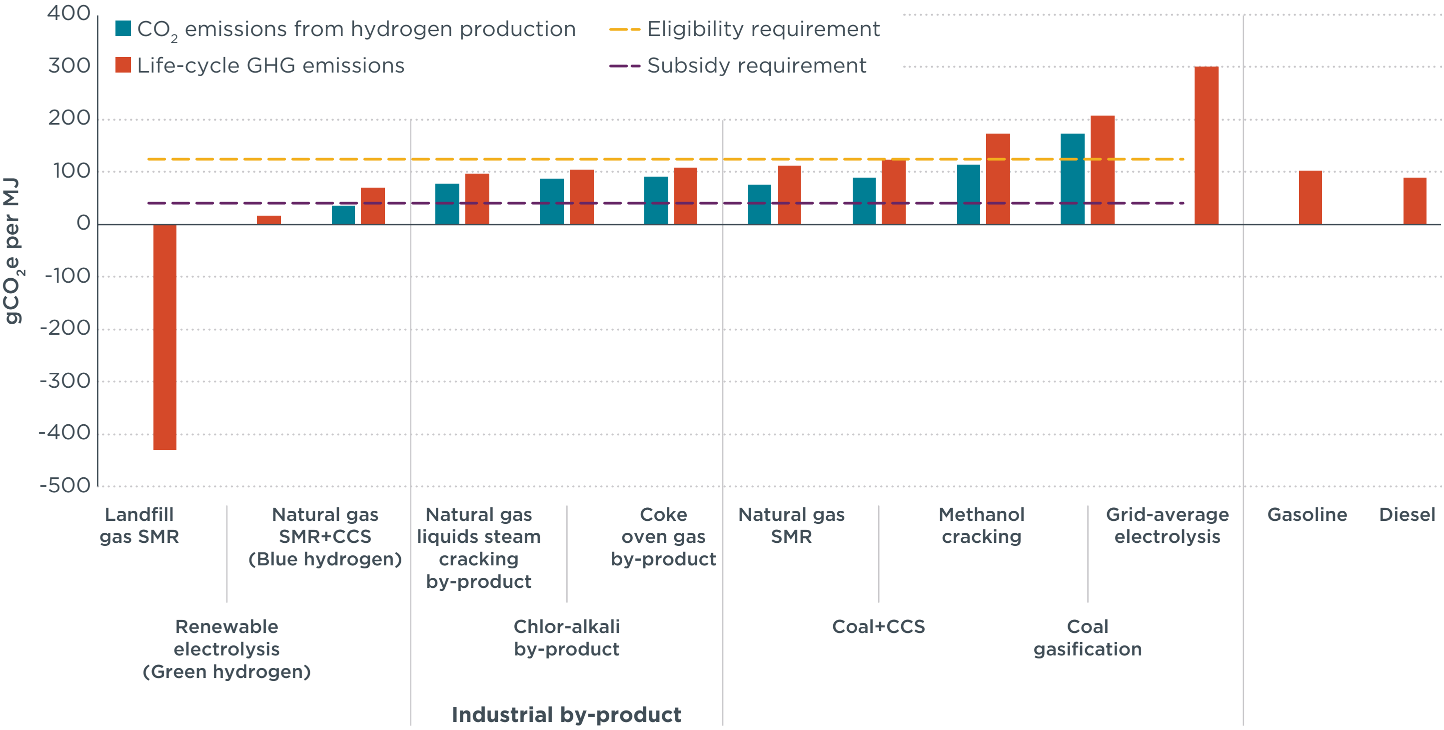

Figure ES1. CO_2 and life-cycle GHG emissions from eleven hydrogen pathways in China, using GWP-100. Grid-average electrolysis is based on national average grid. System expansion methodology is used for industrial by-product hydrogen.

Based on the analysis in this study, we provide the following policy recommendations to the national and local governments in China. These recommendations provide insights for developing a low-carbon hydrogen market that can be applied to the pilot city program as well as to any subsequent hydrogen policies.

1. **Set sufficiently stringent carbon intensity requirements for hydrogen**. This could be done by (1) expanding the system boundary to include life-cycle well-to-wheel GHG emissions; and (2) lowering CI thresholds. China could learn from the European Union's experience by setting a 70% life-cycle GHG reduction threshold for hydrogen to be used in the transport sector, which is equivalent to 28 gCO_2e per MJ or 3.5 kg CO_2e per kg hydrogen.
2. **Require renewable electricity certificates for grid electrolysis hydrogen and prohibit coal as an eligible feedstock for hydrogen production**. For hydrogen producers adopting grid electrolysis, purchase of renewable electricity certificates that cover the amount of electricity they receive from the grid should be required. Coal-based hydrogen poses significant climate risks and prohibiting coal as an eligible feedstock is in line with the national goal of transitioning to cleaner fuels.
3. **Develop a robust carbon accounting, certification, and verification system for hydrogen**. Such a robust system with detailed guidelines on emissions is the key to ensure compliance and avoid potential climate risks from false claims. Besides, it is also necessary to develop a robust certification and verification scheme specific to electrolysis hydrogen that ensures the additionality of renewable electricity. This would avoid displacing existing uses of renewables, which are likely to be replaced by grid electricity, causing substantial GHG emissions.

4. **Provide more financial support for clean, low-carbon hydrogen.** Under the pilot city program, grants devoted to the FCV sector are 7.5 times the amount granted to the hydrogen sector. More financial incentives are needed for scaling up the pathways that are truly low-carbon on a life-cycle basis, such as green hydrogen.
5. **Lift production restrictions for green hydrogen**. Current regulations in China restrict the production of hydrogen to chemical industrial parks. Such a regulation presents an obstacle to the scalability of low-carbon hydrogen.
6. **Explore more non-subsidy policies for the hydrogen industry**. National and local governments in China could explore non-subsidy policy instruments, such as providing discounts on land, taxes, and electricity prices that relieve the financial burden on hydrogen producers, and providing rights-of-way for FCVs, to expand demand for hydrogen.

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INTRODUCTION

OVERVIEW OF HYDROGEN DEVELOPMENT IN CHINA

Transportation is one of the main sectoral emitters of carbon in China. In 2020, its carbon emissions reached 930 million tonnes, accounting for 10% of the nation's total (EV100, 2020). The decarbonization of the transportation sector affects the process of achieving carbon neutrality in China. To date, China has not issued an official document on its decarbonization strategy nor on the carbon neutral target of the transportation sector. The national "Action Plan for Carbon Dioxide Peaking Before 2030" mentions the need to promote the low-carbon transformation of transportation tools and equipment, and to actively expand the application of new and clean energy such as hydrogen in transportation (State Council of the People's Republic of China, 2021). In the future, low-carbon hydrogen and other renewable energy sources will replace fuel oil, natural gas, and other high-carbon fossil fuels to achieve low carbon emissions in transportation, which will be an important landmark in the development of China's transportation industry.

The "Medium and Long-Term Plan for Hydrogen Energy Industry Development (2021-2035)" released by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA), proposes that by 2025, fuel cell vehicle (FCV) ownership will reach 50,000 units (National Development and Reform Commission, 2022), which is expected to reduce carbon emissions in the transportation sector by about 3 million tonnes per year. However, the overall scale of FCVs in China is still small, with only 8,938 units in the entire country in 2021 (China Association of Automobile Manufacturers, 2022). To achieve deep decarbonization in transportation, the adoption of fuel cell vehicles needs to be accelerated.

Hydrogen can be produced in various ways in China, such as coal gasification, natural gas reforming, industrial by-product hydrogen, and electrolysis using grid or renewable electricity. However, not all hydrogen production pathways contribute to decarbonization. Using the correct low-carbon hydrogen is thus crucial. In particular, the national government of China is promoting the production of green hydrogen, which is electrolysis hydrogen made from renewable electricity. The hydrogen industry development plan aims to produce 100,000 to 200,000 tonnes of green hydrogen by 2025 (National Development and Reform Commission, 2022). In order to scale up production and use of FCVs and the use of low-carbon hydrogen, the national government of China developed a pilot city program in 2020 to promote hydrogen use in transportation.

HYDROGEN AND FUEL CELL VEHICLE PILOT CITY PROGRAM

In 2020, five agencies of China's national government[1] together launched a pilot program for the demonstration of FCVs in cities (Ministry of Finance, 2020). This pilot city program, under the administration of the Ministry of Finance (MOF), aims to expand hydrogen production, commercialize the FCV market, promote FCV adoption, and reduce transport emissions through grants. To apply for the program, a city is required to form a cluster with other cities to establish a comprehensive supply chain of hydrogen fuel and FCV components. The lead city has responsibility for overall planning, including elaboration of a development plan that details the roles of each member city within the cluster, such as FCV manufacturing or hydrogen production. The lead city is also charged with tracking the progress made by its member cities and reporting to the MOF.

1 Ministry of Finance, Ministry of Industry and Information Technology, Ministry of Science and Technology, National Development and Reform Commission, National Energy Administration.

During the 4-year pilot period, each selected city cluster can receive up to 1.87 billion RMB (0.3 billion USD[2]).[3] from the national government, and the funding can only be allocated to support the development and deployment of the FCV and hydrogen markets. Once selected, each cluster needs to meet certain hard requirements to be eligible to receive the grant. For example, each pilot cluster needs to have at least 1,000 FCVs whose license plates are registered under the cluster city jurisdictions, and the traveling distance of each FCV on average must exceed 30,000 kilometers each year. Each cluster must have more than 15 hydrogen refueling stations (HRSs) in operation by the end of the pilot period. Each cluster must also produce at least 5,000 tonnes of hydrogen annually and the carbon intensity (CI) of hydrogen needs to be lower than 15 kilograms (kg) of carbon dioxide (CO_2) emissions per kg of hydrogen, equivalent to 125 grams of CO_2 per megajoule (MJ) of hydrogen.[4]

Beyond meeting the hard requirements, the grants available to the selected cities are based on a point evaluation system of their achievements; one point equals 100,000 RMB (15,000 USD). A cluster can earn up to 15,000 points under the category of FCV adoption and up to 2,000 points under the category of hydrogen supply. The two categories have specific sub-criteria for point accumulation. For example, cities can collect 0.9 to 1.95 points per FCV on the road, varying by year and vehicle size, with the points decreasing by pilot year, and with heavier vehicles receiving more points. Beyond the number of FCVs, the use of certain FCV components, assuming they pass reliability testing by an expert committee, qualifies that specific vehicle for an additional subsidy. For example, the cities can collect an additional 0.2 points per vehicle if the vehicle installs a qualifying membrane electrode assembly. Under the hydrogen supply category, pilot cities can collect 3 to 7 points per hundred tonnes of hydrogen used for vehicle refueling in the city, depending on the piloting year. On top of that, if the hydrogen being refueled is clean—meaning it has a CI of less than 5 kg CO_2 per kg hydrogen (or 41.7 gCO_2 per MJ hydrogen)—the pilot cities can collect an additional 3 points per hundred tonnes of hydrogen, which is equivalent to 3 RMB per kg hydrogen (0.5 USD per kg). An additional point per hundred tonnes of hydrogen can be collected (i.e., 1 RMB or 0.15 USD per kg hydrogen) if cities provide hydrogen at a retail price of 35 RMB per kg hydrogen (5.4 USD per kg hydrogen) or less.

Nineteen lead cities, i.e., clusters, applied, totaling more than 40 cities across the country. Between 2021 and 2022, 5 city clusters were selected by the national government; the lead cities are Beijing, Shanghai, Foshan, Zhangjiakou, and Zhengzhou. We provide a full list of the member cities of the five clusters in the Appendix. To ensure the success of the pilot city program, each cluster must develop, as part of its application, a comprehensive deployment plan that specifies the FCV technology development and number and types of FCVs, HRS construction and operation, hydrogen sources and safety, and policy instruments that local governments will provide to support each area. Table 1 and Table 2 summarize the current FCV and hydrogen industry in the five selected lead cities and the planned targets of their clusters by the end of the 4-year pilot period. Table 1 shows the number of FCVs and HRSs, annual hydrogen refueling capacity or demand, and hydrogen production capacity before and by the end of the pilot period. Table 2 indicates the distribution of hydrogen pathways before and after the pilot period. Overall, each of the selected clusters plans to scale up substantially the number of FCVs, primarily in the heavy-duty sector, and the number of HRSs. They also plan to increase their hydrogen production and diversify its supply, not only within the lead cities but also in the partner cities of each cluster. We provide more detailed descriptions of hydrogen pathways in later sections.

2 We assume an exchange rate of 6.5 RMB to 1 USD in this study.

3 A cap of 1.5 billion RMB can be received from FCV adoption and 0.2 billion RMB from hydrogen supply. Well-performed pilot clusters can receive additional 10% grants based on expert evaluation after the 4-year pilot period.

4 The lower heating value of hydrogen at 120 MJ per kg is used for conversion in this study.

Table 1. Current and planned hydrogen and fuel cell vehicle (FCV) industry in the five selected pilot city clusters. Note: Information before the pilot period is taken from the lead city only, due to lack of information from other jurisdictions. Information after the pilot period is for the entire cluster based on the development plan of each pilot cluster.

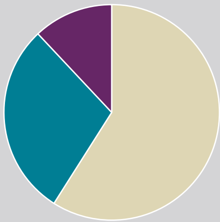
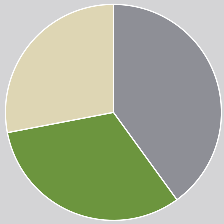
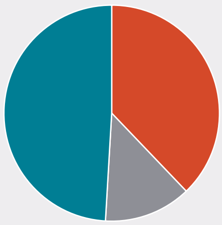
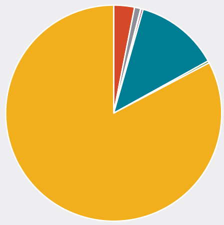
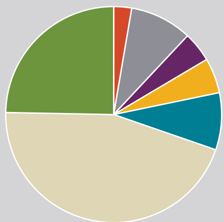
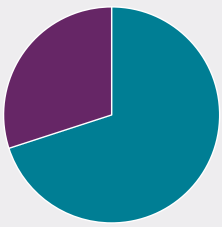
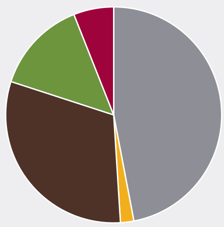
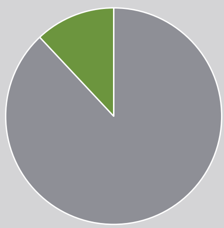
	Before the pilot period			By the end of the 4-year pilot period			
	Number of FCVs	Number of refueling stations	H_2 refueling capacity (tonne/year)	Number of FCVs	Number of refueling stations	H_2 production capacity (tonne/year)	H_2 refueling demand (tonne/year)
Beijing cluster[a]	700 • 78% bus • 16% truck • 6% car	10	2,440	5,300	49	95,000	21,000
Shanghai cluster	1,908 • 70% truck • 25% bus[b]	16	4,050	5,000 • 68% truck • 28% car • 4% bus	73	93,100	13,800
Foshan cluster	1,457 > 70% bus	16	1,811	10,000	200	465,000	79,160
Zhangjiakou cluster[c]	357 > 90% bus	8	2,900	7,710	86	200,000	40,000
Zhengzhou cluster	223 • 100% bus	4	1,100	≥5,000	80	43,200	22,000

a. Hydrogen production capacity and refueling demand of the Beijing cluster by the end of the pilot period is estimated based on member cities' published plans.

b. The remaining 5% includes passenger vehicles and postal cars.

c. Hydrogen production capacity and refueling demand of the Zhangjiakou cluster is based on information in its application. The numbers might be different from the official final document, which had not been released at the time this report was written.

