International Energy Agency

Opportunities for Hydrogen Production with CCUS in China

International Energy Agency

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 31 member countries, 11 association countries and beyond.

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Lithuania
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Republic of Türkiye
United Kingdom
United States

The European Commission also participates in the work of the IEA

IEA association countries:

Argentina
Brazil
China
Egypt
India
Indonesia
Morocco
Singapore
South Africa
Thailand
Ukraine

International Energy Agency
Website: www.iea.org

Abstract

Hydrogen and carbon capture, utilisation, and storage (CCUS) are set to play important and complementary roles in meeting People's Republic of China's (hereafter, "China") pledge to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. Hydrogen could contribute to China's energy system decarbonisation strategy, such as through the use as a fuel and feedstock in industrial processes; in fuel cell electric transport, and for the production of synthetic hydrocarbon fuels for shipping and aviation. The analysis of scenarios in this report suggests that while hydrogen from renewable power electrolysis could meet the majority of hydrogen demand by 2060, equipping existing hydrogen production facilities with CCUS could be a complementary strategy to reduce emissions and scale-up low-emission hydrogen supply.

This report was produced in collaboration with the Administrative Centre for China's Agenda 21 (ACCA21). It explores today's hydrogen and CCUS status in China, and the potential evolution of hydrogen demand in various sectors of the Chinese economy through 2060, in light of scenarios developed independently by the IEA and the China Hydrogen Alliance. The report also provides a comparative assessment of the economic performance and life cycle emissions of different hydrogen production routes. Finally, the report discusses potential synergies and regional opportunities in deploying CCUS and hydrogen, and identifies financing mechanisms and supporting policies required to enable the deployment of hydrogen production with CCUS in China.

Acknowledgements, contributors and credits

This report is the result of a collaboration between the Energy Technology Policy Division, led by Timur Gül, in the Directorate of Sustainability, Technology and Outlooks at the International Energy Agency (IEA), and the Administrative Center for China's Agenda 21 (ACCA21), directed by Jing Huang.

The lead IEA author was Mathilde Fajardy together with former IEA staff Niels Berghout and Dong Xu, with significant input and guidance from Samantha McCulloch (former IEA head of CCUS unit). The report also benefited from valuable inputs and comments from other experts within the IEA, including Praveen Bains, Simon Bennett, Jose Miguel Bermudez Menendez, Sara Budinis, Elizabeth Connelly, Araceli Fernandez Pales, Carl Greenfield, Peter Levi, Rebecca McKimm, Rachael Moore, Uwe Remme, and Erpu Zhu. Zhiyu Yang, Biqing Yang, and Caroline Abettan provided essential support.

The lead ACCA21 author was Xian Zhang. Jing Huang, Bing Ke, and Qizhen Chen provided significant review and guidance. Mingwei Shi and Xueting Peng contributed valuable data and analysis to the report, assisted by Qiao Ma, Guowei Jia, Jiayan Liu, Haodong Lv, Dongyang Zhang, Xuejing Zhang, and Nian Yang.

Several experts from Chinese organisations and research institutes also contributed valuable analysis and input to the report. Yi-Ming Wei, deputy president of the Beijing Institute of Technology (BIT), coordinated input and analysis from all expert Chinese organisations. The list of contributors included:

- China Hydrogen Alliance Research Institute (CHARI), with valuable input and contributions from Yanming Wan, assisted by Yalin Xiong, Xueying Wang, Chenjiang Xiao and under the coordination of Wei Liu.
- New Energy Technology Research Institute (NETRI), China Energy, with valuable input and contribution from Dong Xu, assisted by Zhiyong Wang, and under the coordination of Qingru Cui.
- Beijing Institute of Technology (BIT), with valuable input and contribution from Jiaquan Li, assisted by Xiaoyu Li, Bo Yang, Hua Liao, Qiaomei Liang, Jianing Kang, Yunlong Zhang, Lutao Zhao, Min Dai, Shuo Xu, Hongkun Cui, Song Peng, and Yizhuo Ji, and under the coordination of Yi-Ming Wei.
- Beijing Normal University (BNU), with valuable data and analysis provided by Lancui Liu.

- China University of Mining & Technology-Beijing (CUMTB), with valuable input and contributions from Jingli Fan, assisted by Kai Li, Yuxuan Wang, Xiaojuan Xiang, Yifan Mao, Yujiao Xian, and Bing Wang.
- Institute of Rock Mass and Soil Mechanics, Chinese Academy of Sciences (IRSM, CAS), with valuable data and analysis provided by Ning Wei, assisted by Shengnan Liu.

The IEA Communications and Digital Office also assisted and contributed to the production of the final report and website materials, particularly Astrid Dumond, Clara Vallois, Lucile Wall, and Therese Walsh. The report was edited by Kristine Douaud.

Xian Zhang (ACCA21) and Dong Xu (NETRI) coordinated the translation of the report, with support from Mingwei Shi (ACCA21), Zhiyong Wang (NETRI), Jiaquan Li (BIT), Yanming Wan (CHARI), Lancui Liu (BNU), Jingli Fan (CUMT), Ning Wei (IRMSM), Zhiyu Yang (IEA), Biqing Yang (IEA), and Rebecca McKimm (IEA).

Table of contents

Executive Summary

China's hydrogen and CCUS opportunity

Hydrogen and CCUS are set to play important, complementary roles in meeting the carbon neutrality goals of China. China has pledged to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060, requiring a profound transformation of its energy system. Low-emission hydrogen and carbon capture, utilisation and storage (CCUS) technologies have both been identified as key priorities in China's carbon neutrality guidelines.

China leads the world in hydrogen production, but this production is currently emissions-intensive. In 2020, hydrogen production in China reached around 33 Mt, or 30% of the world total. China's leading position results from its large share of the global chemical market and its considerable oil refining capacity, which are the primary sources of hydrogen demand today. China is the only country in the world that produces hydrogen from coal at significant scale: about two-thirds of China's hydrogen production is fuelled by coal, with around 360 Mt of CO_2 emissions generated in 2020.

Equipping existing hydrogen production facilities with CCUS is a key strategy to reduce emissions and enlarge the country's low-emission hydrogen supply. For hydrogen to contribute to China's carbon neutrality goal, an ambitious shift to low-emission production is essential. The most promising low-emission routes include producing hydrogen from renewable electricity through electrolysis or equipping fossil fuel-based production routes with CCUS. As many of China's existing coal-based hydrogen plants were built recently, are highly emissions-intensive and could be in operation for decades to come, equipping them with CCUS could be critical to reduce their emissions.

CCUS could also provide a viable cost-effective supply option for new hydrogen capacity in regions with abundant coal resources and opportunities for CO_2 storage. Given the low availability of indigenous natural gas resources in China and the country's large coal gasification fleet, coal-to-hydrogen production with CCUS is expected to persist as an important fossil fuel-based hydrogen generation route. Nevertheless, electrolysis is likely to predominate from the 2030s. In fact, anticipated electrolyser and renewable energy cost reductions could mean that renewable electricity-based electrolytic hydrogen would make up as much as 80% of China's hydrogen supply by 2060.

A growing role for hydrogen across the economy

Hydrogen use could tackle a range of energy and emissions challenges in China. Low-emission hydrogen could be employed in a range of sectors (including long-distance transport, chemicals, and iron and steel) to achieve deep emissions reductions. Developing hydrogen as an energy vector can also improve air quality, reduce reliance on fuel imports and drive technological innovation. For these reasons, China Hydrogen Alliance (CHA) has established an initiative to raise the share of hydrogen in China's final energy demand to 20% in 2060.

Hydrogen is set to have a crucial role in China's strategy to achieve carbon neutrality by 2060. The IEA Announced Pledges Scenario (APS) suggests that hydrogen demand could increase more than threefold by 2060 for China to meet its climate goals. Nearly two-thirds of this growth is linked to hydrogen and hydrogen-based fuel use in transport, and around one-third is associated with using hydrogen as a fuel and for feedstock in industrial processes.

Demand for hydrogen grows to 31 Mt in 2030 under the APS, owing partly to the conventional use of hydrogen in methanol production, oil refining and coal-to-chemicals production, although novel uses (including as a fuel or feedstock in non-chemical industries, and in the transport and buildings sectors) also gain ground slowly. The hydrogen market grows strongly during the 2030s to reach just over 90 Mt by 2060, mainly because of rapid market expansion for fuel cell heavy-duty trucks and hydrogen-based fuels for shipping and aviation, and from rising fuel and feedstock demand for industrial processes.

Targeted support could expand China's use of hydrogen. CHA analysis shows that targeted policies and support for hydrogen could result in even greater market uptake of hydrogen. In the CHA study, which is a detailed bottom-up assessment of hydrogen's technical and commercial potential outside the context of an energy system modelling framework, hydrogen demand rises to 37 Mt by 2030 and to 130 Mt by 2060, with particularly strong growth in hydrogen and hydrogen-based fuels for transport as well as for use in industry.

CCUS supports cost-competitive hydrogen expansion

Producing low-emission hydrogen from coal with CCUS will be a low-cost option in regions of China with abundant coal, access to CO_2 storage and limited renewable energy availability. Hydrogen production costs in China vary by region based on several factors, with capital costs and the cost and availability of renewable energy being key determinants. For instance, the average cost of producing hydrogen from coal with CCUS is currently USD 1.4-3.1/kg H_2, while generating electrolytic hydrogen using renewable electricity is more expensive at USD 3.1-9.7/kg H_2, depending on the origin and availability of the electricity.

However, costs are projected to drop substantially in the medium term, potentially falling to around USD 1.5/kg H_2 in the longer term in regions with ample solar and wind resources.

CO_2 capture rates must be high and upstream emissions low to ensure that coal-based production routes with CCUS are truly low-emission. With CO_2 capture rates of 90-95% and upstream fuel emissions accounted for, the greenhouse gas (GHG) emissions intensity of low-emission hydrogen produced from fossil fuels with CCUS in China could be 3.5-4.5 kg CO_2-eq/kg H_2 for coal-based production and 2.6-3.1 kg CO_2-eq/kg H_2 for natural gas-based.

While producing electrolytic hydrogen with grid electricity would result in a GHG emissions intensity of 29-31 kg CO_2/kg H_2 in the current electricity system, electrolytic hydrogen produced from renewables averages 0.3-0.8 kg CO_2/kg H_2, including emissions generated from the manufacturing of the hydrogen production units. The emissions intensities of both coal- and gas-based production with CCUS could therefore meet China's current "clean hydrogen" standard of below 4.9 kg CO_2/kg H_2 (the world's first formal standard). However, thresholds will likely have to be lowered over time, including to meet international market standards currently under development.

Nurturing hydrogen-CCUS synergies can help China achieve carbon neutrality

Deploying hydrogen production and CCUS together can be mutually beneficial and reinforcing. Because hydrogen production offers a relatively pure CO_2 stream, equipping facilities with CCUS is a least-cost CO_2 capture option. At the same time, it offers the Chinese government early opportunities to develop CCUS technologies and to support investment in CO_2 infrastructure in the country. In the APS, 2.6 Gt CO_2 is captured across the Chinese energy sector in 2060.

Industrial clusters can serve as nerve centres to scale-up low-emission hydrogen production and CCUS deployment. Both hydrogen supply and demand are more likely to be concentrated in industrial clusters, some of which are located near potential CO_2 storage sites. Thus, retrofitting existing capacity with CCUS would be a low-cost way to expand low-emission hydrogen infrastructure while simultaneously rolling out facilities for CO_2 transport and storage. Plus, owing to the co-location of potential demand (e.g. for heavy-duty trucks), clusters are also promising sites from which to extend hydrogen use to other sectors.