Table 2. Current and planned hydrogen production pathways in the five selected pilot city clusters. Note: Information before the pilot period is taken from the lead city only, due to lack of information from other jurisdictions. Information after the pilot period is for the entire cluster based on the development plan of each pilot cluster. SMR = steam methane reforming. NGL = natural gas liquids.

	Before the pilot period	By the end of the 4-year pilot period
Beijing cluster	 NGL steam cracking by-product 59% Natural gas SMR 29% Grid electrolysis 12%	 Coke oven gas by-product 40% Renewable electrolysis (Green hydrogen) 32% NGL steam cracking by-product 28%
Shanghai cluster	 Chlor-alkali by-product 37.8% Coke oven gas by-product 13.1% Natural gas SMR 49.1%	 Chlor-alkali by-product 3.1% Coke oven gas by-product 0.9% Grid electrolysis 0.1% Landfill gas SMR 0.3% Natural gas SMR 12.6% Renewable electrolysis (Green hydrogen) 0.3% Methanol cracking 82.7%
Foshan cluster	 Methanol cracking 37% Natural gas SMR 63%	 Chlor-alkali by-product 2.7% Coke oven gas by-product 9.3% Grid electrolysis 4.5% Methanol cracking 5.3% Natural gas SMR 8.5% NGL steam cracking by-product 45% Renewable electrolysis (green hydrogen) 24.7%
Zhangjiakou cluster	 Natural gas SMR 70% Grid electrolysis 30%	 Coke oven gas by-product 47% Methanol cracking 2% Chlor-alkali 31% Renewable electrolysis (green hydrogen) 14% Grid electrolysis 6%
Zhengzhou cluster	 Coke oven gas by-product 100%	 Coke oven gas by-product 88% Renewable electrolysis (green hydrogen) 12%

The development plans submitted by the five selected clusters for the pilot city program suggest that a common policy instrument is to provide financial incentives to FCVs and hydrogen companies using provincial and local government funds, in addition to the grants made by the national government through the pilot city program. In one funding approach, provincial and local governments provide at least a 1-to-1 match of grants from the national government; this is used in the Shanghai cluster, Beijing cluster, and Zhengzhou cluster. For example, if the Shanghai cluster were awarded 1 million RMB from the national government for using clean hydrogen, the provincial and local governments of the cluster would devote a total of at least 1 million RMB for the same area. Another type of funding scheme is done without a specific fund matching with the national government. For instance, cities within Guangdong province under the Foshan cluster plan to allocate a total of 4.3 billion RMB during the 4-year pilot period, regardless of the level of grants from the national government. Under this overall funding scheme by each cluster, lead and member cities provide some specifications regarding the allocation of the provincial and local funds, which can also be categorized into two areas—FCV adoption and HRS operation. Table 3 lists some example financial support rules taken by the lead cities. A more comprehensive list can be found in the Appendix.

Table 3. Financial incentives provided by city and local governments in the five lead cities. Funds are provided to the FCV owners, FCV manufacturers, and HRS operators.

	For FCV adoption	For hydrogen refueling station
Beijing	• 3,000 RMB per 10,000 km traveled for light vehicles[a] • 10,000 RMB per 10,000 km traveled for heavy vehicles	• Subsidies provided to HRS using two categories of daily refueling capacity: ≥ 1000 kg or ≥ 500 kg
Shanghai	• Annual subsidy for trucks and buses traveled > 20,000 km in one year[b] • Max 5,000 RMB per vehicle weighing 12-31 tonnes • Max 20,000 RMB per vehicle weighing > 31 tonnes • Max 10,000 RMB per vehicle for buses	• Subsidy provided at a maximum 30% of HRS capital cost • If retail hydrogen price ≤ 35 RMB per kg, operational subsidy of 20 RMB per kg in 2021, 15 RMB per kg in 2022–2023, 10 RMB per kg in 2024–2025
Foshan	• 6,000 to 11,500 RMB per vehicle depending on vehicle type	• 1–2.5 million RMB per HRS if refueling capacity ≥ 500 kg per day
Zhangjiakou		• 4 million RMB per HRS if daily refueling capacity is 200 to 500 kg; 8 million RMB if capacity > 500 kg
Zhengzhou	• Subsidy of 5% of sales revenue to FCV manufacturers	• Subsidy of 50% of HRS capital cost

a. Light vehicles are those that weigh less than 4.5 tonnes. Heavy vehicles are those that weigh 4.5 tonnes or more, and include buses.

b. Provided up to 3 years by end of 2025.

In addition to financial incentives, some cities of the selected pilot clusters also plan to use other policy instruments to accelerate hydrogen production and FCV adoption. By regulation, hydrogen production plants in China must be located within chemical industrial parks. Some provincial and city governments offer a so-called green path to certain hydrogen producers to be built outside the chemical industrial parks; examples include plants that produce hydrogen from wind electricity in Hebei province and HRSs that have onsite hydrogen production in Foshan. Moreover, Guangdong province and Zhangjiakou are incentivizing electrolysis hydrogen through a discounted electricity price capped at 0.26 RMB per kWh and 0.36 RMB per kWh, respectively. While many vehicles in major cities in China need to follow traffic restrictions, Zibo and Tianjin give right-of-way preference to FCVs.

Despite the many national and local efforts to promote hydrogen and FCV adoptions in China, we found that the majority of existing policy support is toward FCV manufacturing and on-road adoption, with much less going to hydrogen production, especially the production of low-carbon hydrogen. By program design, larger grants under the pilot city program are given for FCV adoption than for hydrogen supply (15,000 points compared to 2,000 points). However, hydrogen fuel cost is an important contributor to the total cost of ownership of FCVs and the viability of hydrogen (Mao et al., 2021), and the CI of hydrogen being used determines the decarbonization progress in transportation.

Although the pilot city program sets a CI threshold for eligible hydrogen and a threshold for clean hydrogen that qualify for additional financial award, important details regarding how pilot cities could implement this piece of policy are lacking. Notably, there is no guidance regarding emission measurement. A foremost issue is that the official documents do not specify the system boundary of the CI (Ministry of Finance, 2020). However, through personal correspondence we learned that the CI requirements are for CO_2 emissions during hydrogen production only, excluding upstream emissions from feedstock extraction and processing and downstream emissions from hydrogen delivery. It is therefore unclear if there is a standardized methodology that all cities need to follow and who is responsible for emission measurement. It is also not clear how the program administrators, such as MOF, would certify and verify the emission estimates. The only industrial standard for hydrogen emission evaluation and certification in China is the *T/CAB 0078-2020 Standard and evaluation of low-carbon hydrogen, clean hydrogen and renewable hydrogen* that went into effect in 2020. This third-party voluntary standard provides some emission measurement guidelines, including the system boundary and verification requirements. In addition, this standard provides the definition of low-carbon hydrogen, clean hydrogen, and renewable hydrogen based on greenhouse gas (GHG) emissions (Table 4) (China Industry-University-Research Institute Collaboration Association, 2020). While the emission thresholds for low-carbon hydrogen and clean hydrogen from T/CAB 0078-2020 are similar to the two qualification requirements for hydrogen CI under the pilot city program, the former includes all GHG emissions (CO_2, methane, and nitrous oxide), while the pilot city program includes only CO_2 emissions. So far, it is not clear which standard will be used for the pilot city program and if so, what compatibility issues between them remain to be resolved.

Table 4. Definition of low-carbon hydrogen, clean hydrogen, and renewable hydrogen in the T/CAB 0078-2020 standard of China.

	GHG emission threshold during hydrogen production ($kgCO_2e$ per kg hydrogen)	GHG emission threshold during hydrogen production (gCO_2e per MJ hydrogen)
Low-carbon hydrogen	14.51	120.92
Clean hydrogen	4.9	40.83
Renewable hydrogen (renewable energy is the energy source for hydrogen production)	4.9	40.83

The purpose of this study is to evaluate the CI of different hydrogen pathways in China and to provide recommendations to policymakers of the pilot city program regarding hydrogen emissions. Specifically, we assess the GHG emissions from multiple hydrogen pathways that could be used in China and evaluate the effectiveness of this program for supporting a low-carbon hydrogen economy in China. Results from this study can be used to inform the pilot city program which hydrogen pathways are able to meet the 15-kg-CO_2-per-kg-hydrogen eligibility requirement and the 5-kg-CO_2-per-kg-hydrogen threshold for additional subsidies. Later in this report, we evaluate the hydrogen market in three pilot clusters as case studies: Beijing, Shanghai, and Foshan. We introduce policies in the European Union (EU) and the United States (U.S.) in supporting low-carbon hydrogen. Based on the evaluation results and international experiences, we identify hydrogen pathways that can offer the greatest decarbonization potential, and we provide recommendations of policy instruments that should be prioritized in China to facilitate deployment of low-carbon hydrogen in subsequent policies.

GREENHOUSE GAS EMISSIONS FROM HYDROGEN IN CHINA

In this section we estimate the life-cycle GHG emissions from various hydrogen pathways that could be deployed in China. This includes a mix of existing and near-term production technologies that could be used over the course of the pilot program, based on production parameters adjusted for the Chinese context. We first introduce the different hydrogen pathways to be evaluated, then give an overview of the methodology used to estimate the GHG emissions. Finally, we present the estimated GHG emissions for each pathway and discuss the implications of the results.

HYDROGEN PRODUCTION PATHWAYS

In our assessment of the development plan for each of the five pilot cities, we identified eleven main hydrogen pathways in China and evaluate the GHG emissions from these eleven pathways in this study, which are hydrogen produced from:

- Steam methane reforming (SMR) using fossil natural gas, with or without carbon capture and storage (CCS)
- SMR using biomethane
- Coal gasification, with or without CCS
- Water electrolysis using renewable electricity or grid-average electricity
- Methanol cracking
- By-product hydrogen from three industrial processes: chlor-alkali, coking, and natural gas liquids (NGL) steam cracking.

These hydrogen pathways include technologies that are already adopted in China or are likely to be adopted in the near future. At the national level, the majority of the hydrogen produced in China comes either from coal (about 40%–60%) or is an industrial by-product (about 20%–30%) (EV100, 2020). The three typical industries that produce gaseous hydrogen as a by-product or co-product[5] include (1) the chlor-alkali industry, (2) the steel coking industry that generates coke oven gas that contains 55% hydrogen by volume, and (3) the steam cracking of natural gas liquids.

SMR is also a popular technology for producing hydrogen in China. While the majority of the SMR-hydrogen uses fossil natural gas as the feedstock, some projects are piloting conversion from biomethane, such as landfill gas. Methanol cracking is another method of hydrogen production used in China. While methanol can be retrieved from different sources, we assume it is sourced from fossil natural gas in this study.

CCS is not yet common in China (EV100, 2020); however, it is generating great interest as a way to reduce CO_2 emissions from fossil-based hydrogen. Therefore, we include CCS for hydrogen from natural gas and from coal in this study to assess its impact. Hydrogen made from fossil natural gas combined with CCS is also known as blue hydrogen.

Water electrolysis is an emerging technology that has not been deployed at a large scale in China. While three different types of electrolyzers are applicable, the alkaline electrolyzer is the most developed in China and has the greatest potential for large-scale application (EV100, 2020). Many cities and companies are planning to scale up electrolysis, especially using renewable electricity, such as solar and

5 Although formal definitions are lacking in LCA methodology, by-products are typically considered to be different from co-products in that by-products are secondary products with inelastic supply relative to demand for them, whereas co-products, like primary products, are primary products with elastic supply (ICF International, 2015).

wind, to meet the country's decarbonization targets. Hydrogen made from 100% renewable electricity, also known as green hydrogen, can be produced two ways. One is to connect the hydrogen production facility directly to a renewable electricity generator. Alternatively, the facility can connect to the electricity grid, then retire renewable electricity certificates for the amount of electricity received from the grid. However, there is another crucial consideration for green hydrogen—the renewable electricity must be additional to what would have been produced in the absence of hydrogen production. This concept, known as additionality, is critical to ensuring that the renewable electricity for hydrogen is not diverted from existing uses or double-counted toward other policies. Otherwise, the CI of the electricity used for hydrogen production would be essentially the same as the average grid CI due to the diversion effects. Moreover, grid-connected hydrogen producers might not purchase renewable electricity certificates at all. We find relevant documents in China showing that the description of electrolysis hydrogen can sometimes be vague in terms of the electricity source and whether renewable certificates are used or not. Therefore in this study, we include a separate electrolysis pathway that represents the scenarios when renewable additionality is not met or where a hydrogen facility uses grid electricity as the energy source without renewable electricity certificates. This pathway is noted as grid-average electrolysis hydrogen throughout the paper.

METHODOLOGY

In this study, we evaluate the life-cycle well-to-wheel GHG emissions from the eleven hydrogen pathways identified above, in the Chinese context. Although the pilot program only factors in emissions from hydrogen production sites, well-to-wheel GHG life-cycle analysis (LCA) that includes emissions from feedstock extraction, fuel production, distribution and fuel combustion enables a more comprehensive understanding of a fuel's overall climate impact. Figure 1 illustrates the different system boundaries for the pilot city program and a full LCA in the study. The feedstock used to produce hydrogen can be a critical source of emissions upstream of the hydrogen production site; depending on the feedstock, these emissions can include upstream emissions from e.g., natural gas extraction, processing, and transportation to the hydrogen production facility. Additionally, there are also emissions attributable to the distribution and downstream processing of hydrogen, such as hydrogen compression or liquefaction. While both gaseous and liquid hydrogen can be used in the transportation sector, this study evaluates gaseous hydrogen only given its greater scalability in the near term. GHG emissions from combustion of hydrogen are essentially zero. In order to understand which hydrogen pathways can meet the CI requirements by the pilot city program, we also provide CO_2 emissions from hydrogen production alone.

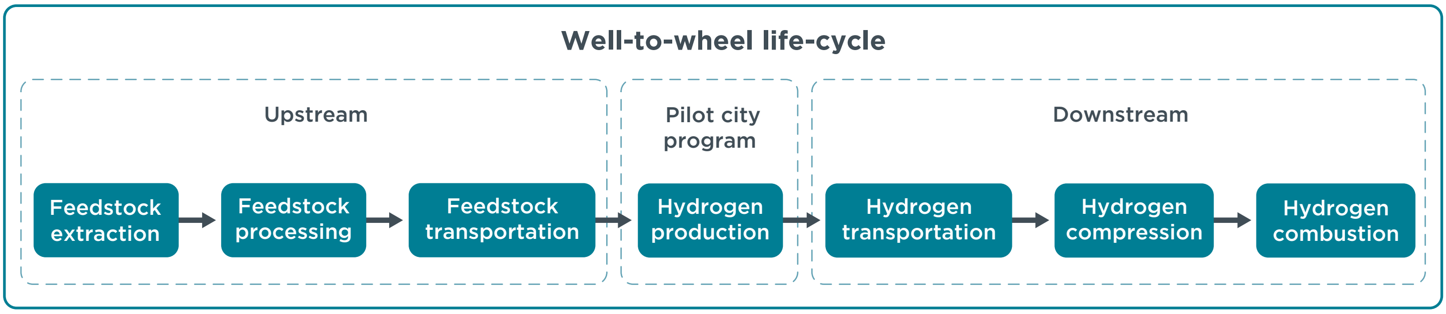


Figure 1. System boundary of the well-to-wheel life-cycle analysis in this study and in the pilot city program

While the hydrogen CI requirements under the pilot city program are based only on CO_2 emissions, this study also includes two other GHGs, namely methane (CH_4) and nitrous oxide (N_2O), to provide a more comprehensive understanding of the overall climate impacts. CH_4 and N_2O are more potent climate forcers than CO_2, and we use the global warming potential (GWP) values from the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) to normalize these gases' impacts into CO_2-equivalents (CO_2e). While these GHGs have different lifetimes and thus varying impacts in the short- or long-term, we evaluate climate impacts on a 100-year timeframe, noted as GWP-100.

We use the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model to estimate the CI of the various hydrogen pathways in this study (Argonne National Laboratory, 2020). GREET can provide a comprehensive framework to assess different types of transportation fuels on a consistent basis, and as a U.S.-based model, has been used in developing regulatory life-cycle emissions estimates for fuels in the United States. Moreover, the model provides flexibility to change the underlying assumptions and inputs, and thus can be adjusted to include regional data to better reflect hydrogen produced in China.

We update the upstream emissions of China's coal and natural gas based on a literature review (Luo et al., 2017; Qin et al., 2017; Gan et al., 2020; China Academy of Envronmental Planning et al., 2022). The CI of grid electricity varies by region. We collect the regional grid mix data in 31 provinces for the year 2021 from the National Bureau of Statistics (2022) and input the collected data into GREET. At the national level, power sources for the electricity grid in China in 2021 consisted of 71% fossil fuel, 5% nuclear, and 24% renewable. The grid mix varies significantly among regions in China. For example, Shanghai's grid mix has the highest share of fossil fuels at 98%, while the grid mix of Xizang province has the lowest share at 4% (National Bureau of Statistics, 2022). Based on a review of the pilot city development plans, we assume that the biomethane used for hydrogen production is sourced from collected landfill gas (LFG). To assess the CI of LFG, we assume that 20% of LFG is currently collected for flaring and the remaining 80% is released to the atmosphere (Cai et al., 2018), with none used for hydrogen production. When LFG is collected for hydrogen production, we assume a collection rate of 75%, a technically feasible rate (Mintz et al., 2010), and thus attribute avoided methane emissions from the current LFG management practice to the produced hydrogen.

In addition to modifying the upstream emissions in GREET to develop China-specific inputs, we make adjustments to the model's treatment of hydrogen production and transportation. Specifically, we change the default amount of CO_2 that is captured for the fossil hydrogen combined with CCS. Previous analyses found that the common industrial practice is to capture only about 55% of CO_2 generated during hydrogen production (Zhou et al., 2021). We thus adjust the default CO_2 capture rate in GREET for pathways using CCS from 90% to 55% to better reflect real-world practices. Although there are several hydrogen pipelines in China, pipeline transportation of hydrogen probably will not be common in the near future (EV100, 2020). Based on the development plans released by the five selected pilot city clusters, truck delivery is popular in China and is likely to remain so. Thus, we change the default transportation mode for hydrogen from pipeline to diesel trucking in GREET and assume the trucking distance between hydrogen production facility and the HRS to be 50 kilometers based on information collected from the pilot city development plans.

Assessing the emissions attributable to industrial by-product hydrogen can be complicated, in part due to the different LCA assumptions and methodological choices that could be applied to its upstream production emissions. Broadly, two LCA approaches can be used to attribute emissions to industrial by-product hydrogen: allocation and system expansion. In the allocation approach, the GHG emissions associated with a given product process (i.e., the industrial process that manufactures hydrogen as a by-product) are split among the various products, including main products, co-products, and by-products, based on their physical or economic properties, such as energy content, mass, or market value (ISO, 2006). In contrast, the system expansion approach evaluates the change in GHG emissions as a response to the change in diverting by-product hydrogen to the FCV market. This approach provides a big picture of GHG emissions associated with that pathway; the system is expanded to consider the change in environmental burdens from the diversion of the by-product hydrogen, which are then attributed to that hydrogen. For this reason, we consider the system expansion approach as our core scenario. Specifically, in the three cases of industrial by-product hydrogen pathways, GREET's assumed default use of hydrogen, along with other by-product gases, is onsite combustion to meet the energy requirement of the facility, based on the most common industrial practices in the United States (Joseck et al., 2008; Lee et al., 2017; Lee & Elgowainy, 2018). When the by-product hydrogen is diverted to the transport sector, natural gas is the substitute for onsite energy demand. However, we note that the industries in China might adopt different practices from replacing diverted hydrogen. Therefore, we also evaluate different allocation methods for a sensitivity analysis of GHG emissions from industrial by-product hydrogen. Getting a more representative result for industrial by-product hydrogen in China would require detailed research on facilities that generate by-product hydrogen in terms of hydrogen yield, the current use of hydrogen, and the potential substitutes, which is beyond the scope of this study.

Later in the report, we use the estimated CO_2 and GHG emissions from each hydrogen pathway to evaluate the overall CI of the hydrogen industry in three case studies, the pilot city clusters of Beijing, Shanghai, and Foshan.

RESULTS AND DISCUSSION

In this section, we present our estimated life-cycle well-to-wheel GHG emissions from each of the eleven hydrogen pathways in China. To assess which pathways meet the two CI thresholds under the pilot city program, we also illustrate a separate comparison of the CO_2 emissions only, from hydrogen production for each pathway. For electrolysis hydrogen produced from grid-average electricity, we show the emissions from different regional grid mixes. For industrial by-product hydrogen, because different LCA methodologies can be used, we later present the range of GHG emissions from using both the system expansion and allocation approaches.

Figure 2 illustrates the estimated CO_2 and GHG emissions of each hydrogen pathway, in grams CO_2 per megajoule (MJ), or CO_2 equivalent (CO_2e) per MJ in the cases of life-cycle GHG emissions. The blue bars show CO_2 emissions from the hydrogen production sites. The orange bars illustrate the life-cycle GHG emissions. The primary difference between the two approaches results from the inclusion of CH_4 and N_2O in addition to CO_2, as well as the inclusion of upstream emissions from feedstocks and downstream emissions from hydrogen transportation and compression. We order the eleven hydrogen pathways from left to right, from the lowest emitting pathways to the highest, on a life-cycle basis. Figure 2 also compares our estimated emissions (blue bars) to the two CI requirements by the pilot city program. The horizontal yellow line represents the 15-kg-CO_2-per-kg-hydrogen (125 gCO_2 per MJ hydrogen) CI requirement for eligible hydrogen to be used under the pilot city program. The horizontal purple line, at 5-kg-CO_2-per-kg-hydrogen (42 gCO_2 per MJ hydrogen), is the maximum CI threshold for pilot cities to receive additional subsidies from the use of clean hydrogen.

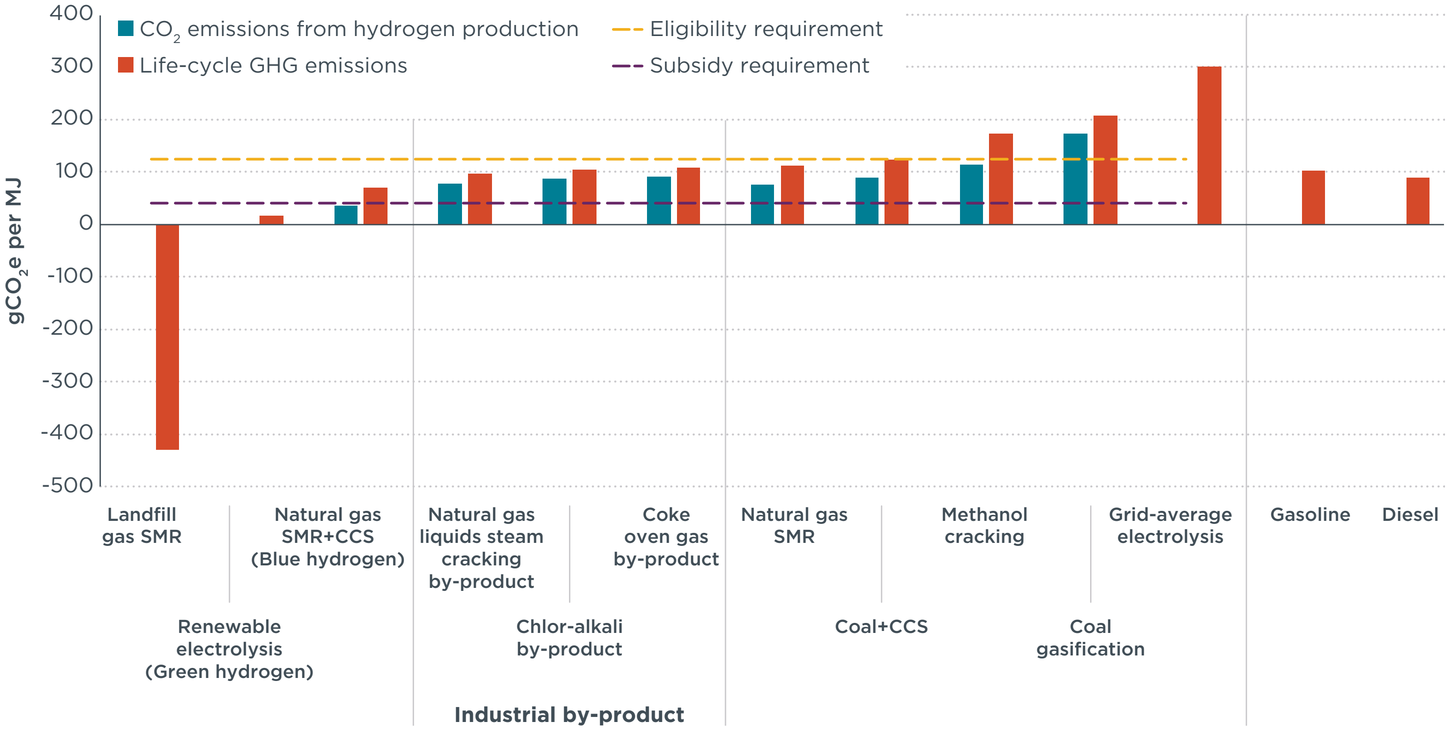


Figure 2. CO_2 and life-cycle GHG emissions from eleven hydrogen pathways in China, using GWP-100. Grid-average electrolysis is based on national average grid. System expansion methodology is used for industrial by-product hydrogen.

To understand the potential climate impacts of switching from fossil fuels to hydrogen, we also show the life-cycle GHG emissions from gasoline (102 gCO_2e per MJ) and diesel (90 gCO_2e per MJ) in China as the two far right orange bars (China Society of Automotive Engineers, 2020). We note that a direct comparison of the fuels' GHG emissions on an energy basis might not illustrate the full effect of replacing petroleum, as the internal combustion engine vehicles (ICEs) and FCVs have different efficiencies. When accounting for vehicle efficiency, hydrogen is more efficient per unit of energy supplied than gasoline or diesel. This means that hydrogen FCVs can travel further than conventional cars or trucks using the same amount of energy. An option in fuel policies that compare different fuels across multiple powertrains is to use an energy economy ratio (EER) for a more appropriate comparison that accounts for the efficiency differences between powertrains, as in the California Low-Carbon Fuel Standard. The EER for hydrogen, typically in the range of 1.3 to 2.5, differs by the type of ICE; for example, EER is around 1.3 comparing FCV with conventional trucks, meaning that FCVs can travel 1.3 times the distance of a diesel truck using the same amount of energy (California Low Carbon Fuel Standard Regulation, 2020; Mao et al., 2021). However, in this study we focus on emissions per unit of delivered energy and do not include vehicle efficiency in our scope.

Based on the results presented in Figure 2, Table 5 further summarizes whether each of the eleven hydrogen pathways meet the eligibility requirement and subsidy threshold based on CO_2 emissions from hydrogen production under the pilot city program.

Table 5. Qualifications of the eleven hydrogen pathways under the pilot city program in China. Grid-average electrolysis is based on the national average grid. System expansion methodology is used for industrial by-product hydrogen.