Captured CO_2 and hydrogen are key inputs for the future production of synthetic fuels. Despite their currently high production costs, synthetic fuels are one of the few solutions to reduce emissions from long-distance transport, particularly aviation, for which the direct use of hydrogen and electrification are challenging. Captured CO_2 in China can also be used for enhanced oil recovery (CO_2-EOR) or to manufacture chemicals or building materials. In applications for which the CO_2 is re-released into the atmosphere (including through synthetic fuel combustion), careful accounting is needed to validate emissions reductions.

Producing hydrogen from bioenergy with CCUS could contribute to carbon removal and balance emissions from other parts of the economy. Carbon removal will need to be an important part of China's plan to achieve its carbon neutrality goals, including to balance residual emissions from the industry and transport sectors. While it is still at a relatively early stage of technology development, producing hydrogen from biomass with CCUS could help enable carbon removal. However, this production route requires access to a sustainable biomass supply, which may be threatened by competing claims on it for other uses, including for fuel production (e.g. biokerosene).

Chapter 1. China's hydrogen opportunity

HIGHLIGHTS

- Low-emission hydrogen can be an important part of China's strategy to achieve carbon neutrality by 2060. It offers a means to accomplish deep emissions reductions in a range of sectors, including long-distance transport, chemicals, and iron and steel. Its use can also help improve air quality, reduce reliance on fuel imports and drive technological innovation.
- China is the global leader in hydrogen production and use. In 2020, its hydrogen production was 26-33 Mt (depending on how by-product hydrogen production is considered). China's leading position stems from its large chemical industry and oil refining capacity, which are the main sources of hydrogen demand today.
- Over two-thirds of China's dedicated hydrogen production currently comes from coal and almost all the remainder from natural gas, so it is associated with significant emissions. According to the IEA, hydrogen production is responsible for around 360 Mt CO_2 emissions (excluding 115 Mt CO_2 captured and used in methanol and urea production).
- Carbon capture, utilisation and storage (CCUS) can support the accelerated, cost-effective scale-up of low-emission hydrogen production in China. The main role for CCUS is to tackle emissions from existing hydrogen plants, many of which could be in operation for decades to come. It may also provide a cost-competitive supply option for new hydrogen capacity in regions with low-cost coal and CO_2 storage, as well as in areas with meagre wind and solar resources.

China's carbon neutrality pledge

In September 2020, President Xi Jinping pledged to the United Nations General Assembly that China would aim to peak national CO_2 emissions before 2030 and achieve carbon neutrality before 2060. This announcement was a major milestone in international climate policy and has had a ripple effect on climate action globally. According to the IEA, China was responsible for one-third of global energy-related CO_2 emissions in 2020, or over 11 billion tonnes (Gt) (IEA, 2021a).

Transitioning to a carbon-neutral economy will demand a rapid and profound transformation of China's energy sector, requiring a broad portfolio of technologies to deliver deep emissions reductions across all economic sectors. Rapid rises in energy efficiency and renewable energy production are central, but a major acceleration in deploying a range of clean energy technologies – including hydrogen and CCUS – will also be needed to reach carbon neutrality.

The value of hydrogen for emissions reductions

Hydrogen holds great promise for aiding the transition to a low-emission energy system. It has many possible applications across a range of sectors and is particularly valuable in those for which few alternative emissions mitigation solutions exist, such as long-distance transport and heavy industry. Potential applications include its use in fuel cell electric vehicles (FCEVs), as a feedstock for manufacturing chemicals and synthetic transport fuels such as ammonia and kerosene, as a reducing agent in industrial processes such as iron and steel production, and in some places to heat buildings.

Hydrogen can be produced from a variety of energy sources, including natural gas, coal, biomass and renewable and nuclear electricity. Furthermore, electrolysis of water – a process in which water is split into hydrogen and oxygen – allows for the indirect use of low-emission electricity in other economic sectors in which electrification is challenging.

Hydrogen use today is dominated by industrial applications and oil refining. Globally, the top three single uses of hydrogen (both in pure form and mixed with other gases) are: oil refining (43%), ammonia production (36%) and methanol production (14%) (IEA, 2021b). Global demand for hydrogen has grown rapidly in recent decades – from close to 60 Mt/yr in 2000 to around 90 Mt/yr in 2020 – and is set to increase further. In energy terms, total annual hydrogen demand worldwide was just over 10 EJ in 2020.[1]

The carbon footprint of hydrogen depends mainly on the primary energy source used to produce it. Even though hydrogen does not emit CO_2 when it is used, its production currently leaves a considerable carbon footprint because of the widespread use of coal and gas. The overwhelming majority of hydrogen produced around the world is from fossil fuels, with around 80% of it coming from "dedicated" hydrogen production facilities in 2020, meaning that hydrogen is the primary product. Most of this production is fuelled by unabated natural gas (74%) and coal

[1] This includes more than 70 Mt H_2 used as pure hydrogen and less than 20 Mt H_2 mixed with carbon-containing gases in methanol production and steel manufacturing. It excludes around 30 Mt H_2 present in residual gases from industrial processes used for heat and electricity generation: as this use is linked to the inherent presence of hydrogen in these residual streams – rather than to any hydrogen requirement – these gases are not considered here as hydrogen demand.

(24%), corresponding to around 240 bcm of natural gas (6% of global natural gas demand in 2020) and 115 Mtce of coal (2% of global demand).

The remaining 20% of global supply is "by-product" hydrogen, meaning that it comes from facilities and processes designed primarily to produce something else, such as iron and steel or methanol. This by-product hydrogen often needs dehydrating or other types of cleaning before it can be sent to a variety of hydrogen-using processes and facilities. Catalytic naphtha reforming (CNR) in refineries is one of the main sources of by-product hydrogen. In 2020, less than 0.8% of total hydrogen production was from water electrolysis (~0.03%) or from fossil fuel plants equipped with CCUS (~0.7% of total production) – the two most mature low-emission hydrogen production routes currently available. As a result, both dedicated and by-product hydrogen production globally emitted close to 900 Mt CO_2 in 2020[2] (IEA, 2021b).

Hydrogen in China today

China has been the world's largest producer and consumer of hydrogen since 2010, owing to growing demand from its industry sector and the availability of low-cost resources. Since 2010, according to data sources in China, national hydrogen consumption has increased an impressive 30% to reach around 33 Mt in 2020, accounting for around 30% of the global total (CHA, 2020a). This includes hydrogen used for onsite co-generation of heat and power in industrial processes, such as coal-coking in steelmaking and chlor-alkali electrolysis in chlorine and caustic soda production. Dedicated hydrogen production and by-product hydrogen production from catalytic naphtha reforming (which is generally the basis of IEA estimates) amount to around 26 Mt[3] (IEA, 2021a).

China dominates global hydrogen demand, as it has roughly 30% of the world's combined capacity for producing ammonia, methanol and high-value chemicals (IEA, 2021a). It also has the second-largest oil refining capacity globally, totalling 17 Mb/d in 2021 (IEA, 2021c). Ammonia production (10-11 Mt/yr, depending on the data source) and oil refining (8-9 Mt/yr) are the largest consumers of pure hydrogen, and methanol production (7-9 Mt/yr) uses hydrogen mixed with other gases (e.g. carbon monoxide) as a raw material. Another 5 Mt/yr of hydrogen is produced and used onsite as a fuel to provide high-temperature heat for other industrial processes (CHA, 2020a). Just under 0.02 Mt of pure hydrogen demand is currently allocated to novel transportation purposes, mainly FCEVs.[4]

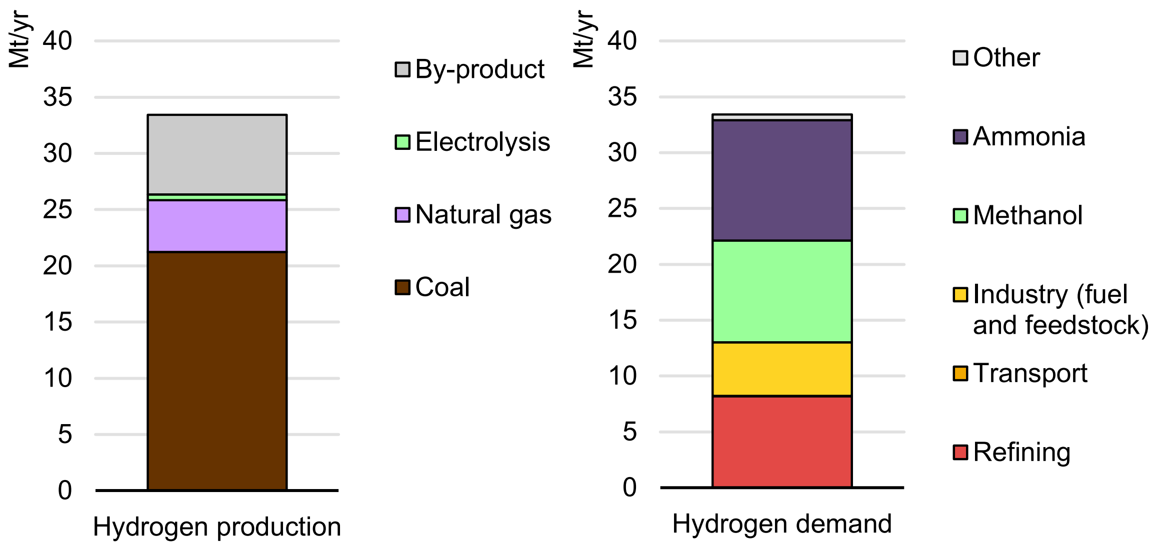
[2] This includes 265 Mt CO_2 captured and used onsite in ammonia and methanol production (and ultimately released to the atmosphere).

[3] As the use of H_2 present in residual gases from industrial processes used for heat and electricity generation (coal-coking in steelmaking, chlor-alkali electrolysis in chlorine and caustic soda production) is linked to the inherent presence of hydrogen in these residual streams – rather than to any hydrogen requirement – these gases are not considered as hydrogen demand in IEA definitions.

[4] Hydrogen currently used in the transport sector is mainly by-product hydrogen.

Coal is the fuel used for most of China's hydrogen production, with nearly two-thirds (21 Mt) made through coal gasification, accounting for 5% of China's total coal consumption. Natural gas reforming is the other main means of dedicated hydrogen production (5 Mt), and only a very small fraction of today's hydrogen comes from water electrolysis. The remainder (7 Mt) is formed as a by-product of several processes: coal-coking in steelmaking; chlor-alkali electrolysis in chlorine and caustic soda production; dehydrogenation; cracking of light oil fractions; and catalytic naphtha reforming (CHA, 2020a).

Hydrogen production and demand in China, 2020



Notes: By-product hydrogen includes hydrogen produced from coal-coking in steelmaking; chlor-alkali electrolysis in chlorine and caustic soda production; dehydrogenation; cracking of light oil fractions; and naphtha catalytic reforming. Dedicated hydrogen production and by-product hydrogen from catalytic naphtha reforming (which is generally the basis of IEA estimates) amount to around 26 Mt.
Source: CHA (2020a), *China Hydrogen Energy and Fuel Cell Industry Development Report.*

IEA analysis shows that the widespread use of fossil fuels for hydrogen production results in annual emissions of around 360 Mt CO_2 (this excludes 115 Mt CO_2 captured and used in methanol and urea production).

China's hydrogen opportunity

The Chinese government aims to expand low-emission hydrogen production and create new end uses, for example by using it as a fuel for FCEVs to address the issues of air pollution and the curtailment of renewable electricity generation from solar PV and wind resources.