	Meets the eligibility requirement? (15 $kgCO_2$ per kg hydrogen)	Meets the subsidy threshold? (5 $kgCO_2$ per kg hydrogen)
Natural gas SMR	Yes	No
Natural gas SMR+CCS (blue hydrogen)	Yes	Yes
Landfill gas SMR	Yes	Yes
Methanol cracking	Yes	No
Coal gasification	No	No
Coal gasification+CCS	Yes	No
Grid-average electrolysis	Yes	Yes
Renewable electrolysis (green hydrogen)	Yes	Yes
Natural gas liquids steam cracking by-product	Yes	No
Chlor-alkali by-product	Yes	No
Coke oven gas by-product	Yes	No

The only pathway disqualified under the pilot city program is hydrogen produced from coal gasification without CCS. This reiterates the importance of phasing out coal in China, not only from the power sector, but also from other industries. In order to meet its carbon peak target by 2030, the Chinese government has released an action plan, that directs the slowed increase in coal consumption during the 14th Five-Year Plan (2021 to 2025) and the decrease in coal consumption during the 15th Five-Year Plan (2026 to 2030), with a particular focus on the power sector (State Council of the People's Republic of China, 2021). Under this pressure, the coal industry in China is seeking alternative uses of coal and intends to divert to hydrogen production. Some may argue for the plausible benefit of zero tailpipe emissions from hydrogen, even if the hydrogen is made from coal. While such hydrogen may have meaningful local air quality and health benefits, it may on the other hand undermine the overall climate impacts of displacing petroleum with hydrogen. An assessment of the life-cycle emissions for hydrogen production suggests that hydrogen produced from coal is far from a clean source of energy and is even worse than petroleum for the climate.

Only four hydrogen pathways qualify to receive the additional clean hydrogen subsidy: blue hydrogen, LFG-based hydrogen, and the two electrolysis hydrogen pathways. However, each of these pathways faces barriers for real-world application. For blue hydrogen, and similar to the coal+CCS pathway, CCS technology is just emerging and requires significant investment that can be even more expensive than hydrogen production itself and thus is unlikely to be adopted in the near future (EV100, 2020). Further, the carbon capture rate of current practices is only 55%. A slightly lower capture rate would disqualify blue hydrogen from meeting the subsidy CI threshold.

LFG-based hydrogen and electrolysis hydrogen have zero CO_2 emissions during hydrogen production (Figure 2). For LFG, any CO_2 emissions during SMR are offset by carbon sequestration in this bio-feedstock. Looking at the life-cycle GHG emissions in Figure 2, LFG-based hydrogen has huge negative emissions, which are attributable to the avoided methane emissions from collecting methane for hydrogen processing rather than releasing it into the atmosphere, which is currently the typical practice in China. We note that if in the future LFG collection becomes more common, or is required by regulation, the counterfactual scenario would need to be updated accordingly, which would result in higher GHG emissions than this study estimated. LFG collection, although common and mature in Europe and the United States, is not yet common in China, and using landfill gas for hydrogen production requires that landfills invest in LFG collection equipment and distribution infrastructure to supply LFG to hydrogen producers. Moreover, the availability of LFG is limited and is likely to decrease in the future, as China is moving away from landfilling to incineration (National Development and Reform Commission, 2021). However, there is the potential of producing biomethane from other sources; for example, through anaerobic digestion of organic materials, such as animal manure and wastewater sludge. Anaerobic digestion is a mature technology and making biomethane from these waste feedstocks would also provide climate benefits from avoided emissions from their current waste management practices, similar to LFG (Zhou et al., 2021).

For hydrogen produced from electricity, whether 100% renewable or national average grid electricity, the process of water electrolysis generates only oxygen and hydrogen, meaning that the two electrolysis pathways meet the subsidy threshold. However, the life-cycle GHG emissions (Figure 2) vary significantly by electricity source—17 gCO_2e per MJ green hydrogen (2 kg CO_2e per kg) compared to 301 gCO_2e per MJ grid-average electrolysis hydrogen (36 kg CO_2e per kg)—because of upstream emissions. For green hydrogen, there are zero upstream emissions from renewables. The high upstream emissions from grid electricity results from the combination of conversion losses in hydrogen production, and the high share of fossil fuels, such as coal and natural gas, that make up around 70% of power generation in China (National Bureau of Statistics of China, 2021). Consequently, hydrogen made from the national average grid electricity has the highest life-cycle emissions among the eleven hydrogen pathways, even higher than hydrogen made directly from coal or natural gas. The large emissions gap between the two electrolysis hydrogen pathways raises the question of whether the current policy design is sufficient. It is crucial to ensure that only additional renewable electricity is used and that green hydrogen incentives be complemented with robust additionality practices; otherwise, the climate benefits of green hydrogen could be significantly undermined. We expand on these implications in the Recommendations section below.

While the grid-average electrolysis hydrogen pathway in Figure 2 is based on the national average grid mix, in Figure 3 we show the non-fossil share of the regional grid for the five selected lead cities and three other provinces, and we find that the well-to-wheel GHG emissions decrease linearly with grid mix. The five lead cities (left five points in Figure 3) have higher shares of fossil fuels in their electricity grid and thus higher GHG emissions from grid-average electrolysis hydrogen, which further emphasizes the additionality issue under the pilot city program. Among all regions in China, Shanghai has by far the highest share of fossil fuels, leading to life-cycle GHG emissions at 53 kg CO_2e per kg for grid-average electrolysis. While electrolysis hydrogen meets the two CI thresholds under the pilot city program as it considers only CO_2 emissions generated during hydrogen production, Figure 3 shows the two threshold values for reference. Only when the share of fossil fuels falls below 28% can grid-average electrolysis hydrogen have less than 15 kg CO_2e per kg life-cycle emissions. Xizang province has the highest non-fossil share in its grid (96%), enabling life-cycle GHG emissions of 2.5 kg CO_2e per kg. Overall, 15 provinces among the 31 regions have non-fossil shares less than or equal to 20%, and only 4 provinces have non-fossil shares greater than 80%.

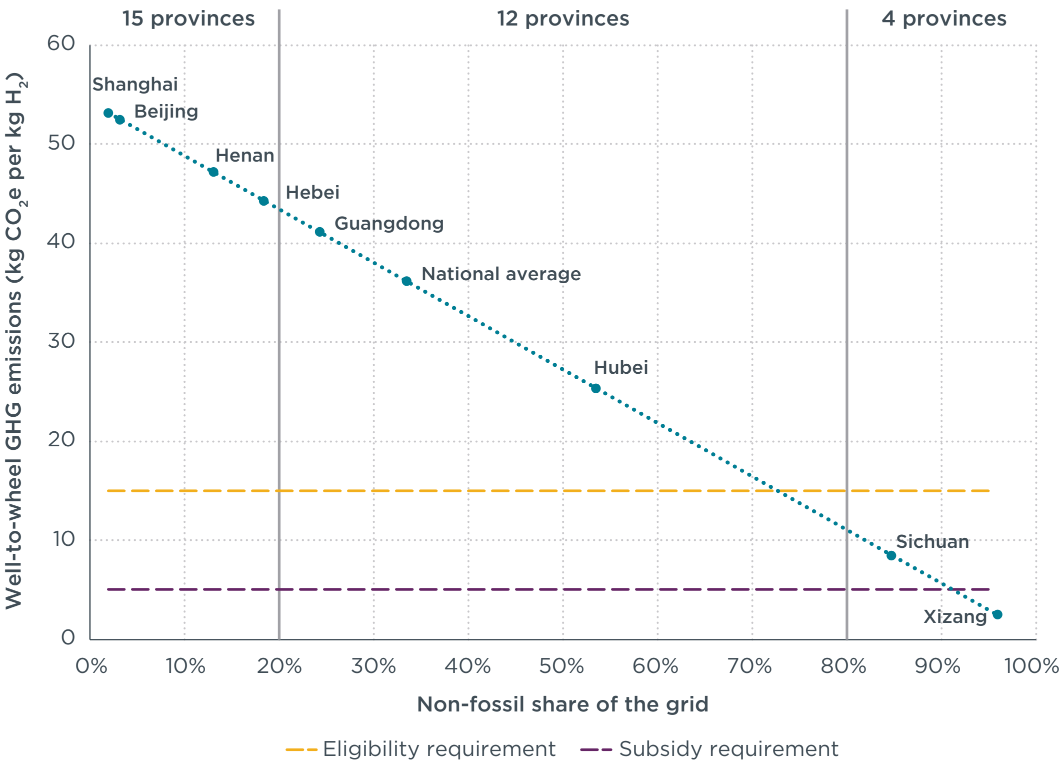


Figure 3. Well-to-wheel GHG emissions of grid-average electrolysis hydrogen varying by non-fossil share of the grid, using GWP-100.

Overall, we find that the difference between the best-performing (LFG-based hydrogen) and worst-performing (grid-average electrolysis) pathway is substantial, with wide variation across the set of pathways depending on feedstock and the conversion process. Assessing the life-cycle GHG emissions for hydrogen can yield emission results approximately 17% to 100% higher than accounting only for CO_2 emissions from hydrogen production, depending on the pathway, except for LFG-based hydrogen. The two pathways with substantial differences are LFG-based and grid-average electrolysis. Accounting only for CO_2 fails to capture the emissions from methane, a more potent GHG. Accounting only for production emissions fails to capture the significant upstream emissions from fossil fuels. Assessing the life-cycle GHG emissions for each pathway not only provides a full understanding of the climate impacts, but also allows for a more consistent comparison with other fuels. If not accounting for vehicle efficiency, we find that only three pathways have lower life-cycle GHG emissions than diesel, which are hydrogen produced from LFG, additional renewable electricity, and natural gas combined with CCS.

For all hydrogen pathways except the three industrial by-product hydrogen pathways, our estimated life-cycle GHG emissions are within the ranges provided by Abejón et al. (2020) that summarized multiple previous studies on hydrogen emissions from different regions of the world. As mentioned in the Methodology section above, multiple LCA approaches could be used to estimate industrial by-product hydrogen. While we use the system expansion approach as the core scenario in Figure 2, because it more accurately reflects the environmental burdens of diverting hydrogen production, Figure 4 shows the estimated life-cycle GHG emissions from the three industrial by-product hydrogen pathways using different LCA methods, presented as the bars.

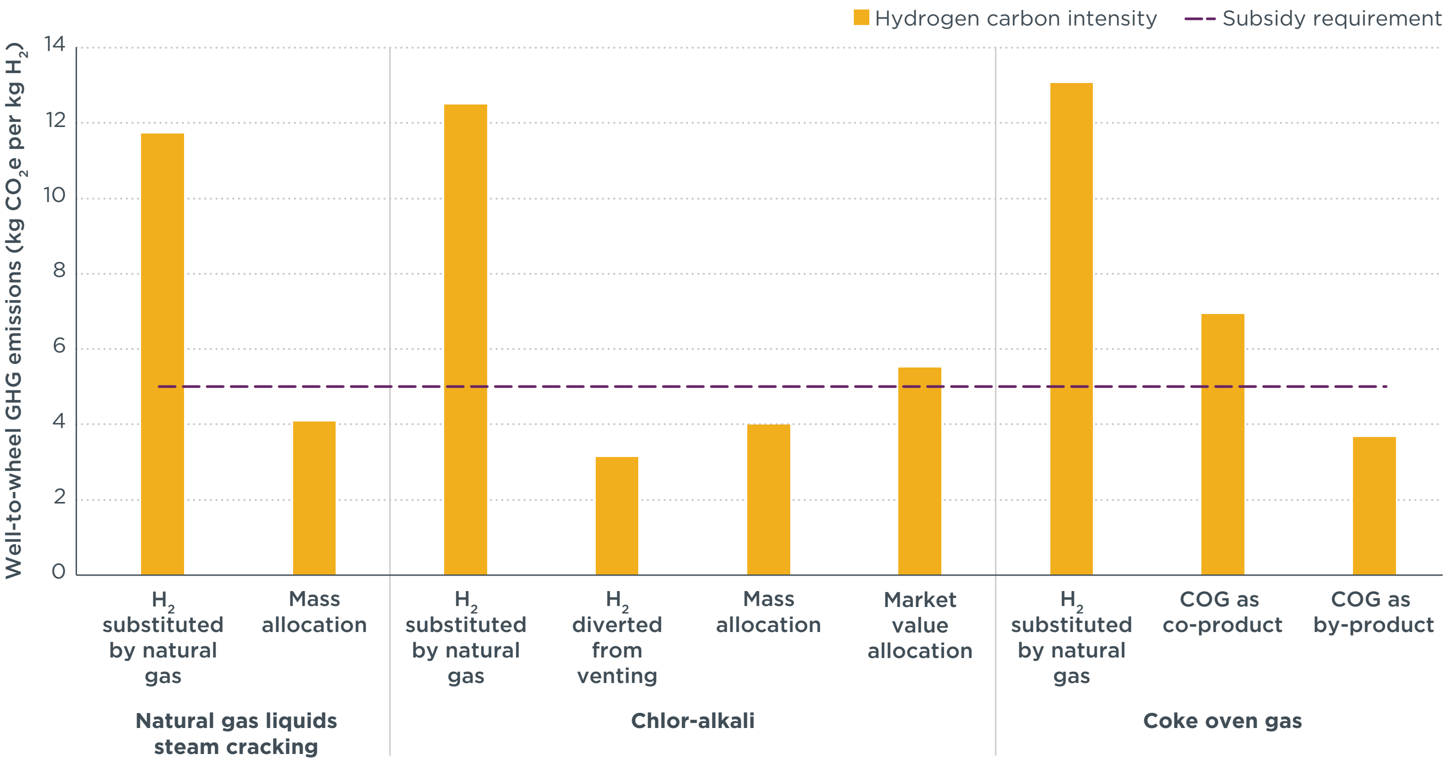


Figure 4. Estimated life-cycle GHG emissions from industrial by-product hydrogen by LCA method, using GWP-100

As illustrated in Figure 4, a wide range of emission estimates exist for industrial by-product hydrogen. These uncertainties come from the choice of LCA approach and the underlying assumptions regarding the industrial processes and the market values of the manufactured products. We find that the system expansion approach generally results in higher GHG estimates than the allocation methods. This is attributable to the relatively high life-cycle emissions from natural gas, which we assume to substitute for diverted hydrogen when it is diverted from its existing use. However, even within the system expansion approach, the assumption of the current fate of hydrogen at the industrial facility can make a huge difference in GHG emissions. Specifically, if the by-product gases, including hydrogen, at the chlor-alkali plant are being vented (fourth from the left bar in Figure 4) instead of being combusted (third from the left bar in Figure 4), chlor-alkali hydrogen would have 75% lower GHG emissions due to avoided emissions from venting. In terms of the allocation approach, the specific allocation method also contributes to estimation uncertainties. In the example of chlor-alkali by-product hydrogen, the market value allocation results in a 40% higher emission estimate than mass allocation. We estimate emissions for industrial by-product hydrogen in this study using the default assumptions in GREET, which are based on U.S. industrial processes and markets and might differ from emissions in China.