China has been actively developing a hydrogen industry for many years, prompted by economic and other imperatives in addition to climate concerns:

- The opportunity to become a **global leader in hydrogen technologies**. Technological innovation could open up new markets, both domestic and international, and promote economic growth. Innovation-driven growth fits well with the government's 14th Five-Year Plan (FYP) and its technological self-reliance strategy.
- The desire to **reduce local air pollution**. While widespread fossil fuel use in industrial manufacturing and transport is a major source of air pollution, hydrogen can be used in vehicles and heating applications without producing the same particulate matter or emissions. Urban air pollution and its related health and environmental impacts are now major considerations in China's energy policy decisions.
- The need to **improve energy supply security**. China relies heavily on imported oil and, especially, gas. Hydrogen has the potential to diversify primary energy supply by allowing the country to shift partly to more affordable domestic resources such as coal (when used with CCUS) and renewable energy, including wind- and solar-based generation that would otherwise be curtailed. The vastness of China's domestic resource base could even allow the country to export hydrogen in the future.

Indeed, the China Hydrogen Alliance's (CHA's) detailed 2020 analysis highlighted the considerable opportunities for China's hydrogen sector, including using hydrogen for FCEVs, as a fuel and feedstock in industrial processes, and in the production of synthetic fuels, identified as key markets for future hydrogen use (CHA, 2020a).

China's support for hydrogen

China's long history of supporting hydrogen and fuel cell development dates to early research activities in the 1950s. Since the 1980s, several government projects have been launched to accelerate hydrogen technology development and commercialisation through the 863 Programme and the 973 Programme. In 2019, the government spent over CNY 2 billion (USD 300 million) on hydrogen-related research, development and demonstration (RD&D) programmes (CHA, 2020b).

China's hydrogen R&D history, 1991-2020

Period	Research and development process	Funding
1991-1995	• Changchun Institute of Chemistry carried out research on PEMFC. • Shanghai Institute of Ceramics, Institute of Chemical Metallurgy and Tsinghua University started research on fuel cells.	
1996-2000	• Research on PEMFC and fuel cell systems.	CNY 40 mln (USD 6 mln)

Period	Research and development process	Funding
2001-2005	• State High-Tech Development Plan (863 Programme): FCEV research carried out by DICP. • PEMFC and hydrogen storage technologies studied at Tsinghua University and Zhejiang University.	CNY 1 200 mln (USD 180 mln)
2006-2010	• National Basic Research Programme (973 Programme) and 863 Programme: research on hydrogen production, hydrogen storage and fuel cell module materials.	CNY 350 mln (USD 53 mln)
2011-2015	• Ministry of Science and Technology held seminar on hydrogen and fuel cell technology at Wuhan University of Technology during 13th FYP period, focusing on development of fuel cells, FCEVs and their key technologies.	CNY 160 mln (USD 24 mln)
2016-2020	• Inception of fuel cell technology innovation platform; attention to methanol fuel cell development; expanding application field for small-scale fuel cells and demonstration and operation of FCEVs.	CNY 500 mln (USD 75 mln)

Notes: DIPC = Dalian Institute of Chemical Physics. PEMFC = proton exchange membrane fuel cell.
Source: CHA (2020b), *China Hydrogen and Fuel Cell Industry Handbook.*

During the 13th Five-Year-Plan period (2016-2020), activity involving hydrogen and fuel cells was ramped up, with the Ministry of Science and Technology supporting 27 hydrogen RD&D projects through the Renewable Energy and Hydrogen Technology programme. In addition, three special hydrogen technology projects were introduced for the 2022 Beijing Winter Olympics, including the construction of hydrogen production and storage facilities, and the introduction of 1 000 fuel cell buses and associated refuelling infrastructure (see Appendix 1 for complete project list) (CHA, 2020b). In 2015, the State Council listed hydrogen production and FCEVs among the key technologies of the Made in China 2025 Initiative.

Policy and regulatory developments in the last three years indicate that hydrogen is gaining strategic interest in China. For instance, ten policy documents mentioning hydrogen were issued in 2019, including the important State Council's Work Report, which emphasised hydrogen infrastructure development. In the first half of 2020, six more policy documents from different ministries expressed support for hydrogen-related technologies, particularly for the transport sector (Yue and Wang, 2020). In April 2020, the National Energy Administration introduced hydrogen as an energy carrier in the draft Energy Law.

Following this trend, the hydrogen economy features prominently in subsector plans for the 14th Five-Year Plan adopted in March 2021. In March 2022, the National Development and Reform Commission released the Medium and Long-

Term Plan for Development of the Hydrogen Energy Industry (2021-2035), China's first medium-term plan for establishing a low-emission hydrogen industry. The plan aims to deploy 50 000 FCEVs by 2025, produce 0.1-0.2 Mt of renewable hydrogen annually (using electrolysis or bioenergy), and expand hydrogen infrastructure by 2035 (China, NDRC, 2022).

Interest in hydrogen is also growing among local and regional governments. At the end of 2019, at least ten provinces and municipalities had issued action plans for hydrogen and fuel cells, which have been identified as economic growth opportunities. During the first six months of 2020 alone, local governments published 30 policies supporting hydrogen (Tu, 2020). The success of the policies is reflected in rising FCEV sales, and growth in other hydrogen-related industries.

In recent years, the governments of Beijing, Guangdong, Hebei, Jiangsu, Shandong and Shanghai as well as other local governments have released regional hydrogen development plans, based on their industries and resource bases. In fact, these provinces and cities now host around half of all new hydrogen-related enterprises in China. In 2020, sales of FCEVs in Guangdong, Beijing and Hebei accounted for 80% of China's total sales for that year. The city-clusters demonstration programme, which aims to stimulate R&D and the large-scale demonstration of hydrogen production, supply, delivery and use in FCEVs in Beijing-Tianjin-Hebei, Shanghai and Guangdong provinces, also illustrates China's ambition to deploy hydrogen in the transport sector.

Selected policies and documents supporting hydrogen development in China, 2014-2022

Year	Authority	Policy or document	Key purpose
2014	State Council	Energy Strategic Action (2014-2020)	Officially adopted hydrogen and fuel cell technology as the strategic direction in terms of energy technology innovation.
2016	CPC Central Committee and the State Council	National Innovation-Driven Development Strategy Programme	Indicated that hydrogen is a vital element in the energy technology development strategy.
2018	Several ministries,* National Energy Administration and People's Bank of China	Catalogue for the Guidance of Green Industries 2019	Encouraged hydrogen infrastructure, fuel cells, new energy vehicles and hydrogen applications in shipping.
2019	National People's Congress (NPC)	State Council's Work Report	Promoted the development of hydrogen infrastructure for the first time.
April 2020	National Energy Administration	Energy Law (draft for comments)	Classified hydrogen as an energy source for the first time.

Year	Authority	Policy or document	Key purpose
April 2020	National Energy Administration	Note on preparation of the 14th Five-Year Plan for the development of renewable energy	Called for the integration of new technologies, including hydrogen.
September 2021	Several ministries** and the National Energy Administration	Notice on developing fuel cell vehicle demonstration application plan (2021-2025)	The city-clusters programme selected 12 cities in Beijing-Tianjin-Hebei, Shanghai and Guangdong provinces to carry out large-scale FCEV demonstrations.
March 2022	National Development and Reform Commission, and National Energy Administration	Medium- and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035)	Targets 50 000 FCEV ownership and 0.1-0.2 Mt annual renewable (electrolysis or bioenergy) hydrogen production by 2025, as well as hydrogen infrastructure scale-up by 2035.

* Ministry of Ecology and Environment; Ministry of Housing and Urban-Rural Development; Ministry of Industry and Information Technology; Ministry of Natural Resources; and the National Development and Reform Commission.
** Ministry of Finance; Ministry of Industry and Information Technology; Ministry of Science and Technology; and the National Development and Reform Commission.
Sources: CHA (2020b), *China Hydrogen and Fuel Cell Industry Handbook*; IEA (2021a), *An Energy Sector Roadmap to Carbon Neutrality in China*; China, NDRC (2022), *Medium and long-term plan for the development of hydrogen energy industry* (2021-2035).

CCUS in low-emission hydrogen production

CCUS can play a significant and diverse role in meeting China's climate ambitions. It can offer deep emissions reductions in key industry subsectors such as cement, iron and steel, and chemicals, and can be employed to reduce emissions from existing coal- and gas-fired power plants. It also underpins an important technological approach for removing carbon from the atmosphere, which is essential to achieve a net-zero energy system. CCUS technology can support the scale-up of low-emission hydrogen production and use in three key ways by:

- **Reducing emissions from existing hydrogen production facilities.** China is home to some of the world's youngest chemical production and oil refining assets. The average age of its current fleet is 8 years for methanol plants and 17 for ammonia plants, with 30 years being the typical lifetime of a chemical plant (IEA, 2020a). This low average age means there is a risk of CO_2 emissions from these plants being locked in for decades to come. If operated under the typical conditions observed in recent years, all of China's existing energy infrastructure and plants would produce around 175 Gt CO_2 of cumulative emissions between 2020 and 2060 (IEA, 2021a). Equipping plants with CCUS would thus enable their continued operation, but with significantly reduced emissions. Today, around 15 large-scale facilities producing hydrogen from fossil fuels with CCUS are in operation around the world, capturing over 10 Mt CO_2/yr.
- **Providing a cost-effective means to scale-up new hydrogen production in some regions.** The cost of electrolytic hydrogen is expected to drop considerably

over time and become a cost-effective production route in Chinese regions that have abundant solar and wind resources. Meanwhile, in other regions, coal-based hydrogen production with CCUS can support the scale-up of low-emission hydrogen production if methane emissions from coal mining can be minimised. Coal-based hydrogen production with CCUS is likely to remain a cost-effective option in the medium term in regions with high CO_2 storage capacity, low-cost fossil fuel availability and limited renewable resources. New fossil fuel-based hydrogen production capacity equipped with CCUS is therefore in planning or under construction in multiple regions around the world, with the potential to generate over 10 Mt/yr of hydrogen and capture around 80 Mt/yr of CO_2.

- **Supplying captured CO_2 and hydrogen to produce transport fuels.** CO_2 can be used to convert hydrogen into a synthetic carbon-based fuel that is as easy to handle and use as a drop-in replacement for gaseous or liquid fossil fuels, but with a smaller CO_2 footprint. CO_2 can be captured from a range of origins (e.g. concentrated fossil and biogenic sources, air), but the source will have a substantial impact on the emissions reductions achieved, recognising that the utilised CO_2 will be released when the fuel is combusted. To achieve carbon neutrality, the CO_2 would increasingly need to be captured from biogenic sources or from the air. Synthetic fuels could become important in sectors that will continue to rely on carbon-based fuels because the direct use of electricity or hydrogen is challenging, for example aviation. At the global scale, several companies have operated pilot plants or are building industrial-scale facilities to produce liquid fuels from hydrogen and CO_2. The Chinese government is therefore exploring the potential of using low-emission fuels for long-haul transport (Energy Foundation China, 2020).

Large-scale facilities with CCUS currently producing hydrogen around the world

Country	Project	Operation date	Application	CO_2 capture capacity (Mt/year)	Primary storage type
United States	Enid fertiliser	1982	Fertiliser production	0.7	EOR
Netherlands	Shell heavy residue gasification Pernis	1997	Refining	0.4	EOR
United States	Great Plains Synfuel plant	2000	Coal-to-gas	3.0	EOR
Canada	Horizon H_2 capture tailings CCS	2009	Refining	0.4	EOR
United States	PCS Nitrogen	2013	Fertiliser production	0.3	EOR
United States	Port Arthur Air Products SMR	2013	Refining	0.9	EOR

Country	Project	Operation date	Application	CO_2 capture capacity (Mt/year)	Primary storage type
United States	Coffeyville Gasification	2013	Fertiliser production	1.0	EOR
France	Port Jerome	2015	Refining	0.1	Use
Canada	Quest	2015	Hydrogen production	1.0	Storage
Abu Dhabi	Al Reyadah phase 1	2016	Iron and steel	0.8	EOR
China	Karamay Xinjiang Dunhua methanol plant	2016	Chemicals (methanol)	0.1	EOR
Canada	Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 stream	2020	Fertiliser production	0.3	EOR
Canada	ACTL with NWR Sturgeon Refinery CO_2 stream	2020	Hydrogen production	1.3	EOR
China	Sinopec Qilu Petrochemical Shengli	2022	Fertiliser production	0.2	EOR

Note: Only industrial facilities capturing at least 0.1 Mt/yr of CO_2 are included.
Sources: IEA analysis based on IEA tracking and GCCSI (2021), CCS Facilities Database 2021.

CCUS projects and policy support in China

China has made significant progress in developing and deploying CCUS over the past decade. In 2021, it had nearly 50 CCUS demonstration and commercial-scale projects at various stages of development and with different focus areas, with a total planned capture capacity of around 7 Mt CO_2 per year. China's operational commercial and demonstration projects are currently capturing close to 3 Mt CO_2/yr (Zhang et al., 2021a).

The China National Petroleum Corporation (CNPC) Jilin project, in operation since 2008, captures some 600 kt CO_2 per year from a natural gas processing plant and transports it via a 50-km pipeline to the Jilin oilfield, where it is used for enhanced oil recovery (CO_2-EOR). Meanwhile, construction of the Sinopec Qilu Petrochemical CCUS facility was completed in January 2022. It is designed to capture 1 Mt/year of CO_2 from Qilu's refineries and transport it 75-150 km by pipeline to oilfields where it will also be used for CO_2-EOR. The project will generate hydrogen, both as a pure gas for ammonia production and mixed with other gases to manufacture chemicals. Several smaller capture and storage demonstration projects, mainly related to coal-fired power plants and chemical facilities, have also been operated successfully over the last decade.

Demonstration and commercial CCUS facilities in operation in China

Project	Location	CO_2 point source	Capture capacity (kt/yr)	CO_2 storage / use
Sinopec Nanjing Chemical Industries CCUS Cooperation Project	Nanjing (Jiangsu)	Chemical plant	200	EOR
CHN Energy Guohua Power Jinjie	Yulin (Shaanxi)	Coal-fired power plant	150	EOR
35-MW oxygen-enriched combustion demonstration project of Huazhong University of Science and Technology	Wuhan (Hubei)	Coal-fired power plant	100	-
Carbon capture and purification demonstration project of Conch Group	Wuhu (Anhui)	Cement plant	50	Used as raw material in protective gas and fire extinguishers
Carbon capture demonstration project of Chongqing Shuanghuai power plant of China Power Investment	Chongqing	Coal-fired power plant	10	-
CCUS full-chain demonstration project of Huadong Oilfield of Sinopec	Yancheng (Jiangsu)	Chemical plant	50	EOR
Changqing EOR project	Xi'an (Shaanxi)	Methanol plant	50	EOR
CO_2-ECBM project of China United Coalbed Methane Company (Liulin)	Liulin (Shanxi)	Coal-fired power plant	-	ECBM
CO_2-ECBM project of China United Coalbed Methane Company (Shizhuang)	Qinshui (Shanxi)	Coal-fired power plant	-	ECBM
Daqing EOR project	Daqing (Heilongjiang)	Natural gas processing	160	EOR
Dunhua methanol plant EOR	Karamay (Xinjiang)	Methanol plant	100	EOR
Gaobeidian power plant of Huaneng Group	Beijing	Coal-fired power plant	3	-

Project	Location	CO_2 point source	Capture capacity (kt/yr)	CO_2 storage / use
Haifeng carbon capture test platform of China Resources	Haifeng (Guangdong)	Coal-fired power plant	20	-
Huaneng IGCC project	Tianjin	Coal-fired power plant (IGCC)	100	-
Power plant of China Guodian Corporation	Tianjin	Coal-fired power plant	20	-
Research facility of clean energy power system	Lianyungang (Jiangsu)	Coal-fired power plant (IGCC)	30	-
Shengli EOR project of Sinopec	Dongying (Shandong)	Coal-fired power plant	40	EOR
Shidongkou power plant of Huaneng Group	Shanghai	Coal-fired power plant	120	-
Tongliao CO_2-enhanced uranium leaching project of National Nuclear Corporation	Tongliao (Inner Mongolia)	-	-	Uranium leaching
Yanchang coal-to-chemicals CO_2 capture demonstration project	Xi'an (Shaanxi)	Coal-to-gas plant	50	EOR
Wuqi Baibao CCUS Demonstration Zone	Yanan (Shaanxi)	Coal chemical industry	50	EOR
China Energy Investment Corporation Jinjie Power Plant demonstration project	Yulin (Shaanxi)	Coal-fired power plant	150	-
Indirect mineralisation of steel slag and fly ash CCU demonstration	Lvliang (Shanxi)	Coal-fired power plant	15	Chemical utilisation
Research and demonstration of CO_2-EOR in PetroChina Jilin Oilfield	Jilin (Jilin)	oilfield	640	EOR
CO_2 mineralisation and desulphurisation CCU demonstration	Xichang (Sichuan)	Coal, electricity and steel	15	Chemical utilisation

Sources: IEA analysis; GCCSI (2021), CCS Facilities Database 2021; CAEP (2020), *China Status of CO_2 Capture, Utilisation and Storage (CCUS) 2019.*

There are also plans to develop a large CCUS hub in North-West China to capture and store CO_2 from refineries' hydrogen production units. This project would involve gradual CCUS deployment, starting with a capture volume of 1.5 Mt CO_2 per year during 2020-2023 and growing to 10 Mt CO_2/yr during 2030-2040 (Zhang, 2021a).

China's growing number of policies and initiatives to support CCUS development reflect its interest in the technology. Although multiple government reports in the past have highlighted the importance of CCUS and R&D promotion, the 14th Five-Year Plan (2021-2025) is the first five-year plan to mention the deployment of large-scale CCUS demonstrations, targeting important coal-producing areas such as Shanxi, Shaanxi, Mongolia and Xinjiang.

Furthermore, several ministries and commissions have introduced policies that have direct bearing on CCUS, including the National Emissions Trading Scheme. China's national policy guidance on peaking CO_2 emissions before 2030 and achieving carbon neutrality by 2060, issued in October 2021, identified CCUS as one of the key pillars of its decarbonisation plan. Interest in CCUS is also growing at the regional level, with 29 of 34 administrative divisions having issued CCUS-related policies (Zhang, 2021a), and R&D activities have also been launched both nationally and regionally.

In 2019, the Administrative Centre for China's Agenda 21 (ACCA21) issued a Roadmap for Development of CCUS Technology in China, which presents an overall vision for CCUS technology development in the country (ACCA21, 2019). It defines several phase goals in five-year increments to 2050. By 2030, CCUS should be ready for industrial applications, and long-distance onshore pipelines with capacities of 2 Mt CO_2 should be available. It also aims to reduce the cost and energy consumption of CO_2 capture by 10-15% by 2030 and by 40-50% by 2040. By 2050, CCUS technology is to be deployed extensively, supported by multiple industrial CCUS hubs across the country. The roadmap earmarks several regions as suitable for CCUS hubs.

Low-emission hydrogen standards in China

Emissions-accounting frameworks and emissions standards need to be put in place to ensure hydrogen production is indeed low-emission.

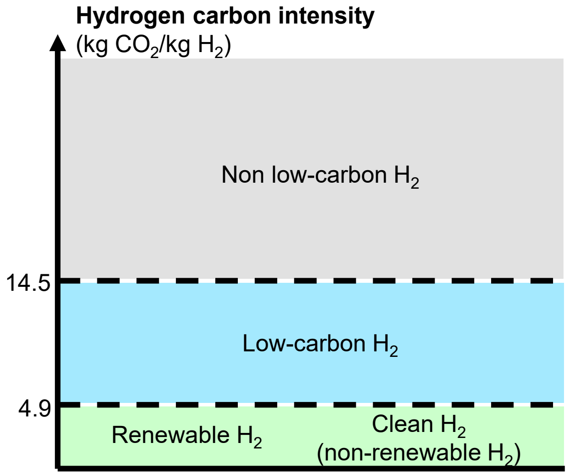
In China, five government departments issued the document Notice on the Development of Fuel Cell Vehicle Demonstration Applications (hereafter "the Notice") to encourage companies to adopt low-emission hydrogen production methods. The aim of the Notice was to establish safe, stable and economically viable sources of hydrogen production for FCEV demonstration projects and to drive renewables-based hydrogen production development and cost reductions (China, MOF et al., 2020).

In late 2020, the China Hydrogen Alliance (CHA) officially released its Standard and Evaluation of Low-Carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen report, containing a set of lifecycle carbon intensity standards for hydrogen production (CHA, 2020c). This is the first such standard worldwide, and it aims to support hydrogen and fuel cell demonstration and promotion in China.

Lifecycle carbon intensity standards in China are based on an assessment of China's hydrogen development status and field data collection, such as for coal-based hydrogen production with and without CCUS. The lifecycle carbon emissions threshold adopted for "low-carbon" hydrogen is 14.5 kg CO_2/kg H_2. It was established at this level to correspond with a 50% reduction relative to the upper boundary of lifecycle CO_2 emissions of hydrogen produced from coal gasification, which has been assessed at 29.0 kg CO_2/kg H_2 including upstream CO_2 emissions (from coal mining, washing and transport) and downstream emissions (from electricity use for CO_2 compression, transport and storage, based on current grid electricity carbon intensity) (Zhang et al., 2021b). The 50% reduction was mandated by the National Plan for Tackling Climate Change 2014-2020.

Meanwhile, the threshold adopted for "clean" hydrogen is 4.9 kg CO_2/kg H_2, which corresponds to a 65% reduction relative to "low-carbon" hydrogen and an over 80% reduction relative to coal-based hydrogen. The 65% reduction was mandated by the Energy Supply and Consumption Revolution Strategy 2016-2030. When this threshold is met, hydrogen produced through electrolysis using renewable electricity or biomass is labelled as "renewable hydrogen."

Threshold values for the carbon intensity of hydrogen production in China



Notes: The "low-carbon", "renewable" and "clean" terminologies are drawn from the Fuel Cell China standard and do not reflect an IEA definition of low-emission hydrogen. "Renewable" includes hydrogen produced through electrolysis with renewable electricity and from biomass.
Source: CHA (2020c), *Standard and Evaluation of Low-Carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen*.

While no international standard for low-emission hydrogen production currently exists, definitions of "low-carbon" and "clean" hydrogen are likely to become more restrictive in the future. Low-emission hydrogen in IEA scenarios includes hydrogen produced via electrolysis where the electricity is generated from a low-emission source (renewables or nuclear), biomass or fossil fuels with CCUS. Production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if a high rate of capture is applied to all CO_2 streams associated with the production route, and if all CO_2 is permanently stored to prevent its release into the atmosphere.

Chapter 2. Outlook for China's hydrogen industry

HIGHLIGHTS

- Two analytical frameworks assess China's hydrogen prospects, including hydrogen made from fossil fuels with CCUS. The IEA Announced Pledges Scenario (APS) considers all fuels and technologies needed to peak CO_2 emissions before 2030 and reach carbon neutrality by 2060. Meanwhile, China Hydrogen Alliance (CHA) provides a detailed bottom-up assessment of the technical and commercial potential of hydrogen outside an energy system modelling framework.