PILOT CITY CASE STUDIES

This section uses three selected lead cities as case studies: Beijing, Shanghai, and Foshan. For each city, we first give an overview of the hydrogen and FCV industry and discuss the challenges facing each city. We then assess the overall climate performance of the hydrogen being produced in its cluster based on the LCA results from the previous section.

BEIJING

Hydrogen supply

Before the pilot period, Beijing already had nearly 700 FCVs, mainly buses, light trucks, and refrigerated trucks, with a cumulative total of 22 million km operational mileage and a cumulative total hydrogen refueling volume of 1,200 tons. Before the pilot period in Beijing hydrogen mainly came from Yanshan Petrochemical Co., Ltd., and Huanyu Jinghui Co, Ltd., which were also the two hydrogen providers for the Beijing Winter Olympic Games in 2022. The designed capacity of Yanshan Petrochemical's hydrogen production plant is 2,000 Nm^3/h, equivalent to an annual production of 1,440 tonnes. This plant uses hydrogen by-products from the company's oil refining system and purifies hydrogen using pressure swing adsorption (PSA). Huanyu Jinghui mainly produces hydrogen from natural gas and grid electricity, with a capacity of 800 Nm^3/h and 500 Nm^3/h respectively, totaling 10.4 million Nm^3/year or 1,000 tonnes/year. Currently, there are 10 HRSs in operation in Beijing with a total daily hydrogen refueling capacity of 13.8 tonnes (or 5,037 tonnes annually). Of this total, the HRS at Daxing International Hydrogen Energy Demonstration Zone has a daily hydrogen refueling capacity of 4.8 tonnes, which is by far the largest HRS in the world (BDCN Media, 2021). Assuming the 700 vehicles each travel 30,000 km per year as per the pilot requirement, 1,470 tonnes of hydrogen would be required each year,[6] and the current hydrogen production capacity and hydrogen refueling capacity in Beijing can fully meet this demand. However, in February 2022, Beijing made it clear that by the end of the year, the city planned to adopt more than 800 new FCVs (Beijing Daily, 2022), and the "Implementation Plan for the Development of Beijing Hydrogen Energy Industry (2021-2025)" sets a target of 3,000 FCVs by 2023 and 10,000 by 2025 (Beijing Municipal Bureau of Economy and Information Technology, 2021). The expanding fleet of FCVs will put pressure on hydrogen production and refueling capacity.

Hydrogen in the 2022 Beijing Winter Olympics

During the 2022 Beijing Winter Olympic Games, more than 1,000 FCVs were put into use in Zhangjiakou, Yanqing, and Beijing for commuting. This was the largest FCV demonstration project in a major international event to date and the record for the largest number of fuel cell buses serving an international sporting event (Chinanews, 2022). Using FCVs can greatly reduce tailpipe CO_2 emissions compared to conventional vehicles, contributing to a low-carbon Beijing Winter Olympics (Chinanews, 2022). However, from the perspective of life-cycle emissions, some of the hydrogen pathways have high emissions and the hydrogen producers need to produce cleaner pathways to reach decarbonization.

Challenges

Due to the restrictions in the *Technical Specification for Hydrogen Refueling Stations GB50516-2010 (2021 version)*, HRSs cannot be built in the central area of a city. Therefore, no HRS has been approved to be built in urban areas in Beijing. Instead, HRSs in Beijing are concentrated in Fangshan, Yanqing, Daxing, and other remote suburban areas, for the purpose of serving the Winter Olympic Games. As a result,

6 Assuming a hydrogen need of 7 kg per km traveled for buses.

there is a disconnect between vehicle application and refueling, which is not conducive to the large-scale adoption of FCVs in the future.

Land costs in Beijing are high—up to ten thousand RMB per square meter to build an HRS in an urban area. The cost of a single station is too high if the land needs to be purchased. Using the current land resources of existing gas stations in urban areas to build hydrogen-gas joint stations can not only save costs by avoiding the need to purchase land for new HRSs, but can also save land resources and shorten the approval time of construction. However, the transformation of gas stations into HRSs in urban areas has not been realized due to above-mentioned location restrictions for HRSs.

In addition, the current number of FCVs in Beijing is relatively small, which leads to insufficient demand for hydrogen refueling. HRSs that cannot operate at full capacity have difficulty making profits. In the future, there will be a need to balance the synergistic development of the supply side and the application side. The target of 10,000 FCVs by 2025 in Beijing means an annual hydrogen demand of 21,000 tonnes, which is much greater than the current hydrogen refueling capacity of 5,037 tonnes in Beijing. It is necessary to increase the number of HRSs according to the planned number of vehicles, and to improve the hydrogen supply infrastructure network.

Hydrogen carbon intensity

Table 6, Table 7, and Table 8 show the hydrogen pathways and the volumes that the Beijing, Shanghai, and Foshan clusters, respectively, are planning to produce by the end of the 4-year pilot period. Based on the annual output, we calculate the volumetric share of each pathway (the same as in Table 2), which we then use to calculate the weighted average CI to get an overall hydrogen CI value for each cluster, based on CO_2 emissions from hydrogen production or life-cycle GHG emissions. The planned annual production of each pathway, and consequently the volumetric share and weighted average CIs, vary from year to year, and we show only the planned amount by the end of the pilot period in the three tables. The weighted average CIs represent only the hydrogen production sector rather than refueled hydrogen for the transportation sector. It is possible that the produced hydrogen will be used in other industries and thus the share of hydrogen pathway being refueled might differ from the share being produced.

By the end of the 4-year pilot period, industrial by-product hydrogen will be the dominant hydrogen source in the Beijing cluster. The remaining 32% is green hydrogen, which is the only pathway that qualifies for additional subsidy among the three adopted in the Beijing cluster. The calculated weighted average CO_2 emissions during hydrogen production is 7 kg CO_2 per kg hydrogen, which is 24% lower than the life-cycle GHG emissions.

Table 6. Share of hydrogen production pathway and carbon intensity by end of the pilot period in the Beijing cluster.

Hydrogen pathway in plan	Annual production in plan (tonne)	Volumetric share %	CO_2 emissions during hydrogen production (kg CO_2 per kg hydrogen)	Life-cycle GHG emissions (kg CO_2e per kg hydrogen)
By-product hydrogen from coke oven gas	38,000	40%	10.93	13.05
By-product hydrogen from NGL steam cracking	26,600	28%	9.36	11.73
Renewable electrolysis (green hydrogen)	30,400	32%	0	2.08
Total	95,000	100%	-	-
Weighted average CI	-	-	7.0	9.2

SHANGHAI

Hydrogen supply

Before the pilot period, Shanghai had 1,908 FCVs with a total mileage of about 17 million km, mainly covering logistics, public transportation, and commuting. Hydrogen was mainly produced by Hualin Gas, Shanghai Chemical Industrial Zone Gas, and Baoshan Base of Baosteel, with a total annual hydrogen production capacity of 4,050 tonnes. Among them, hydrogen supplied by Hualin Gas and Shanghai Chemical Industrial Zone Gas was produced by natural gas SMR, with an annual production capacity of 3,000 tons and 750 tons, respectively. Hydrogen supplied by Baoshan Base of Baosteel Corporation is purified by-product hydrogen from coke oven gas; the base has an annual capacity of 300 tonnes. Shanghai has built 9 HRSs with a total daily hydrogen refueling capacity of 8.9 tonnes (annual capacity of 3,249 tonnes). Among them, Shanghai Anting HRS was put into operation in 2007 and is the longest operational HRS in China. Shanghai Yilan HRS is equipped with two refueling pressures, 35MPa and 70MPa, and is the first HRS with pipeline hydrogen transmission and the first commercial 70MPa HRS in China. Sinopec Anzhi Road Oil-Hydrogen Combined Station and West Shanghai Oil-Hydrogen Combined Station are the first batch of gas-hydrogen joint stations in Shanghai that have obtained the operation license, which is a milestone for the future operation and management joint stations. If each of the current fleet of 1,908 hydrogen fuel cell vehicles travels 30,000 km per year, the annual hydrogen refueling demand in Shanghai will be about 4,000 tons, which is close to the hydrogen refueling capacity of Shanghai.

Innovations

Shanghai's hydrogen and FCV industry is at the forefront of the country in terms of demonstration and promotion, financial investment, and safety supervision. For example, in terms of demonstration and promotion, the "Implementation Measures of Shanghai Municipality to Encourage the Purchase and Use of New Energy Vehicles" was released in March 2018, which provided free licenses to FCVs. In terms of financial investment, Shanghai has devoted substantial resources to strategic new industry projects, industrial foundation projects, scientific research and special innovation initiatives, and special policies for industrial transformation and upgrading, with a total investment of more than 1 billion RMB in financial funds. Compared with other pilot cities, Shanghai is also more aggressive in offering financial support; for example, the national subsidy and the municipal subsidy would reach the ratio of 1:2 for FCV purchasing. In terms of safety supervision, relying on the Shanghai New Energy Vehicle Public Data Collection and Monitoring Research Center, Shanghai has implemented the collection and monitoring of FCV operation data and analysis, and has accessed 1,483 FCVs. Shanghai also built a public data platform for HRSs and FCVs to realize station data synergy and provide reference for future safety supervision of the industry. Nevertheless, Shanghai is facing challenges similar to those of Beijing.

Hydrogen carbon intensity

Methanol cracking from Ningdong city will be the number one hydrogen source for the Shanghai cluster, making up 82.7% of the total share. Hydrogen made from renewable feedstocks, i.e., LFG and renewable electricity, contributes less than 1%. As a result, the weighted average CIs in Shanghai cluster are relatively high. Thirteen percent of the hydrogen produced in the Shanghai cluster qualifies for receiving additional subsidies under the pilot city program. However, the system boundary under the pilot city program would underestimate the overall emission impacts from hydrogen by 34%. The weighted average life-cycle GHG emissions in the Shanghai cluster will be higher than 15 kg CO_2e per kg hydrogen. The Shanghai cluster has the highest emissions from hydrogen among the three case studies evaluated in this study.

Table 7. Share of hydrogen production pathway and carbon intensity by end of the pilot period in Shanghai cluster. Grid-average electrolysis hydrogen is based on Shanghai grid mix.

Hydrogen pathway in plan	Annual production in plan (tonne)	Volumetric share %	CO_2 emissions during hydrogen production (kg CO_2 per kg hydrogen)	Life-cycle GHG emissions (kg CO_2e per kg hydrogen)
By-product hydrogen from chlor-alkali industry	86,400	3.1%	10.4	12.49
By-product hydrogen from coke oven gas	26,000	0.9%	10.93	13.05
Natural gas SMR	349,000	12.6%	9.18	13.42
Landfill gas SMR	8,000	0.3%	0	-51.4
Grid-average electrolysis	2,200	0.08%	0	53.2
Renewable electrolysis (green hydrogen)	9,000	0.3%	0	2.08
Methanol cracking	2,300,150	82.7%	13.6	20.9
Total	2,780,750	100%	-	-
Weighted average CI	-	-	12.83	19.37

FOSHAN

Hydrogen supply

Before the pilot period, Foshan had 1,457 FCVs with a total mileage of about 13.9 million km; these are mainly fuel cell buses. Hydrogen in Foshan was supplied mainly by gas companies from surrounding cities,[7] with an annual hydrogen production capacity of about 1,811 tonnes. The major hydrogen pathways are chlor-alkali or NGL by-product hydrogen and hydrogen made by methanol cracking. Foshan has built 16 HRSs with a total daily refueling capacity of 11.35 tons (annual capacity of 4,143 tons). Among them, the Songgang Chantan Road HRS completed in 2019 was the first domestic HRS constructed based on the standard SAE J2601 "Fuel refueling protocol for light gaseous hydrogen surface vehicles" and standard J2601-2 "Fuel refueling protocol for heavy gaseous hydrogen vehicles." This HRS is in line with the international development trend of HRS technology and has become the benchmark for domestic HRSs. The hydrogen refueling capacity of Foshan can meet its current demand. However, the hydrogen production capacity within the city is slightly insufficient, and Foshan needs to import hydrogen from the surrounding cities. In the future, with

7 The gas companies that supply hydrogen to Foshan include Linkye Gas Co.,Ltd., Huate Gas Co.,Ltd., Linde Gas Co.,Ltd., Praxair gas Co.,Ltd., Air Liquide Co.,Ltd.

the increasing number of vehicles, Foshan will need to form a more robust hydrogen supply chain with the surrounding areas.

Hydrogen fuel cell industry

The hydrogen and FCV industry in Foshan is relatively well developed, and the city is taking a leading position in China, with more than 90 hydrogen-related enterprises and science and innovation platforms. The city has cultivated a number of well-known enterprises—especially in the production of hydrogen fuel cell reactors, power systems, and air compressors—and the hydrogen and FCV industry chain has taken its initial shape. In addition, Foshan Gaoming District has built a hydrogen fuel cell tram repair base to promote the industrial development and commercial operation of hydrogen fuel cell trams.

Innovations

Foshan is the first city in China to successfully build an integrated hydrogen production and refueling station. Through the coordination mechanism of the working group of hydrogen industry development in Foshan, the city clarified that the hydrogen production-refueling station is a supporting project for industry and is allowed to be built outside the chemical industrial park. As a result, the Nanzhuang Station was built and is operated through such a self-production and self-use mechanism. This mechanism solves the problems of an absence of local hydrogen and inefficient hydrogen storage and transportation. On July 28, 2021, Nanzhuang Station, the first hydrogen-natural gas joint refueling station in China, started its trial operation. The hydrogen production capacity of the station is 500 Nm^3/h from natural gas and 50 Nm^3/h from electrolysis. This capacity can meet the refueling demand of 100 buses or 150 logistics vehicles every day. Nanzhuang station can effectively alleviate hydrogen energy shortages in the region and avoid hydrogen transport, significantly reducing the cost of hydrogen supply.

Challenges

At present, only Huate Gas Co., Ltd. can produce hydrogen within Foshan, and the production capacity is only about 1 tonne/day, which is mainly for industrial uses. Hydrogen for HRSs is mainly purchased from Guangzhou, Jiangmen, Dongguan, Zhuhai, and other surrounding areas, which makes ensuring sufficient supply difficult when the market for hydrogen fluctuates. Hydrogen supply is the bottleneck in Foshan and the city needs to scale up its domestic production.

Due to the lack of a local hydrogen supply, the selling price of hydrogen at Foshan's HRS is relatively high, as much as 80 RMB per kg in 2021. The high price of hydrogen will be a major obstacle to the promotion of hydrogen passenger cars in the future.

The central areas in Foshan, such as Nanhai District and Chancheng District, are short of land resources, and land development has slowed as a result. The high cost of land poses a great constraint to the scalable development of the hydrogen industry, as site selection of HRSs and hydrogen production plants faces great difficulties, bringing serious challenges to spatial expansion of the industry.

Hydrogen carbon intensity

By the end of the pilot period, more than half of the hydrogen produced in the Foshan cluster will be industrial by-product. The Foshan cluster will also scale up electrolysis hydrogen. Overall, 38% of hydrogen produced in the Foshan cluster qualifies for receiving additional subsidies. The calculated weighted average CO_2 emissions during hydrogen production in the Foshan cluster is the same as in the Beijing cluster. However, the discrepancy in life-cycle GHG emissions, at 29%, is the largest among the three clusters due to a higher share of grid-average electrolysis hydrogen.

Table 8. Share of hydrogen production pathway and carbon intensity by end of the pilot period in Foshan cluster. Grid-average electrolysis hydrogen is based on Guangdong grid mix.

Hydrogen pathway in plan	Annual production in plan (tonne)	Volumetric share (%)	CO_2 emissions during hydrogen production (kg CO_2 per kg hydrogen)	Life-cycle GHG emissions (kg CO_2e per kg hydrogen)
Renewable electrolysis (green hydrogen)	107,549	24.7%	0	2.08
Grid-average electrolysis	19,600	4.5%	0	41.15
Natural gas SMR	37,200	8.5%	9.18	13.42
Methanol cracking	22,900	5.3%	13.6	20.9
By-product hydrogen from NGL steam cracking	196,000	45%	9.36	11.73
By-product hydrogen from coke oven gas	40,500	9.3%	10.93	13.05
By-product hydrogen from chlor-alkali industry	11,700	2.7%	10.4	12.49
Total	435,449	100%	-	-
Weighted average CI	-	-	7.0	11.44

INTERNATIONAL HYDROGEN POLICIES

This section reviews some of the hydrogen-related policies developed in the European Union (EU) and the United States. Both regions provide policy support for hydrogen production and hydrogen infrastructure. Regarding hydrogen production, both regions prioritize the deployment of green hydrogen. Example policy support includes setting a target for the amount of green hydrogen to be used and providing incentives based on GHG reductions.

EUROPEAN UNION

The European Commission has developed multiple strategies and policies to accelerate the production and use of low-carbon hydrogen, especially hydrogen produced from renewable electricity, for meeting EU's decarbonization target, i.e., reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels. In particular, the 2020 Hydrogen Strategy Communication set staged goals of renewable hydrogen production to be 1 million tonnes by 2024, 10 million tonnes by 2030, and a fully mature renewable hydrogen industry between 2030 and 2050 (European Commission, 2020). The recast Renewable Energy Directive (REDII) requires a 70% life-cycle GHG reduction for renewable fuels of non-biological origin (RFNBOs), which includes green hydrogen, compared to fossil petroleum at 94 gCO_2e per MJ. This requirement is equivalent to 28 gCO_2e per MJ or 3.5 kg CO_2e per kg hydrogen. In a recent proposed revision to the REDII, the Commission has proposed that 2.6% of the energy used in the transport sector come from RFNBOs (European Commission, 2021b). The same proposal also includes a target that 50% of hydrogen used in the industry sector be renewable (European Commission, 2021b). Member states may thus incentivize green hydrogen in order to meet the above requirements in the REDII.

Beyond policy support for hydrogen production, the European Commission has proposed incentives to scale up hydrogen infrastructure. Specifically, the European Commission is committed to building a hydrogen pipeline network with detailed rules and regulations in its proposed Gas Package (European Commission, 2021c). In this proposal, renewable hydrogen can access the hydrogen network at a discounted tariff. In addition to pipeline infrastructure, the EU's Alternative Fuels Infrastructure Regulation (AFIR) was proposed in 2021 and this regulation sets targets for the deployment of HRSs in cities and along highways (European Commission, 2021d). Furthermore, the European Commission also provides funding to develop an HRS network under the Connecting Europe Facility–Transport instrument over the 2021 to 2027 period (European Commission, 2021a). Policy support is not only provided at the EU level, member states within the EU also took the initiative to support hydrogen deployment. For example, Germany has allocated 60 million Euros worth of funding to HRS construction in 2021 (Petrol Plaza, 2021).

UNITED STATES

Several policies to support hydrogen deployment are in place or have been proposed in the United States to decarbonize the transport sector. At the federal level, lawmakers have proposed a tax credit for clean hydrogen producers, and the maximum credit is 3 USD per kg hydrogen for green hydrogen (Heinrich, 2021; Larson, 2021). The Bipartisan Infrastructure Law (BIL) provides 9.5 billion USD to support clean hydrogen initiatives, including the establishment of regional clean hydrogen hubs and scaling up renewable electrolysis (U.S. Department of Energy, 2022). While the definition of clean hydrogen has not been determined, most of the proposals require a life-cycle GHG emissions reduction of at least 40% to 80% compared to hydrogen produced by natural gas SMR (Larson, 2021; Tonko, 2021). This would mean life-cycle GHG emissions of 15 to 46 gCO_2e per MJ hydrogen (2 to 5.5 kg

CO_2e per kg hydrogen) for clean hydrogen, assuming 77 gCO_2e per MJ hydrogen from natural gas SMR in the United States (Sun et al., 2019).

Some U.S. states are also providing incentives for hydrogen to be used in the transport sector. For example, California's Low Carbon Fuel Standard (LCFS) program allows hydrogen producers to generate credit for hydrogen sold in California. The LCFS aims to reduce the full life-cycle GHG emissions of the state's transportation fuel pool by 20% by 2030, compared to the 2010 average fuel mix (California Air Resources Board, 2020). The amount of credit available to hydrogen producers is based proportionally on the GHG intensity of their hydrogen pathway, after an adjustment for EER (with different EER values for heavy-duty and light-duty vehicles). The maximum carbon price is currently capped at 222 USD per tonne CO_2e reduction, though present-day values are less than half that as of early 2022 (California Air Resources Board, 2022). Assuming this maximum credit price, producers of green hydrogen with an EER-adjusted life-cycle CI of 9 gCO_2e per MJ can receive a credit of 2.4 USD per kg hydrogen under the LCFS.

In addition to subsidies provided to hydrogen production, policy support for HRS can help accelerate hydrogen adoption in the transportation sector, triggering an increase in hydrogen supply induced by the increased demand. For example, California passed Assembly Bill 8 (AB 8) (Perea, Chapter 401, Statutes of 2013) that allocates up to 20 million USD annually to provide funding for HRSs until at least 100 stations operate publicly. Under this funding scheme, hydrogen stations were awarded an average grant of 825 USD to 2,350 USD per kg of daily refueling capacity (Baronas & Achtelik, 2020). In addition, the LCFS program provides infrastructure credits for certain HRSs. Specifically, the LCFS refueling infrastructure incentive program provides LCFS credits based on the installed hydrogen refueling capacity, subtracting the dispensed quantity of hydrogen (which generates its own credits within the program). This policy design is especially helpful in the early establishment of the market, as it ensures that HRSs receive incentives even during early stages of deployment and without a consistent market. As of November 2021, 62 HRSs were approved to receive this LCFS infrastructure credit (California Air Resources Board, 2021). As a result of these policies, the number of operational HRSs in California increased from 25 in 2016 to 45 in 2020 with an increase in average daily hydrogen dispensed from 340 kg to 2,800 kg (Baronas & Achtelik, 2020).

RECOMMENDATIONS

Based on our analysis of life-cycle GHG emissions from the eleven hydrogen pathways, the detailed case study of three pilot clusters, and international experiences, we make several recommendations to the national and local governments in China for development of a clean, low-carbon hydrogen industry. We focus on three key areas: (1) establishing stringent CI requirements for hydrogen and ensuring compliance, (2) expanding financial and non-financial support for low-carbon hydrogen production, and (3) developing a robust hydrogen and FCV supply chain. The recommendations provided in this section can support the pilot cities in better implementing the pilot city program. Moreover, these recommendations can be used by any national and local governments in China for developing hydrogen-related policies in the future.

SET SUFFICIENTLY STRINGENT CARBON INTENSITY REQUIREMENTS FOR HYDROGEN

We find that CI requirements for hydrogen established in the pilot city program in China are insufficiently stringent and can encourage certain hydrogen production pathways that are not necessarily low-carbon. We provide two recommendations: (1) expand the system boundary to include the full life-cycle well-to-wheel GHG emissions; and (2) set lower CI values for hydrogen as required thresholds.

In Table 9, we summarize the CI thresholds in China—for the pilot city program as well as the industrial standard—and how they compare to the thresholds in the EU and the United States and to the diesel CI. The outstanding discrepancy between China and other countries is that China defines hydrogen based only on emissions during hydrogen production, rather than life-cycle emissions. Although the industrial standard T/CAB 0078-2020 provides guidelines on life-cycle GHG emissions estimates, the definitions of low-carbon or clean hydrogen are essentially based on production site emissions. Leaving out large parts of the hydrogen life cycle can provide a distorted understanding of the climate impacts of some hydrogen pathways and risks incentivizing pathways with adverse climate impacts, particularly those with high upstream emissions, such as grid-average electrolysis hydrogen. Grid-average electrolysis hydrogen has zero emissions during hydrogen production and thus meets the two CI thresholds under the pilot city program. However, its life-cycle GHG emissions can be as high as 443 gCO_2e per MJ (53 kg CO_2e per kg) in Shanghai, the worst case in China, or 301 gCO_2e per MJ (36 kg CO_2e per kg) assuming the national average grid. Allowing grid-average electrolysis hydrogen to receive the additional subsidy for clean hydrogen would send the wrong signal to the hydrogen industry and cause irreversible, adverse climate impacts that undermine China's purpose of using hydrogen for decarbonization. Besides including upstream and downstream emissions, it is also necessary to include other GHGs in addition to CO_2. CH_4 and N_2O are much more potent than CO_2 and their emissions and climate impacts should not be neglected.

Table 9. Carbon intensity thresholds for hydrogen in the China pilot city program, China T/CAB 0078-2020 standard, the EU, the United States, and carbon intensity of diesel in China

	China pilot city program		T/CAB 0078-2020 in China	EU CI threshold for hydrogen used in transport	U.S. federal CI threshold for clean hydrogen	Diesel CI in China
	Eligibility CI threshold	Subsidy CI threshold				
CO_2 emissions during hydrogen production (gCO_2 per MJ)	125	42	-	-	-	-
GHG emissions during hydrogen production (gCO_2e per MJ)	-	-	Clean hydrogen: 41; Low-carbon hydrogen: 121	-	-	-
Well-to-wheel GHG emissions (gCO_2e per MJ)	-	-	-	28	15 – 46	90

A second recommendation is to set lower CI threshold values. The CI requirement for hydrogen eligible for use under the pilot city program or for the "low-carbon hydrogen" in the industrial standard is even higher than the CI of fossil diesel—125 or 121 gCO_2 per MJ hydrogen compared to 90 gCO_2e per MJ diesel—and the diesel value is based on life-cycle GHG emissions. An insufficiently stringent CI requirement would violate China's goal of reducing emissions by switching from conventional vehicles to FCVs, and would fail to contribute to China's decarbonization targets. An example that China could consider is the 70% life-cycle GHG reduction threshold for hydrogen to be used in the transport sector in the EU. This requirement, equivalent to 28 gCO_2e per MJ or 3.5 kg CO_2e per kg hydrogen, is even more stringent than China's threshold for additional clean hydrogen subsidy under the pilot city program or the CIs for clean or renewable hydrogen in the T/CAB 0078-2020 standard. While it might be hard for China to set a target as aggressive as that of the EU, it is nonetheless necessary for China to implement a stringent CI requirement for hydrogen to ensure that at a minimum it is delivering GHG reductions relative to petroleum used in transportation.

REQUIRE RENEWABLE ELECTRICITY CERTIFICATES FOR GRID ELECTROLYSIS HYDROGEN AND PROHIBIT COAL AS AN ELIGIBLE FEEDSTOCK FOR HYDROGEN PRODUCTION

The results of this analysis illustrate that not all hydrogen pathways can bring climate benefits; instead, some may even have adverse climate impacts. The life-cycle GHG emissions vary from -429 gCO_2e per MJ (LFG SMR) to 301 gCO_2e per MJ (national average grid electrolysis). We therefore recommend that the national government in China take measures to address two[8] hydrogen pathways with life-cycle GHG emissions that are higher than the CI value of eligibility threshold of 125 gCO_2 per MJ (Figure 2). Specifically, we recommend that the national government require grid electrolysis hydrogen producers to purchase renewable electricity certificates that cover the same amount of electricity they receive from the grid. We also recommend that the national government prohibit allowing coal to be an eligible feedstock for hydrogen production. These two measurements shall be applicable not only for the pilot city program, but also for the entire hydrogen market in China, given that other cities not participating in the pilot city program may also possess large hydrogen markets. Such a policy can serve as a safeguard that can be set in place before other kinds of policy measures, such as stringent CI thresholds, are designed and implemented.

8 Methanol cracking estimated in this study also has higher life-cycle GHG emissions than allowed under the eligibility CI standard. This study assumes natural gas as the feedstock for methanol, whereas other feedstocks could be used that lead to lower emissions.

As shown in Figure 2, the life-cycle GHG emissions from coal gasification are significant; indeed, they are higher than the CI eligibility value by 66%. Even when combined with CCS, the emission is barely lower than the CI eligibility value and is worse than petroleum. Prohibiting coal as an eligible feedstock also aligns with the national goal of transitioning to cleaner fuels. Electrolysis hydrogen using national average grid-average electricity results in the highest life-cycle GHG emissions among the eleven hydrogen pathways and is more than double the eligibility value. The five selected pilot lead cities all have higher shares of fossil fuels in their regional grids than the national average, leading to even worse climate impacts from using grid-average electrolysis hydrogen in those regions. While grid mix varies by region in China, only four provinces—Qinghai, Sichuan, Yunan, and Xizang—have fossil shares lower than 20% in their regional grids, enabling life-cycle GHG emissions from grid-average electrolysis of less than 12 gCO_2e per MJ (1.5 kg CO_2 per kg) (Figure 3). Requiring renewable electricity certificates addresses only one side of the issues regarding electrolysis hydrogen, extra policy instruments are needed to address the additionality issue for renewable electricity; we provide recommendations for these in the next section.