- Both the IEA and CHA judge that hydrogen could be of great value in meeting China's energy and climate goals. Focused on affordability, climate change mitigation and energy security, the APS shows that hydrogen demand grows to 31 Mt in 2030 and to over 90 Mt in 2060, boosted by new uses and applications across China's economy. Meanwhile, the CHA recognises even greater hydrogen potential, with demand growing to 37 Mt in 2030 and 130 Mt by 2060. Targeted policies and support for hydrogen will be important for future market growth and realisation of hydrogen's full potential in China.

- Despite their differences, both analytical approaches envision that around 60% of the growth in hydrogen demand is in transport (including for ammonia and synthetic hydrocarbon fuels for shipping and aviation), and around 30% in industrial processes, which use hydrogen as a feedstock, reducing agent and fuel, including iron and steel production. Small amounts will also be used for heating in buildings and for flexible electricity generation and storage.

- Demand for current uses in refining and ammonia production (for non-fuel applications) declines by 2060. Although demand in refining climbs slowly in the upcoming decade as gasoline quality requirements tighten, it then shrinks considerably after 2030 with energy efficiency improvements and the use of electricity in transport. In the APS, hydrogen use in ammonia production drops 50% as fertiliser use becomes more efficient, while its use in methanol production increases slightly.

- In both the IEA and CHA analyses, hydrogen supplies become more diversified and low-emission. Production from fossil fuels with CCUS and from electrolysis both gain ground in 2030, while unabated fossil-based production declines. By 2060 in both scenarios, 80% of demand is met by hydrogen from electrolysis and renewable electricity, and 16% by CCUS-equipped fossil fuel-based plants.

Modelling the future role of hydrogen in China

China's large hydrogen industry is on the verge of ambitious transformation and growth owing to various critical energy challenges, including the need to decarbonise the energy system. Using the projections of the IEA APS (IEA, 2021a) and the CHA (CHA, 2020a), this section explores the potential evolution of hydrogen demand in various sectors of the Chinese economy through 2060.

The APS lays out a pathway to carbon neutrality in China's energy sector in which CO2 emissions peak before 2030 and fall to net-zero in 2060, in line with China's stated goals. Broadly outlining the energy sector's evolution and the underlying technological transformation that would be required to reach China's climate goals, this scenario assesses what is needed to meet these goals in a technology-agnostic, realistic and cost-effective way.

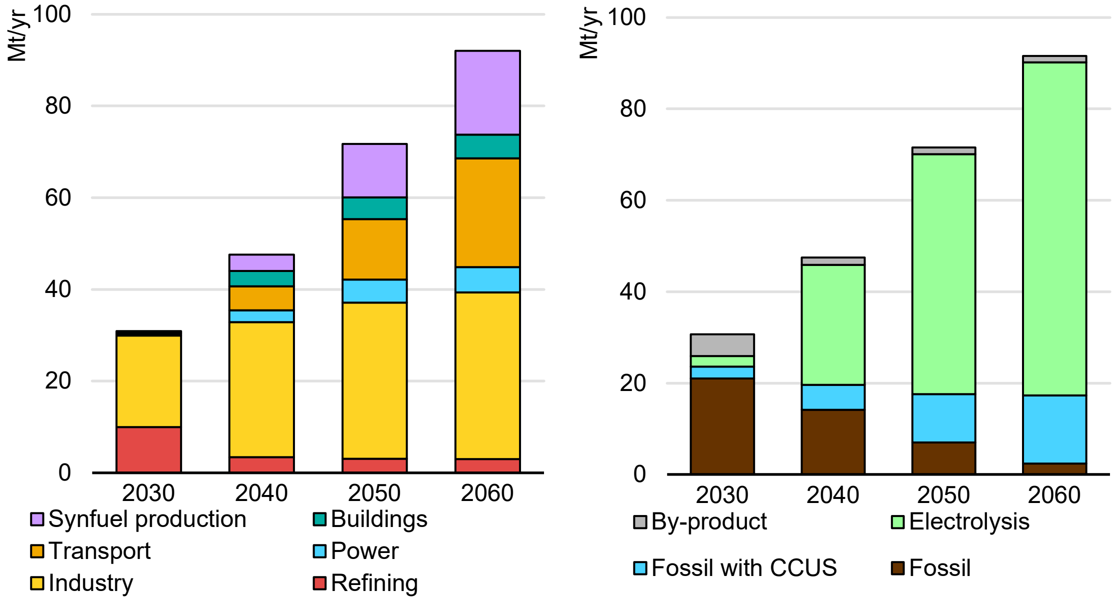
In its 2020 China Hydrogen Energy and Fuel Cell Industry report, the CHA studied the technology, market and policy status of China's hydrogen energy and fuel cell industry in detail and presented a hydrogen market outlook out to 2060. In contrast with the IEA APS, the CHA analysis was designed to assess hydrogen potential in China only, and it is not part of a wider energy system decarbonisation exercise (CHA, 2020a).

While they are not directly analogous in their design, comparing these scenarios can reveal important insights. While the CHA's bottom-up analytical work provides a domestic expert organisation's assessment of potential market size by sector, the IEA's APS illustrates just how much of this market potential may need to be tapped into to meet overriding climate, affordability and energy security objectives. The differences between these assessments indicate that tapping into the hydrogen potential as assessed by the CHA may require other drivers or considerations than those assumed in the APS (for instance, technology-specific policies and support).

Outlook for hydrogen production and demand in China

In both scenarios, the contribution of hydrogen and hydrogen-based fuels to China's energy transition increases progressively to 2060, with especially strong uptake after 2030. Total hydrogen demand increases 11-20% by 2030 and then three- to fourfold by 2060. In the APS, hydrogen demand reaches just over 90 Mt by 2060, and make up around 6% of China's final energy consumption.[5] In CHA projections, hydrogen plays an even greater role in China's energy sector, with demand reaching 130 Mt in 2060.

Outlook for hydrogen demand (left) and production (right) in China in the Announced Pledges Scenario, 2030-2060



Notes: "Industry" includes merchant and onsite use of hydrogen for heat and as a feedstock in all industry subsectors including methanol and ammonia (for fertiliser). "Synfuel production" includes production of ammonia as a fuel. "Buildings" includes hydrogen for blending in the natural gas network.
Source: IEA (2021a), *An Energy Sector Roadmap to Carbon Neutrality in China.*

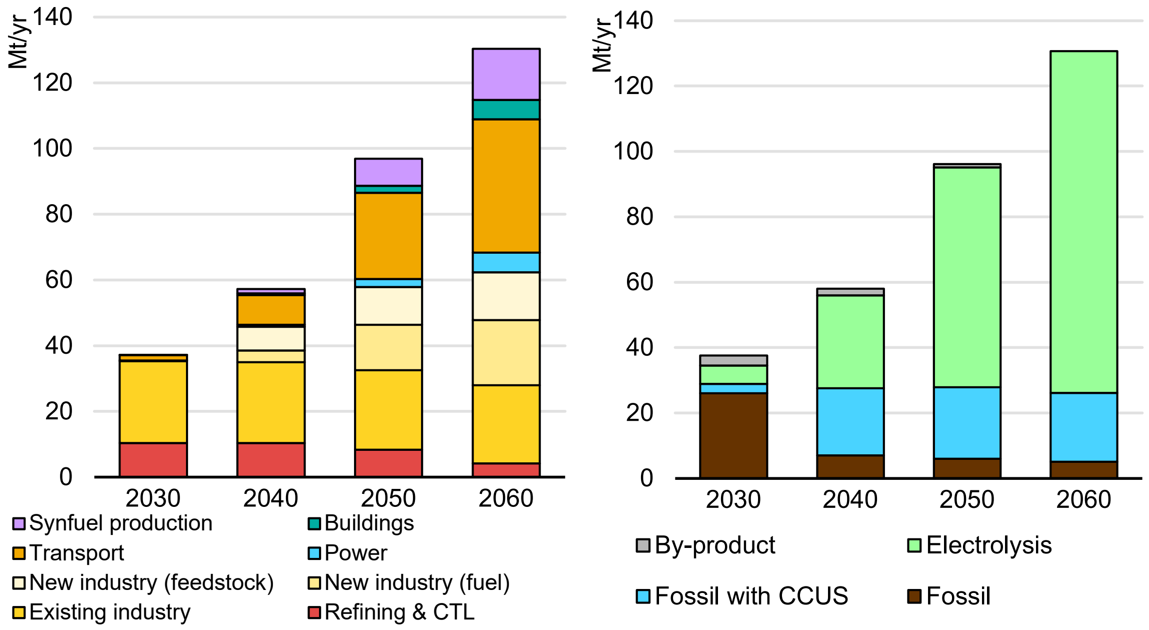
Proportionally, the fastest-growing sectors are the same in the APS and CHA assessments. The transport sector boosts demand the most (36-42% of growth) owing to FCEV deployment, followed by synthetic hydrocarbon and ammonia production (16-28%) and industrial processes (30-35%), which use hydrogen as a feedstock and fuel.

Electrolytic hydrogen makes up most of the growth in low-emission hydrogen production in the short term (electrolysis projects tend to have shorter development times because electrolysers can be mass-manufactured and also require less new infrastructure). In fact, electrolytic hydrogen could meet 8-15% of total hydrogen demand in 2030. In the APS, almost 90% of electrolytic hydrogen is produced in the chemical industry (through electrolytic ammonia and methanol production) and the steel sector (through the hydrogen-based direct reduced iron route, or DRI).

[5] 6% excludes onsite hydrogen production and use in the industry sector, which accounts for around 8% of industrial energy demand in the APS by 2060. Including on-site hydrogen production in industry, hydrogen and hydrogen-based fuels meet 10% of China's final energy consumption. In CHA projections, H2 and hydrogen-based fuels meet 20% of China's final energy consumption.

In both the APS and CHA projections, nearly all hydrogen demand is met by low-emission technologies by 2060, with almost 80% produced through electrolysis, which emerges as a competitive production route. Meanwhile, hydrogen production from CCUS-equipped fossil fuel-based plants expands to meet 16% of hydrogen demand in 2060.

Potential hydrogen demand (left) and production (right) in the China Hydrogen Alliance assessment, 2030-2060



Notes: CTL = coal-to-liquids. "Synfuel production" includes production of ammonia as a fuel. "Buildings" includes hydrogen for blending in the natural gas network. "Existing industry" includes hydrogen use for existing methanol and ammonia production and industrial heat. "New industry (fuel)" includes new hydrogen uses for industrial heat, and "New industry (feedstock)" includes new hydrogen uses as a feedstock in industrial processes (DRI).
Source: CHA (2020a), *China Hydrogen Energy and Fuel Cell Industry Development Report.*

Using hydrogen and hydrogen-based fuels from low-emission sources could avoid the emission of 16 to23 Gt CO_2 cumulatively to 2060 in China (IEA, 2021a; CHA, 2020a). In the APS, CO_2 emissions from hydrogen production drop 80% by 2060, direct emissions (i.e. excluding downstream emissions from using hydrogen-derived products such as urea and methanol) drop from around 360 Mt in 2020 to 300 Mt in 2040 and to 60 Mt in 2060, with some residual emissions from plants equipped with capture facilities.

Existing fossil-based hydrogen plants are retrofitted with CCUS to reduce emissions. The largest CO_2 emissions reductions from these fuels are in the industry sector, especially from chemical and steel production. These subsectors account for more than 50% of the avoided emissions, with hydrogen and ammonia in shipping and synthetic kerosene in aviation together contributing 20%, and hydrogen use in road transport adding another 13% reduction.