DEVELOP A ROBUST CARBON ACCOUNTING, CERTIFICATION, AND VERIFICATION SYSTEM FOR HYDROGEN

Setting stringent CI requirements for hydrogen is a start; however, meeting CI requirements requires a robust system of monitoring, reporting, and verification. To ensure compliance, the hydrogen market would need a robust certification system to ensure that hydrogen production for the pilot program matches its reported production parameters. This certification could be used to ensure the accuracy of carbon accounting and avoid potential climate risks from false claims.

Currently, the method by which hydrogen producers estimate their fuel's GHG emissions and become certified is not clear, not only under the pilot city program but more broadly for the general hydrogen market across the entire country. Since there is no consensus on data collection and carbon accounting, different companies in China would estimate different CIs for the same hydrogen pathway. While the T/CAB 0078-2020 standard exists, it is not clear under what circumstance this standard can be used; for instance, whether this is the standard to be followed under the pilot city program. Moreover, while the T/CAB 0078-2020 standard lists some evaluation and certification requirements for GHG emissions, we found that details are missing. For instance, the standard references two other national standards for LCA methodology (GB/T 24040 and GB/T 24044), while these standards are not hydrogen- or fuel-specific. In addition, the technical details for emission measurements are not clear—for example, whether the measurement shall be done onsite or through estimates using emission factors, the specific data that needs to be collected and data sources, the detailed certification process, and the qualification of the certifiers.

Having a robust hydrogen emission measurement and certification standard in place is necessary and crucial; however, without providing detailed guidelines, successful implementation of the standard would be difficult. Life-cycle GHG analysis is complicated and requires a great deal of underlying data and assumptions to support a comprehensive analysis. Therefore, we recommend that China develop a centralized life-cycle tool and database where carbon accounting can be carried out facilitated by detailed methodology and instructions. An example is California's LCFS. Under the LCFS program, California provides default GHG values for the corresponding fuel pathways in a look-up table that fuel producers use. The LCFS also provides a LCA model developed by regulators paired with the state's own LCA factors. Fuels producers can submit their own GHG emission estimates using the model and have it approved and certified in order to use their facility-specific LCA values.

When developing the carbon accounting methodology, one type of hydrogen pathway that might need special attention is industrial by-product hydrogen. Given that industrial by-product hydrogen is the second largest source of hydrogen in China and given that the Chinese government is prioritizing the use of by-product hydrogen in the near term because it presents few economic and technology barriers (National Development and Reform Commission, 2022), it is crucial to have a better understanding of the climate performance of this pathway. To avoid the potential uncertainties from using different LCA methods and to account for the overall climate impact on society, we recommend use of the system expansion approach to account for the diversion emissions attributable to by-product hydrogen. In order to conduct LCA that accurately reflect China's industry, it may be necessary to conduct surveys to evaluate the current uses of industrial by-product hydrogen. Prior to a comprehensive assessment of the industry, we recommend classifying industrial by-product hydrogen as ineligible for additional subsidies, even if the fuel producers claim low emissions. In addition to uncertainties in GHG emissions, another drawback of industrial by-product hydrogen is that its availability is limited by the size of the industry. In the long term, especially with the surging hydrogen demand and the urgency to meet decarbonization targets, China likely can no longer depend on industrial by-product hydrogen. It might be a safer practice to invest in other low-carbon hydrogen pathways, such as green hydrogen, which can be scaled up earlier in the process to avoid potential technology lock-in with low-hanging, but inferior, fruit.

If fuel producers estimate their own GHG emissions, it is also necessary to have an independent third-party review and certify the GHG estimates. Such a certification and verification process can help ensure that carbon accounting is done appropriately, and that the estimates are accurate. Moreover, with regard to the pilot city program, since the CI requirement is for the hydrogen being refueled at HRSs rather than being produced, a robust certification system is particularly important and can help avoid potential fraud from using high-emission hydrogen in place of low-emission sources, especially when one company can produce hydrogen using different feedstocks.

For hydrogen produced through water electrolysis, the electricity source is important and can make a significant difference in GHG emissions. Given that electricity sources are only vaguely identified in many documents in China and the risk of using grid-average electricity is high, China needs not only to prohibit the use of grid-average electricity for hydrogen production, but also develop a robust certification and verification scheme to ensure additionality, which would avoid displacing existing use of renewables from other sectors, which in turn are likely to be replaced by grid electricity. A vital first step is to have stakeholders in China, including the national and local governments and companies, clearly state the source of electricity whenever referring to electrolysis hydrogen and clarify if renewable electricity certificates are purchased in the case of using grid electricity. One potential approach to ensure renewable additionality is to show that the renewable electricity installation is financially supported only by the green hydrogen producer and does not receive any other policy or private funding. A mechanism for this purpose could be Power Purchase Agreements (PPAs) combined with certification showing the used renewables were not supported by other policy incentives, which demonstrates that the renewable electricity is generated only for the purpose of green hydrogen production (Timpe et al., 2017; Malins, 2019).

PROVIDE MORE FINANCIAL SUPPORT FOR CLEAN, LOW-CARBON HYDROGEN

As detailed in the Introduction, the pilot city program provides grants based on cities' achievements in FCV adoption or hydrogen supply. However, the maximum award that cities can receive under the FCV adoption category, 1.5 billion RMB, is 7.5 times the amount available under the hydrogen supply category (0.2 billion RMB). Further, the additional subsidy for clean hydrogen is equivalent to 3 RMB per kg hydrogen (0.5 USD per kg) and for low-cost hydrogen (retail price of 35 RMB per kg hydrogen or less) is 1 RMB per kg hydrogen (0.15 USD per kg). For comparison, the price of diesel in China was around 7.6 RMB per kg in 2020, while ICCT researchers estimated the green hydrogen price to be 77 RMB per kg in Shanghai or 94 RMB per kg in Beijing (Mao et al., 2021), which is significantly higher than diesel price. We thus recommend that national and local governments in China consider providing more financial support for the hydrogen production industry. When doing that, incentives should be prioritized to the pathways that are truly low-carbon on a life-cycle basis, such as green hydrogen.

LIFT PRODUCTION RESTRICTIONS FOR GREEN HYDROGEN

Current regulations in China restrict the production of hydrogen to chemical industrial parks. However, chemical industrial parks in China typically are not located near with hydrogen production feedstocks, especially renewable electricity. In China, chemical industrial parks are located mainly in the eastern coastal areas, while renewable electricity is mostly abundant in the north. We recommend that national and local governments in China lift the production restriction and allow green hydrogen to be produced outside of chemical industrial parks. This is a prerequisite for scalability of low-carbon hydrogen. Policy makers could learn from the experience in Hebei and Foshan, which benefit from lifting spatial restrictions to allow hydrogen production.

EXPLORE MORE NON-SUBSIDY POLICIES FOR THE HYDROGEN INDUSTRY

The initial development of the hydrogen and FCV industries depends on supporting policies not only on the production side, but also through expanding demand. In addition to providing direct financial subsidies, such as for the construction and operation of HRSs and the purchase of FCVs, other non-subsidy policy instruments are available. For example, local governments could provide preferential policies in terms of discounts in land, taxes, and electricity prices, all of which can reduce the financial burden on hydrogen and FCV companies. In addition, policy makers could explore instruments to enhance the substitutability of FCVs at the consumer end. One example is to provide rights-of-way for FCVs. This could effectively encourage consumers to choose FCVs over conventional vehicles.

CONCLUSION

This study estimates the carbon intensity of eleven hydrogen pathways in China and compares them to the qualification requirements for the China pilot city program hydrogen pathways, assessing which pathways can meet the 15-kg-CO_2-per-kg-hydrogen eligibility requirement and the 5-kg-CO_2-per-kg-hydrogen threshold for receiving additional subsidies for using clean hydrogen. Among the eleven hydrogen pathways analyzed, we find that only hydrogen made from coal gasification is not eligible to be used under the pilot program. Four hydrogen pathways meet the additional subsidy threshold, which are hydrogen made from natural gas combined with CCS, hydrogen made from LFG, and electrolysis hydrogen using 100% renewable electricity or grid-average electricity. However, cautions are needed with these results.

The two hydrogen CI requirements under the pilot city program include CO_2 emissions during hydrogen production in their scope. Such a requirement is insufficient for a comprehensive understanding of the overall climate impacts from hydrogen. In particular, hydrogen made from grid-average electricity has zero emissions during production and qualifies for the clean hydrogen subsidy; however, if assuming national average grid emissions, its life-cycle GHG emissions are actually the highest among the eleven hydrogen pathways and are more than double the 15-kg-CO_2-per-kg-hydrogen eligibility CI value. Therefore, we recommend that the national and local governments in China require the life-cycle well-to-wheel GHG emissions in any of their hydrogen policies. A full life-cycle GHG analysis can help better inform the overall climate impact from the adoption of alternative fuels.

In addition, we find the CI thresholds for hydrogen are set too high to drive meaningful decarbonization—the CI threshold for eligible hydrogen under the pilot city program, at 125 gCO_2 per MJ hydrogen, is even higher than the CI of fossil diesel, 90 gCO_2e per MJ. Similarly, the CI threshold defining "low-carbon hydrogen," listed in the only industrial standard for hydrogen in China, T/CAB 0078-2020, is as high as 121 gCO_2 per MJ hydrogen. Therefore, it is necessary for the national government in China to set more stringent CI requirements for hydrogen and to expand the scope to life-cycle GHG emissions. Otherwise, it will be hard for China to use hydrogen effectively to meet the national decarbonization targets. One example that China could learn from is the European Commission requirement that a 70% life-cycle GHG reduction threshold for hydrogen be used in the transport sector, which is equivalent to 28 gCO_2e per MJ or 3.5 kg CO_2e per kg hydrogen.

In case the pilot city program cannot revise its CI requirements at this stage, we recommend that local governments of selected cities prohibit the production and use of coal-based and grid-average electrolysis hydrogen. In the meantime, to ensure compliance with the CI requirements, it is necessary to have a robust carbon accounting, certification, and verification system. Currently in China, there is no standardized carbon accounting and verification system for the hydrogen industry. As a result, companies in China are using different methods and data to estimate carbon emissions, and their estimates for the same pathway can vary significantly. Because the pilot city program is already ongoing, a key task for the national government in China is to establish a standardized and robust carbon accounting and verification system to support the evaluation of hydrogen qualifications for the pilot city program and for additional subsidies. Such a system would ensure the correct use of a consistent carbon accounting methodology and avoid climate risks from potential false claims.

While green hydrogen and hydrogen made from natural gas combined with CCS and LFG can both meet the program requirements, green hydrogen has the highest potential for large-scale deployment. CCS and collection of LFG are not yet common in China and their implementation would face barriers in multiple respects, including technical, economic, and standardization barriers. In contrast, the national government in China is aiming to scale up the production of green hydrogen significantly. To ensure that green hydrogen delivers real GHG reductions, it is crucial to ensure that the renewable electricity used for hydrogen production is additional, instead of being displaced from existing uses. Otherwise, the climate benefit would be greatly undermined, given that fossil fuels constitute a high share of China's electricity grid. Therefore, we recommend a certification system that shows the electricity origin in conjunction with certification that shows that renewable electricity used was not supported by other policy incentives, but only for the purpose of green hydrogen production. Another incentive for green hydrogen that national and local governments could consider is to lift the location restriction for its production by allowing green hydrogen to be produced outside of chemical industrial parks.

Hydrogen is and will remain an important fuel in China's energy transition and in meeting the national decarbonization targets. While China is moving in the right direction of scaling up green hydrogen production, it nonetheless needs to refine the eligibility requirements for hydrogen subsidies to promote lower-carbon hydrogen sources and encourage the development of deeper GHG reductions from the hydrogen industry. The recommendations in this study aim to help national and local policy makers in China during the implementation of the pilot city program and when developing any subsequent hydrogen policies.

APPENDIX

Table A1. Lead and member cities of the five selected pilot clusters

City cluster	Beijing-Tianjin-Hebei cluster	Shanghai cluster	Guangdong cluster	Hebei cluster	Henan cluster
Lead city	Beijing Daxing District	Shanghai	Foshan City, Guangdong Province	Zhangjiakou City, Hebei Province	Zhengzhou City, Henan Province
Participating cities	Beijing Haidian District	Suzhou, Jiangsu Province	Guangzhou, Guangdong Province	Tangshan City, Hebei Province	Xinxiang City, Henan Province
	Beijing Jingkai District	Nantong City, Jiangsu Province	Shenzhen, Guangdong Province	Baoding City, Hebei Province	Kaifeng City, Henan Province
	Beijing Yanqing District	Jiaxing City, Zhejiang Province	Zhuhai, Guangdong Province	Handan City, Hebei Province	Anyang City, Henan Province
	Beijing Shunyi District	Zibo City, Shandong Province	Dongguan City, Guangdong Province	Qinhuangdao, Hebei	Luoyang City, Henan Province
	Beijing Fangshan District	Ningxia Hui Autonomous Region Ningdong Chemical Energy Base	Zhongshan City, Guangdong Province	Dingzhou city, Hebei province	Jiaozuo City, Henan Province
	Beijing Changping District	Erdos City, Inner Mongolia Autonomous Region	Yangjiang, Guangdong Province	Xinji, Hebei	Shanghai Jiading District
	Tianjin Binhai New Area		Yunfu City, Guangdong Province	Xiong'an New District, Hebei Province	Fengxian District, Shanghai
	Tangshan District, Hebei		Fuzhou City, Fujian Province	Wuhai City, Inner Mongolia Autonomous Region	Shanghai Lingang New Area
	Baoding District, Hebei		Zibo City, Shandong Province	Fengxian District, Shanghai	Zhangjiakou City, Hebei Province
	Binzhou, Shandong		Baotou, Inner Mongolia Autonomous Region	Zhengzhou City, Henan Province	Baoding City, Hebei Province
	Zibo City, Shandong		Liuan City, Anhui Province	Zibo City, Shandong Province	Xinji City, Hebei Province
				Liaocheng City, Shandong Province	Yantai City, Shandong Province
				Xiamen, Fujian Province	Zibo City, Shandong Province
					Weifang City, Shandong Province
					Foshan City, Guangdong Province
					Ningxia Hui Autonomous Region Ningdong Town