Hydrogen in industry and fuel transformation

As industry and fuel transformation consume nearly all China's current hydrogen production, meeting this demand with cleaner hydrogen – by applying CCUS to hydrogen produced from fossil fuels, switching to electrolytic hydrogen or producing hydrogen from bio-feedstock – would help decarbonise this sector. There is also significant potential to expand hydrogen use to new applications, including as a feedstock for industrial processes (e.g. DRI in steelmaking), as a fuel for industrial heating, and as an input in the production of long-distance transport fuels such as synthetic kerosene.

Industry and fuel transformation are among the primary contributors to rising hydrogen demand to 2060 in both the APS and CHA analyses. In the APS, hydrogen use in industry reaches close to 40 Mt by 2060, after the availability and cost of alternative technology options, as well as measures to limit energy demand, are accounted for. Meanwhile, the CHA market analysis assessed potential at 62 Mt (CHA, 2020a; IEA 2021a).

Chemicals and hydrogen-based fuels

Chemical manufacturing is the single largest source of hydrogen demand in China. Production of both methanol and ammonia have increased in recent years, with methanol showing the largest output growth. Demand for ammonia comes mainly from the agriculture sector, where it is used to make nitrogen fertilisers. Despite increasing demand for food, ammonia consumption for existing uses (i.e. agriculture) is projected to remain constant or decrease slightly to 2060, mainly owing to greater fertiliser application efficiency and the development of other fertilising methods. Another source of demand is the manufacture of industrial explosives for mining, quarrying and tunnelling, which is also projected to decrease with the phaseout of unabated coal-fired power generation. Ammonia could also be used as an energy carrier to store renewable electricity or as a carbon-free fuel in the transport and power sectors.

Hydrogen demand for methanol consumption for existing uses is anticipated to grow slowly, reaching 11 to12 Mt H_2 by 2060 (IEA, 2021a; CHA, 2020a). Methanol is mostly used in industry to make other chemicals that can be further processed into plastics, paints and textiles. Future methanol applications could include its use as a fuel for vehicles or as an intermediate to make primary chemicals such as olefins (ethylene and propylene) and aromatics (benzene, toluene and xylenes), which are the main building blocks of the petrochemical industry.

New production methods involve combining hydrogen with carbon monoxide, CO_2 or nitrogen to produce synthetic hydrocarbons (such as methanol, diesel and kerosene) or ammonia.[6] Hydrogen and energy needs vary significantly depending on the chemical and the production pathway. These synthetic hydrogen-based feedstocks and fuels are expected to become increasingly important. In fact, hydrogen demand for the production of ammonia (as a fuel) and synthetic hydrocarbon fuels could reach 16 to 18 Mt by 2060, mainly to decarbonise shipping and aviation (IEA, 2021a; CHA, 2020a).

Oil refining and coal-derived chemicals

Considerable volumes of hydrogen are also used in oil refining and coal-derived chemical production. Oil refineries use hydrogen as a feedstock and energy source, with hydrotreatment and hydrocracking being a refinery's main hydrogen-consuming processes. Hydrotreatment removes impurities from oil, especially sulphur, and accounts for a large share of refinery hydrogen use, while hydrocracking is a process that uses hydrogen to upgrade heavy residual oils into higher-value oil products. In addition to hydrotreatment and hydrocracking, some hydrogen that is used or produced by refineries cannot be economically recovered and is therefore burnt as fuel in a mixture of waste gases. In refineries, hydrogen is produced as part of the catalytic naphtha reforming process and is used onsite to cover part of the refinery's hydrogen demand.

In the coal-to-chemicals industry, hydrogenation is one of the main sources of hydrogen demand. While this industry is currently important in China for producing fuel and petroleum derivatives (e.g. olefins, aromatics, ethylene glycol), production is also expected to decrease after 2030, in line with coal phaseout (CHA, 2020a).

Hydrogen demand in refining is expected to increase slightly in the upcoming decade because of stricter gasoline quality requirements (i.e. lower allowable sulphur content). After 2030, however, hydrogen demand in the oil refining sector is anticipated to decline considerably owing to continuous energy efficiency improvements and greater availability of fuel alternatives in the transport sector. Thus, hydrogen demand in oil refining is projected to grow to 10 Mt by 2030, then decline to 3 to4 Mt by 2060 (IEA, 2021a; CHA, 2020a).

Iron and steel manufacturing and other industries

Today, the iron and steel sector already produces hydrogen mixed with other gases as a by-product (e.g. coke oven gas) through its main primary production route, the blast furnace-basic oxygen furnace (BF-BOF). Some of this mixed hydrogen gas is consumed within the sector and some of it is distributed for use elsewhere, for example for methanol production or for onsite co-generation of heat and power. The other main primary production route, the direct reduction of iron-

[6] In this report, synthetic hydrocarbons refer to CO_2 and H_2 combinations, while fossil-based synthetic fuels cover coal-to-liquid (CTL) and coal-to-gas (CTG) products.

electric arc furnace (DRI-EAF) method, uses a mixture of hydrogen and carbon monoxide as a reducing agent, which helps cleave oxygen from the iron ore molecules.

Replacing carbon monoxide with hydrogen as a reducing agent in both primary production routes can help reduce emissions. Hydrogen-based DRI, using 100% electrolytic hydrogen, is at the full prototype level of development (technology readiness level [TRL] 6), and efforts are under way globally to demonstrate the process at industrial scale as early as 2026.

In the meantime, low-emission hydrogen could be integrated into existing processes currently based on natural gas and coal to lower their overall CO_2 intensity. Both the partial use of hydrogen with coal in the BF-BOF process, and with natural gas in the DRI-EAF process, are at the pre-commercial demonstration stage (TRL 7). In the past two years, domestic steel companies such as BAOWU Steel Group and HBIS Group have signed framework agreements to carry out hydrogen-based steel manufacturing test projects.

However, using hydrogen raises the cost of steel manufacturing considerably. For example, a 100% hydrogen-based DRI-EAF route using electrolytic hydrogen could be 20-70% more expensive than its natural gas-based counterpart, depending on natural gas and electricity prices. It would be competitive only if the price of electricity were to fall below around USD 20/MWh (CNY 135/MWh). While this electricity price may be realistic in some Chinese regions when dedicated low-cost renewable resources can be employed, it would be difficult to achieve across the country (IEA, 2020b).

Among other low-emission pathways for steel production currently being explored, CCUS routes are at a more advanced stage of development. For instance, gas-based DRI with CCUS is already in commercial operation (TRL 9) and smelting reduction with CCUS is at the pre-commercial demonstration stage (TRL 7). CCUS routes are also typically 10-50% less expensive than hydrogen-based DRI depending on energy prices (IEA, 2020b).

Hydrogen can also replace coal and natural gas as a low-emission fuel to generate high-temperature heat in the cement, steel, chemical and oil refining industries. Hydrogen is one of the few options available to supply high-temperature heat in a low-emission manner, but furnaces and boilers would have to be retrofitted with special burners able to combust hydrogen.

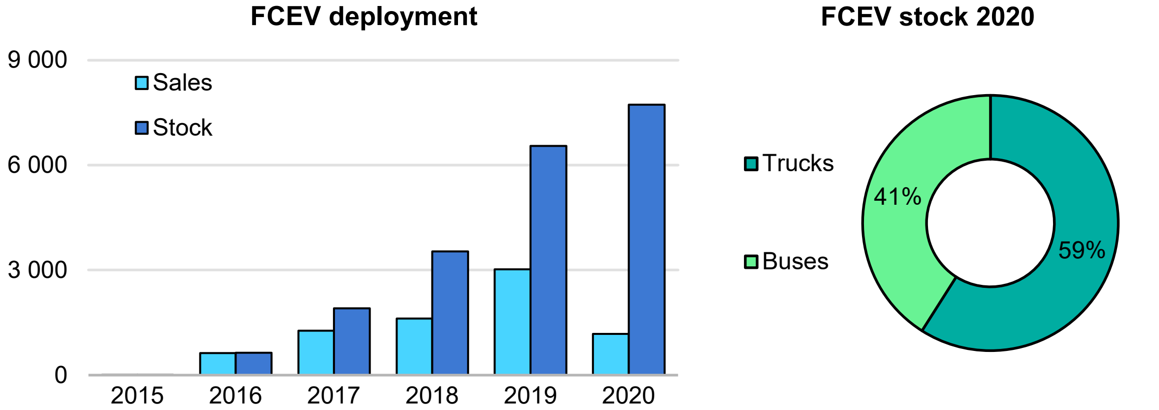
In the APS, hydrogen used as a feedstock in steelmaking and as a fuel for industrial heating grows to 20 Mt by 2060 (IEA, 2021a). This is only just over half of the sector's potential according to the CHA assessment, which foresees greater use of hydrogen as a fuel for high-grade heat generation in industrial processes (20 Mt H_2 by 2060) and as a feedstock in iron and steel production (15 Mt by 2060)[7].

Hydrogen in transportation

In both the IEA and CHA analyses, transport is the sector that boosts hydrogen demand the most through 2060. Although China has a long history of supporting FCEV development, it was not until 2016 that FCEV uptake began to gain traction, with the greatest increase in 2019. By the end of 2020, China had deployed over 7 700 FCEVs (particularly buses and trucks, according to CHA data), making the country the world's largest FCEV market (CHA, 2020a). Given the large size of China's vehicle market and the sheer volumes of fuel involved, hydrogen uptake in transport could quickly make this sector the single largest source of hydrogen demand in the future.

However, actual hydrogen deployment will depend on many factors, including overall vehicle sales trends; FCEV prices and how they compare with the cost of electric vehicles; refuelling infrastructure buildout; hydrogen production costs; and supporting policies. To date, electric vehicles have had a head start and China is currently the largest market for light-duty electric vehicle sales in the world.

Deployment of fuel cell electric vehicles in China, 2015-2020



Source: CHA (2020a), *China Hydrogen Energy and Fuel Cell Industry Development Report*.

In the APS, FCEVs contribute to transport sector decarbonisation, with 24 Mt of hydrogen consumed for road transport in 2060 (IEA, 2021a). However, this is equivalent to only just over half the technical potential assessed by the CHA, which

[7] Hydrogen demand for onsite heat generation is greater in CHA projections than in the APS partly because the CHA assessment covers a wider range of cases in which hydrogen could be used onsite to generate heat for industrial processes, including coal-coking in steelmaking and chlor-alkali electrolysis in chlorine and caustic soda production, which are not included in the APS.

estimates 41 Mt H_2 for FCEVs. Tapping into this potential may very well require other levers and technology-specific support not considered in the IEA scenario.

According to the CHA, FCEV sales are limited by the high cost of fuel cells (around USD 800/kW) and hydrogen storage tanks (around USD 120/kW), which make the current price of fuel cell trucks 3-4 times higher than for comparable gasoline or diesel vehicles (CHA, 2020a). However, the cost of equipment such as fuel cells and hydrogen storage tanks is expected to fall in the future as manufacturers gain experience and achieve economies of scale (although cost reduction potential for storage tanks is somewhat lower, mainly because of higher material costs). The CHA therefore judges that cost reductions could boost FCEV deployment for road transport from just below 10 000 in 2020 to over 72 million by 2060, with passenger FCEVs making up over 85% of the fleet.

Another critical cost factor is the price of fuel, particularly for conventionally fuelled heavy-duty and medium-duty trucks, for which fuel expenses can make up 60-70% of their total cost. According to the CHA, the cost of producing hydrogen and distributing it to refuelling stations is currently around USD 7/kg H_2 (over CNY 50/kg H_2) (excluding station costs), but total supply chain costs could fall quickly if a major hydrogen industry scale-up materialises (CHA, 2020a).

For maritime transport, inland and coastal shipping can be decarbonised through battery or hydrogen fuel cell technology, but long-distance oceangoing vessels are likely to rely on other options such as biofuels, hydrogen or zero-carbon ammonia. The technological development of fuel cell ships is currently at the large-scale prototype stage (TRL 7), behind battery ships, which are beginning to operate at commercial-scale (TRL 8-9). By 2060, all of the hydrogen potential quantified by the CHA in the shipping sector (3 Mt) needs to be tapped into to meet wider energy system decarbonisation targets in the APS (3 Mt) (IEA, 2021a; CHA, 2020a).

Long-distance aviation will need to rely increasingly on biofuels and synthetic kerosene made from hydrogen and CO_2 to decarbonise, whereas direct electrification and fuel cell aircrafts are potential options for short and medium-distance flights. At present, a variety of aircraft models are being developed and tested. Since hydrogen planes are still at the concept/prototype stage (TRL 3-4) and low-emission alternatives are available, no direct use of hydrogen in aviation is considered in the APS (IEA, 2021a). The technical potential exists, though, as indicated by the CHA's expectation that hydrogen consumption could reach 2 Mt in aviation, accounting for about 5% of total aviation energy demand in CHA projections (CHA, 2020a).

Hydrogen for power generation

Hydrogen use in China's power sector today is close to zero. China has the largest power sector in the world. In fact, electricity generation accounted for 46% of China's primary energy consumption in 2019.

There are two main routes for using hydrogen in power generation. The first is (co-firing hydrogen in gas turbines, which could be a low-emission source of flexibility in the Chinese power system with a high share of variable renewables (hydrogen-enriched gas turbines have been successfully demonstrated in Italy, Japan and South Korea). Hydrogen can also be combined with nitrogen to make ammonia, which can be (co-)fired in gas- or coal-fired power plants. Co-firing can help reduce emissions in the power sector as the blend of hydrogen (or ammonia) increases over time.

The second route involves using hydrogen in fuel cells for flexible power generation. In 2020, global fuel cell power generation capacity totalled around 2.2 GW_e, with systems installed mainly in the United States and South Korea.[8] Most of these systems currently rely on natural gas, and the 50-MW Doosan plant in Korea is the largest hydrogen-fired fuel cell power plant (IEA, 2021b). In China, the only hydrogen-fired fuel cell power plant demonstration project currently operating is a 2-MW_e demonstration plant at Yingkou, Liaoning province.

Hydrogen or hydrogen-based fuels (e.g. ammonia) can also be used for long term and seasonal electricity storage. As such, these fuels can provide electricity during long periods when very little wind and/or solar energy resources are available. Salt caverns are the best choice for underground storage of pure hydrogen because of their tightness and low risk of contamination, but alternative underground options such as depleted oil and gas fields are also being investigated. Large steel tanks are already commonly used in the fertiliser industry to store ammonia.

Given the growing need for flexibility services in the power sector, hydrogen has strong deployment potential. Thus, hydrogen consumption in the power sector is estimated to reach around 6 Mt in 2060 in both scenarios (CHA, 2020a; IEA, 2021a).

Hydrogen use in buildings

China's buildings sector accounted for close to 20% of the country's final energy consumption in 2020, including consumption of electricity, mostly for heating, cooking, household appliances and lighting (IEA, 2021a).

There are two main ways to use hydrogen for heating in buildings. The first involves blending hydrogen into existing natural gas pipeline networks, which has

[8] Mainly solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC) and phosphoric acid fuel cell (PAFC) technologies.

garnered considerable interest in Western Europe and North America. It is possible to blend in small shares of hydrogen by making only minor changes to natural gas infrastructure and end-user appliances, if changes are needed at all. The maximum allowable blending share varies by type of end use and grid status, with 20% (vol) being the upper limit currently under experimentation (IEA, 2019a).

As China's natural gas pipeline network is completely integrated, the country could store large amounts of energy in the form of hydrogen by blending it into the gas grid, although the environmental benefits are likely to be limited. In the longer term, this option could evolve into 100% hydrogen-firing in dedicated boilers, provided that the necessary hydrogen infrastructure is installed and hydrogen boilers are competitive (they are currently at TRL 9).

The second route is small-scale power and heat co-generation at the building level, which Japan has been pursuing. The country has deployed over 350 000 household fuel cell combined heat and power systems (called ENE-FARM) (albeit currently running on natural gas), and installation subsidies are no longer required. In both outlooks, hydrogen consumption in buildings could reach 5 to 6 Mt in 2060 (IEA, 2021a; CHA, 2020a).

Chapter 3. Production routes for low-emission hydrogen

HIGHLIGHTS

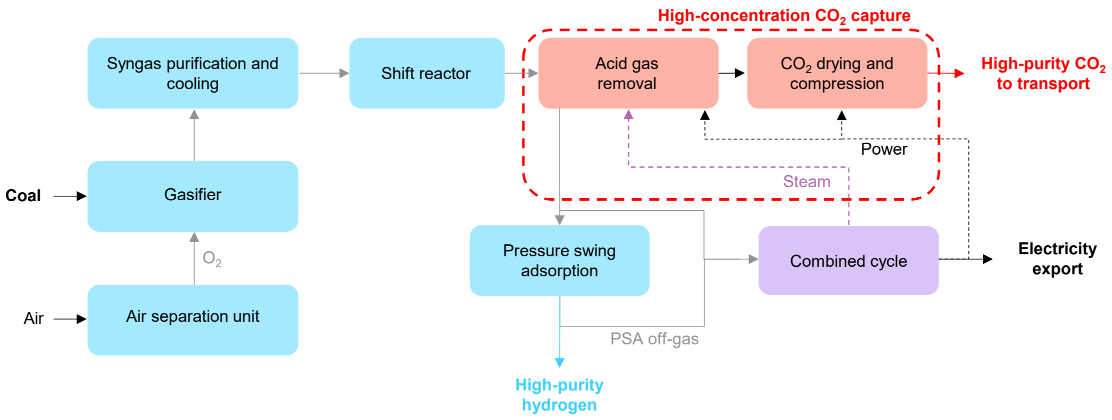
- Dedicated hydrogen production in China is currently dominated by coal, which fuels close to two-thirds of production.
- In the medium term, coal gasification with CCUS remains cost-effective (~USD 1.4 to 3.1/kg H_2) to produce low-emission hydrogen in regions with inexpensive coal and CO_2 storage resources, as well as lower renewable energy source availability. Cost reductions for CCUS-based production routes could be achieved with economy-of-scale benefits and technological learning, but they are likely to be more limited than for electrolysis.
- Electrolysis using low-emission electricity to produce hydrogen needs to be deployed on a larger scale to reduce costs to a level that would make it competitive with CCUS-equipped coal-fired facilities. The cost of electrolytic hydrogen could fall to around USD 1.5/kg H_2 in regions with ample wind and solar resources.
- Tracking both direct and indirect emissions is critical to ensure that all routes produce hydrogen that meets China's clean hydrogen standards. With fossil-CCUS production, the CO_2 capture rate and fuel supply source are key determinants of lifecycle emissions. For biomass-CCUS production, biomass sustainability is essential to maximise the potential for negative emissions while minimising environmental impacts.

Hydrogen with CCUS

Hydrogen from coal

Producing hydrogen through coal gasification is a mature and well-established technology in China, used for many decades by the chemical and fertiliser industries to produce ammonia and methanol. The gasification process involves converting coal into synthesis gas, a mixture consisting primarily of carbon monoxide and hydrogen. This synthesis gas can be further converted (together with extra CO_2) into methanol, or it can be used to produce more hydrogen and CO_2 in the water-gas shift reactor. In the latter case, the H_2-CO_2 gas mix will have to be separated (using an acid gas removal unit) to create a pure hydrogen stream (after pressure swing adsorption), either for direct use or to produce ammonia. The CO_2 is then recovered from the acid gas removal unit.

Hydrogen production through coal gasification with CO_2 capture



Notes: Integrating a combined-cycle unit enables the generation of steam and electricity for internal use and grid export. The energy required for CO_2 capture (steam for chemical absorption and electricity for compression) is partly recovered from the process, decreasing the amount of electricity that can be exported to the grid.

Of the roughly 130 coal gasification plants in operation globally, more than 80% are in China. CHN Energy, China's largest power company, is also the world's foremost hydrogen producer, with 80 coal gasifiers producing around 8 Mt of hydrogen per year (IEA, 2019a).

Coal gasifiers produce high-CO_2-concentration (~80%, from the acid gas removal unit) high-pressure gas streams.[9] This means that CO_2 can be captured relatively easily after impurities (e.g. sulphur, nitrogen) have been removed, with overall CO_2 capture rates reaching 90-95%. Integrating a combined-cycle unit enables the generation of steam and electricity for internal use as well as grid export. The energy required for CO2 capture (steam for chemical absorption and electricity for compression) is partly recovered from the process, reducing the amount of electricity available for export to the grid.

The cost of transporting CO_2 depends on transport distance and mode (barge, ship, truck or pipeline). In China, CO_2 pipeline costs are estimated at USD 0.01 to 0.12/t CO_2 per km (CNY 0.05 to 0.75/t CO_2 per km) for a 100-km pipeline with CO_2 transport capacity of 1-35 Mt per year (Wei et al., 2016). CO_2 storage costs can also vary significantly, depending on storage type. In China, CO2 storage and monitoring costs are estimated at around USD 8/t CO_2 (CNY 50/t CO_2) for depleted oil and gas fields, around USD 9/t CO_2 (CNY 60/t CO_2) for onshore saline

[9] Concentration is expressed as percent (%) per volume throughout this report.

aquifers, and around USD 50/t CO_2 (CNY 300/t CO_2) for offshore saline aquifers (ACCA21, 2019).

However, revenues generated from using captured CO_2 for CO_2-EOR can offset part of CO_2 capture and transport costs. During this process, a large portion of CO_2 can be permanently trapped underground, provided that CO_2 injection and storage are carefully monitored. Nevertheless, the economic viability of EOR depends strongly on CO_2 costs and oil prices. Appendix B presents a case study exploring the techno-economics of retrofitting a coal gasification plant with CCUS in the Ningdong region, with and without CO_2 use for EOR. Results show that the cost of hydrogen from coal gasification rises 40% when CCUS is applied, but the cost increase can be limited to 20-30% when 40% of the captured CO_2 is used for EOR.

Hydrogen from natural gas

Globally, natural gas is the primary fuel source for hydrogen production, but it is the third source after coal and industrial by-products in China. Natural gas is used relatively less than coal in China because its availability is limited and its commodity price is high. The main consumers of hydrogen produced from natural gas are the ammonia, methanol and oil refining industries.

Steam methane reforming (SMR) is the most widespread method for producing hydrogen from natural gas. It consists of two sequential processes: reforming natural gas with steam to produce a synthesis gas made up of carbon monoxide and hydrogen, followed by a water-gas shift reaction (with more steam) to produce hydrogen and CO_2 if pure hydrogen is the main product. Typically, 30-40% of the natural gas is combusted to fuel the process, giving rise to a “diluted” CO_2 stream, while the rest of it is split into hydrogen and a more highly concentrated CO_2 stream. Autothermal reforming (ATR) is an alternative technique in which the required heat is produced in the reformer itself, meaning that all the CO_2 is in the shifted syngas. Other technologies include gas-heated reformers and partial oxidation of natural gas.