Table A2. Financial incentives provided by local governments in the lead and member cities of the five pilot clusters

	Policy documents	Promulgation time	Policies related to hydrogen refueling stations, storage, and transportation	Policies related to hydrogen fuel cell vehicle adoption and manufacturing
Guangdong Province	Implementation Plan for Accelerating the Development of Hydrogen Fuel Cell Vehicle Industry in Guangdong Province	11/12/2020	Subsidies are given to HRSs built and put into operation before 2022 with a daily hydrogen refueling capacity (calculated according to the refueling capacity of the compressor working 12 hours a day) of 500 kg and above. Among them, the subsidy is 2.5 million RMB per station for the integrated refueling stations of oil, hydrogen, gas, and electricity. For fixed HRSs, each station is subsidized with 2 million RMB. Each skid-mounted HRS is subsidized with 1.5 million RMB. Local governments provide additional subsidies based on actual situations. Total subsidy amount shall not exceed 5 million RMB per station and not exceed 50% of the HRS's capital investment. Any excess will be deducted from the provincial level subsidies.	
Foshan City	Foshan City Fuel Cell Vehicle Financial Subsidy Funds Management Measures	11/25/2021		Local subsidies for each FCVs are determined in accordance with 100% of the amount from the national government.
	Measures for the management of support funds for the operation of new energy freight vehicles for urban distribution in Foshan (Draft)	11/09/2021		Subsidy provided based on four FCV types: light (total mass less than 4.5 tons), medium (total mass 4.5 tons and above, less than 12 tons), heavy (total mass 12 tons and above), and hydrogen fuel cell refrigerated vehicles. In each accounting year, if the mileage is between 10,000 and 50,000 kilometers, the incentive amount for each vehicle of the above four types is 1.5 RMB/km, 2.0 RMB/km, 2.5 RMB/km, and 2.3 RMB/km respectively; if the vehicle mileage is more than 50,000 kilometers, the maximum annual incentive amount for each vehicle is 75,000 RMB, 100,000 RMB, 125,000 RMB and 115,000 RMB respectively.
Nanhai District of Foshan City	Promotes the construction and operation of hydrogen refueling stations and hydrogen energy vehicle operation support measures (revised) in Foshan Nanhai District	12/16/2019	Each fixed HRS with a daily hydrogen refueling capacity of 500 kg or less, built after December 21, 2019, is subsidized with 3 million RMB; capacity of 500 kg above, with a maximum subsidy of 5 million RMB.	
Huangpu District of Guangzhou City	Detailed rules for the implementation of measures for promoting the development of hydrogen energy industry in Guangzhou Development Zone of Huangpu District	06/28/2021	Subsidies will be given to HRSs with a daily capacity of more than 500 kg that have been built and put into operation within the effective period of the policy	For FCV manufacturers to meet the pilot program requirements, a 15% subsidy is provided for those with fixed asset investment of 500 million RMB or more. The same enterprise receives a maximum subsidy of 100 million RMB.
	Measures for promoting the development of hydrogen energy industry in Guangzhou Development Zone of Huangpu District	04/13/2020	Subsidies are provided for HRSs built and put into operation within the policy period. 2.5 million RMB per station for those with a daily capacity of 500 kg and above; 2 million RMB per station for fixed HRSs; 500,000 RMB per station for skid-mounted stations. The operation of hydrogen refueling stations will be subsidized: in 2020-2021, if the hydrogen sales price after receiving subsidies is not higher than 35 RMB/kg, a subsidy of 20 RMB/kg will be provided; in 2022, if the subsidized sale price is not higher than 30 RMB/kg, a subsidy of 18 RMB/kg will be provided.	

	Policy documents	Promulgation time	Policies related to hydrogen refueling stations, storage, and transportation	Policies related to hydrogen fuel cell vehicle adoption and manufacturing
Shenzhen	Financial support policy for the promotion and application of new energy vehicles in Shenzhen in 2017			Vehicle purchase subsidy. Fuel cell passenger cars are 200,000 RMB / vehicle, fuel cell light buses and trucks are 300,000 RMB / vehicle, and fuel cell large and medium-sized buses and medium and heavy trucks are 500,000 RMB / vehicle.
Baotou	Trial measures to promote the development of fuel cell vehicle industry in Inner Mongolia Autonomous Region			Inner Mongolia will provide subsidies at the 1:1 ratio to the national subsidy. Inner Mongolia and its cities will each bear 50% of the subsidies amount.
Daxing District of Beijing	Interim Measures for Promoting the Development of Hydrogen Energy Industry in Daxing District (Revised Edition in 2022) (Draft)	12/31/2021	For hydrogen transporters using vehicles, a one-time subsidy of 20% of the total vehicle purchase cost will be provided, capped at 5million RMB per year per company.	Subsidy for FCV purchase. For companies that purchased FCVs in 2021, 2022 and 2023, a subsidy in accordance with 40%, 30% and 20% of the national subsidy amount is provided, respectively. For companies with an annual FCV component purchase amount of 10 million RMB (inclusive), a subsidy of 5% of the actual purchase cost in the previous year will be provided, capped at 10 million RMB per year per company.
Beijing	Notice on the application of Beijing fuel cell vehicle demonstration and application project in 2021-2022	04/08/2022	Subsidy provided by HRS capacity at ≥ 1000kg or ≥ 500kg. Based on the audit results of Beijing Transportation Development Research Institute, with on-site verification and expert review, the scale of subsidy funds for the construction of hydrogen refueling stations is reviewed and approved, and allocated to the construction enterprises of hydrogen refueling stations within one month after the end of each accounting year.	Vehicle promotion incentive: subsidy provided at 1:1 ratio to the national subsidy. Vehicle operation incentive: for FCVs under the pilot city program, the operation incentive is given to light vehicles (total mass below 4.5 tons) and medium and heavy vehicles (total mass 4.5 tons and above, including buses) at 0.3 million RMB / 10,000 kilometers and 10,000 RMB / 10,000 kilometers, respectively. FCV components innovation incentives: subsidy provided at 1:1 ratio to the national subsidy for FCV components that meet the national requirements.
Shanghai	Measures on supporting the development of fuel cell vehicle industry in the city	11/03/2021	*Subsidies for the construction of HRS.* A subsidy of no more than 30% of the total investment will be given to HRS that is completed and licensed before 2025. Among them, for those licensed in 2022, 2023 and 2024-2025, the maximum subsidy for each HRS shall not exceed 5 million RMB, 4 million RMB and 3 million RMB respectively. Applications shall be accepted by the municipal housing and urban rural construction management committee. Funds are provided by the city government and district government at a 1:1 ratio. *Hydrogen retail price subsidy*. Before 2025, the operating HRS whose retail price of hydrogen is not more than 35 RMB / kg will be subsidized according to the actual sales volume of hydrogen: 20 RMB per kilogram in 2021; 15 RMB per kilogram from 2022 to 2023; 10 RMB per kilogram from 2024 to 2025. Applications shall be accepted by the municipal housing and urban rural construction management committee. Funds are provided by the city government and district government at a 1:1 ratio.	Subsidy for vehicle procurement. For those meet the pilot city program requirements, the city provides 200,000 per point. Subsidy for vehicle operation. By 2025, each vehicle will be rewarded for up to 3 years since its operation. Medium-sized trucks (total mass of 12-31 tons) are rewarded no more than 0.5 million RMB per vehicle per year; heavy trucks (total mass of more than 31 tons) are rewarded with no more than 20,000 RMB per vehicle per year; commuter buses are rewarded no more than 1 million RMB per vehicle per year.
Zhangjiakou	Implementation plan for the construction of Zhangjiakou hydrogen energy supply system phase I Project	02/27/2020	A one-time construction subsidy of 4 million RMB will be given to HRS with a daily capacity of 200-500 kg, and 8 million RMB for HRS with a daily capacity of more than 500 kg.	

	Policy documents	Promulgation time	Policies related to hydrogen refueling stations, storage, and transportation	Policies related to hydrogen fuel cell vehicle adoption and manufacturing
Zhengzhou	Three documents including several policies of Zhengzhou to support the development of automobile industry	08/19/2019	From 2019 to 2020, a subsidy provided at 50% of the investment in HRS equipment	For FCV manufacturers listed in the catalogue of recommended models for the promotion and application of new energy vehicles by the Ministry of Industry and Information Technology, subsidies will be given at 5% of the sales revenue, and a single enterprise cannot receive 10 million RMB.
Suzhou	Notice of financial subsidies for the promotion and application of new energy vehicles in Suzhou in 2020			The city provides a maximum subsidy amount for the purchase of FCVs not exceeding 50%, provided by the national government for each operating vehicle. Idled vehicles will not be subsidized.
Binhai New District of Tianjin	Tianjin hydrogen industry development action plan (2020-2022)		A subsidy of 30% of HRS's capital investment will be provided, capped at 5 million RMB for each HRS.	
	Several policies of Tianjin Port Free Trade Zone on supporting the development of hydrogen energy industry		*Subsidy for HRS construction*. For HRS constructed in 2020-2022 within the Free Trade Zone, the local government provides subsidies at 50% of the amount from the city government. *Subsidy for HRS operation*. A subsidy of 10 RMB per kg hydrogen refueled provided to HRS within the Free Trade Zone, capped at 20 million RMB. This subsidy does not apply to the enterprise's own hydrogen refueling station. The operation subsidy stops from January 1, 2023.	Subsidies are given for the purchase of hydrogen fuel cell forklifts. From 2020 to 2024, the subsidy is given at 7,000 RMB/kW. The subsidy for fuel cell forklift leasing is at 60% of its rental cost, capped at 3,500 RMB per forklift per month.
Wuhai	Detailed rules for the management and implementation of financial subsidies for the promotion and application of hydrogen energy vehicles and supporting infrastructure construction in Wuhai City (Trial) (2019-2022)	12/31/2019	For fixed hydrogenation stations with a daily capacity of 350 kg (including) to 500 (excluding) kg, the local government will provide a subsidy of 3 million RMB, and 5 million RMB if daily capacity of 500 kg or more. For skid mounted HRS with a daily capacity of not less than 200 kg, the local government will provide a subsidy of 1.5 million RMB	The local government will provide a subsidy of 50% of the amount from the national government for FCVs.
Ordos	Ordos' policy of supporting the Shanghai cluster in FCV pilot city program	04/15/2022	*For HRS construction*. By the end of 2025, subsidies will be provided at a rate not exceeding 30% of the total HRS investment. The maximum subsidy for capacity of 500-1000 kg / day is 3 million RMB per station, and for capacity ≥ 1000 kg / day is 4.5 million RMB per station. The subsidy fund is allocated in three years and provided by city government and district government at a 1:1 ratio. *To reduce retail price*. By the end of 2025, if the retail price of is not higher than 20 RMB / kg, a subsidy will be provided at 30 RMB / kg in 2022, 18 RMB / kg in 2023, 11 RMB / kg in 2024, and 3 RMB / kg in 2025. The subsidy is provided by city government and district government at a 1:1 ratio.	By the end of 2025, subsidy for each purchased FCV will be provided at 1:1 ratio to the national subsidy and provided by city government and district government at a 1:1 ratio.

	Policy documents	Promulgation time	Policies related to hydrogen refueling stations, storage, and transportation	Policies related to hydrogen fuel cell vehicle adoption and manufacturing
Zibo	Several policies on supporting the development of hydrogen energy industry		*Subsidy for HRS construction*. For new, reconstructed and expanded fixed HRS with a daily capacity of no less than 500 kg, a one-time subsidy of 30%–40% of the investment (excluding land costs) will be given when it's in operation. The maximum subsidy for each HRS is 5 million RMB. *Subsidy for HRS operation*. For HRS operators registered in the city with a daily capacity no less than 500 kg and the sales price of hydrogen no higher than 45 RMB / kg, the operational subsidy in 2021 is 15 RMB / kg and in 2022 is 10 RMB / kg. The annual amount for each HRS shall not exceed 2 million RMB. *Subsidy for hydrogen production and storage*. For enterprises produce high-pressure hydrogen, produce and store liquid hydrogen, and store solid hydrogen, a subsidy is provided at no more than 10% of the investment amount, capped at 5 million RMB. *Subsidy for hydrogen transporters.* A subsidy of 1.5 RMB / kg is provided according to the annual amount of transported hydrogen, capped at 1.5 million RMB.	Subsidy for FCV purchase. Local governments provide a subsidy of 1:1 ratio based on the amount from the national government. Subsidy for FCV manufacturing. For equipment and components listed in the province's first major technical equipment and key core parts catalogue, a reward of 500,000 RMB will be given. The same product of the same enterprise will be double subsidized, and the maximum annual reward amount of the same enterprise will not exceed 3 million RMB. For manufacturers applying for insurance compensation for the first time, on top of their provincial insurance compensation policy, the city will give another 20% of the insurance compensation, with a maximum of 1 million RMB.
Jiaxing	Detailed rules for the implementation of financial subsidies for promoting the development of hydrogen energy industry in Jiaxing	1/24/2021	*Subsidy for HRS construction*. For fixed or integrated HRSs with a daily capacity of more than 500kg that have finished construction by the end of 2025, a subsidy of 20% of the equipment investment will be provided, capped at 4 million RMB. *Subsidy for hydrogen price*. By the end of 2025, for HRS with a retail price meeting the pilot city program, subsidies will be provided according to the actual annual sales of hydrogen. Starting from June 1, 2021, the subsidy is 15 RMB /kg, decreasing by 3 RMB /kg year by year.	Subsidies will be given to FCVs that meet the first-year mileage quota, based on the national subsidy standard.
Jiashan District of Jiaxing City	Several policy opinions of Jiashan on accelerating the development of hydrogen energy industry	11/13/2020	A one-time subsidy of 20% of the equipment investment (by the audit excluding tax) will be given to each HRS.	For FCVs registered in the District, a subsidy of 15 RMB /kg in 2020 and 10 RMB /kg in 2021 is provided.
Xinxiang	Implementation opinions on the development of hydrogen energy and fuel cell industry in Xinxiang City		For fixed HRSs, a one-time maximum subsidy of 3 million RMB will be offered to those with a daily capacity of 350 to 500 kg; 5 million RMB If the daily capacity is 500 kg or more. For skid mounted HRS, the maximum one-time subsidy of 1.5 million RMB is provided to those with a daily capacity of more than 200 kg. The accumulated subsidy shall not exceed 50% of the HRS's total investment. For hydrogen producers and transporters, subsidies will be given at 5% of the total investment in new equipment, capped at 5 million RMB.	

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