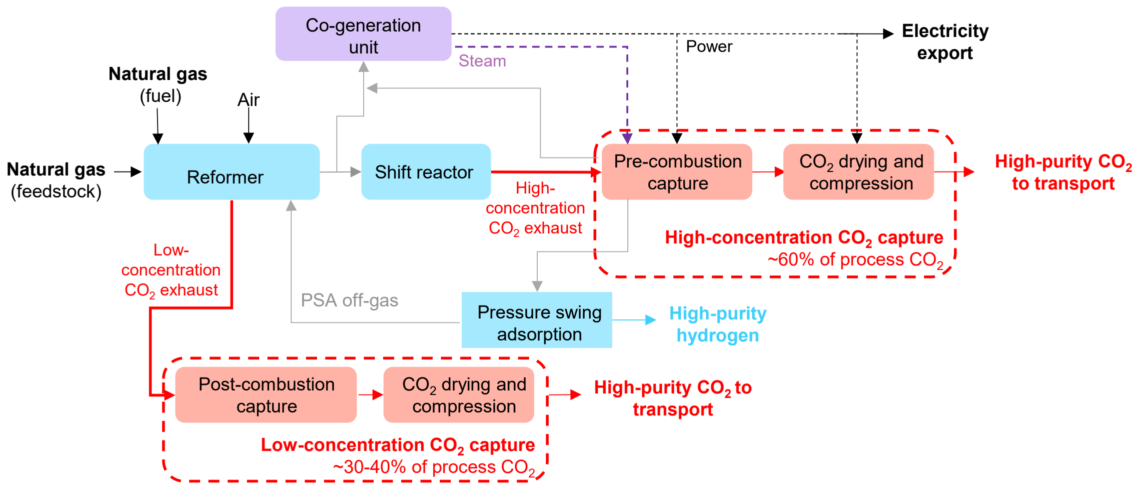
Gas reforming in China is responsible for around 45 Mt of direct CO_2 emissions per year, so applying CCUS could achieve deep emissions reductions.[10] CO_2 capture at an SMR plant can take several forms. Roughly 60% of the system’s CO_2 can be recovered from the high-CO_2-concentration shifted syngas using a pre-combustion capture system. CO_2 can also be captured from the more diluted furnace flue gas, with post-combustion capture rates of 90-95%. This can boost the level of overall emissions reductions to 90% or more, but it also raises costs and the energy penalty.

[10] Assuming an average emissions factor of 10 kg CO_2/kg H_2.

Meanwhile, integrating a co-generation unit would produce steam and electricity for internal use as well as for grid export. The energy required for CO_2 capture (steam for solvent regeneration and electricity for compression) is typically

recovered from the process, reducing the amount of electricity available for export to the grid and slightly increasing natural gas use. In ATR, most of the CO_2 can be recovered from the syngas.

Hydrogen production through steam methane reforming with CO_2 capture



Notes: Integrating a co-generation unit enables the generation of steam and electricity for internal use and grid export. Roughly 60% of the system's CO_2 can be recovered from the high-CO_2-concentration shifted syngas using a pre-combustion capture system, while the rest can be captured from the reformer's low-CO_2-concentration furnace boiler exhaust with a post-combustion capture system. The energy required for CO_2 capture (steam for solvent regeneration and electricity for compression) is recovered from the process, reducing the amount of electricity available for export to the grid and slightly increasing natural gas use. In ATR, the process is driven by heat generated in the reformer, which means most of the CO_2 can be recovered from the syngas.

Other low-emission routes

Hydrogen from water and electricity

Water electrolysis is an electrochemical process that splits water into hydrogen and oxygen. Only a few kilotonnes of China's total annual hydrogen production comes from water electrolysis today, and the hydrogen produced by this means is used mostly in markets in which high-purity hydrogen is necessary (e.g. electronics) (CHA, 2020a). In addition to the dedicated production of hydrogen through water electrolysis, a small amount is also created as a by-product of chlor-alkali electrolysis in chlorine and caustic soda production.

Three main electrolyser technologies exist today: alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs). Alkaline electrolysis is a commercial technology with relatively high efficiency (63-70%) that is widely used for hydrogen production in the float glass, electronics and food industries.[11] PEM electrolysers are less widely deployed. While they have the advantage of being relatively small and producing compressed hydrogen, which is useful for storage, they require expensive catalysts and membrane materials, have lower efficiency (56-60%) and their lifetime is currently half that of an alkaline electrolyser (IEA, 2019a).

SOECs, which use ceramics as the electrolyte and have low material costs, are the least-developed electrolysis technology. They operate at high temperatures and at high electrical efficiency (74-81%), but they use water in the form of steam and therefore require a heat and water source in addition to electricity. One key challenge for those developing SOEC electrolysers is the material degradation that results from the high operating temperatures. Further RD&D is expected to improve the performance of all three electrolysis technologies (IEA, 2019a).

With the cost of renewable electricity declining, particularly for solar PV and wind, interest in electrolytic hydrogen is growing in China. An increasing number of projects with significant electrolyser capacities have been commissioned or announced in recent years, especially to support the sustainability agenda of the Beijing Winter Olympics in 2022. An example is the Guyuan 20-MW wind-to-hydrogen project in Zhangjiakou.

Several factors determine the cost of producing hydrogen through water electrolysis, the most important being electricity costs, conversion efficiency, capital requirements and annual operating hours. Electricity is the most influential factor, accounting for 50-90% of total hydrogen production costs (IEA, 2019a). A tenfold increase in the electricity price translates into roughly a sixfold rise in hydrogen production costs.

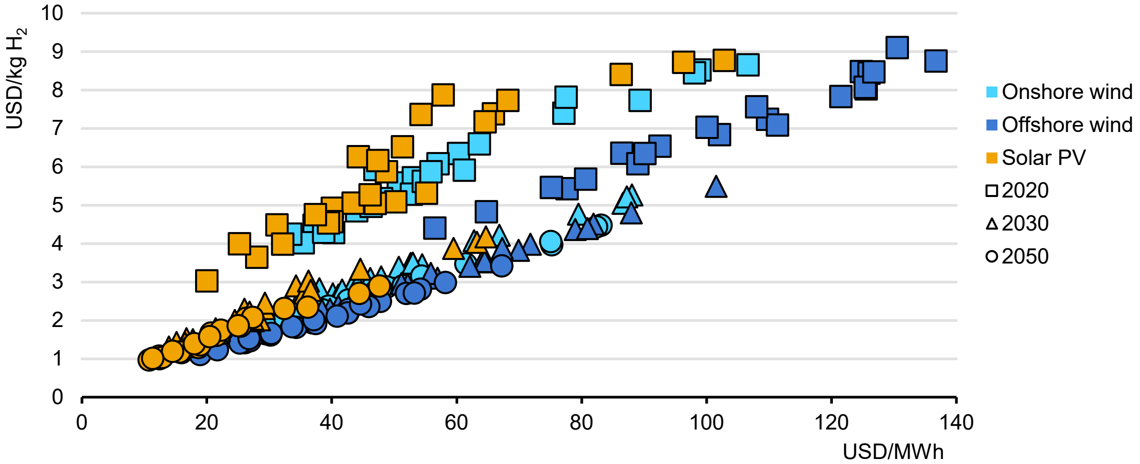
Electricity costs and operating hours depend critically on the location and source of the electricity, while capital requirements and conversion efficiencies vary considerably by electrolyser technology. As electrolyser operating hours increase, the impact of capital costs on the levelised cost of hydrogen (LCOH) declines. Access to low-cost electricity in amounts sufficient to ensure relatively high full-load hours of electrolyser operation is therefore essential to produce low-cost hydrogen.

Electrolyser systems can be operated in several ways, with each affecting the number of annual operating hours, the cost of electricity and the carbon footprint. Electrolytic hydrogen is only as low-emission as the electricity used to power the electrolyser. Thus, the high carbon intensity of Chinese power generation makes it prohibitive to produce low-emission hydrogen from grid electricity-powered electrolysers. In a future decarbonised electricity system with high shares of variable renewables, surplus electricity may be available at low cost. Today,

[11] Efficiency is evaluated on a lower heating value (LHV) basis.

however, low-cost electricity is generally available for only very few hours per year, which implies low electrolyser usage and thus high capital-cost impacts on total hydrogen production costs.

Impact of electricity price on global hydrogen production cost, 2020, 2030 and 2050



Source: IEA (2021b), *Global Hydrogen Review 2021.*

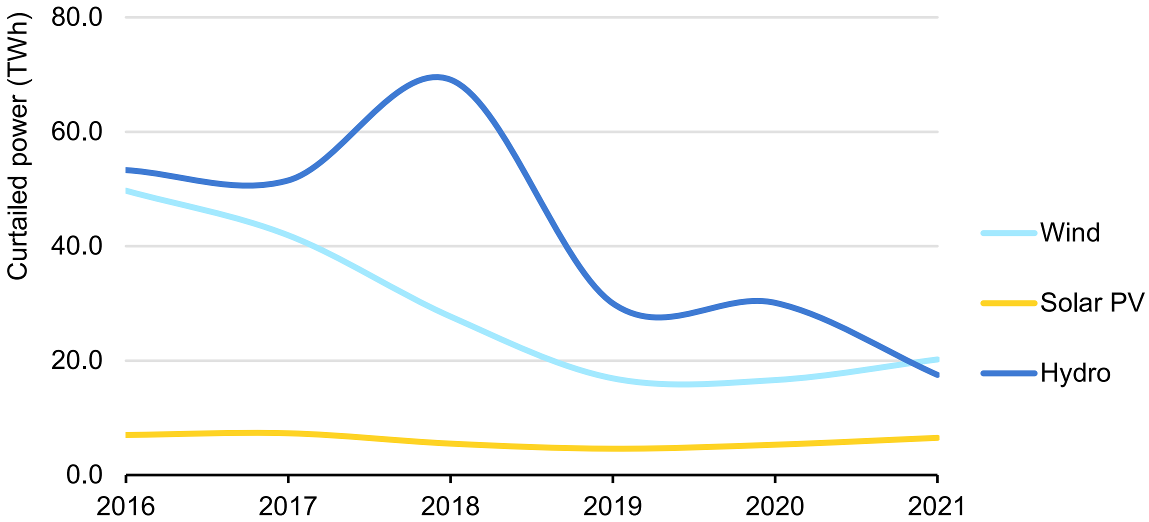
Alternatively, operators could run electrolysers at full load but would have to pay high electricity prices during peak hours. The optimum operating regime involves trade-offs between capital expenditures and electricity prices, which in most cases amounts to the equivalent of 3 000-6 000 full-load hours (IEA, 2019a).

Nevertheless, the potential to use surplus renewable electricity is high in some regions of China, with the country's renewable power capacity reaching 1 063 GW in 2021, accounting for nearly 45% of the power system's total capacity. This capacity generated 2 480 TWh in 2021, which was nearly 30% of the country's electricity generation, effectively making China the global leader in renewable electricity generation (NEA, 2022).

But renewable energy resources are not evenly distributed across China: onshore wind resources are mainly concentrated in the north, solar energy in the north and east, and hydropower in the centre (Sichuan province) and south (Yunnan province). Distributing large quantities of renewable power across China is challenging because of the power grid's limited transmission capacity. In several regions, power companies are regularly forced to curtail renewable power generation during periods of low local demand, as they cannot transmit surplus electricity to other parts of the country. Indeed, curtailment of hydro, wind and solar power generation combined reached a high of 110 TWh in 2016.

While curtailment has decreased in recent years, it was still 44 TWh in 2021. Declining curtailment has resulted from power system reform and market-oriented trading, as well as improved power grid mobilisation capabilities. Theoretically, 0.8 to 2.1 Mt of hydrogen could have been produced from the amount of renewable electricity generation curtailed during 2016-2021 (44 to110 TWh/yr).[12] If no other (local) sources of demand arise in upcoming years, the price of this electricity could be low or even zero. Assuming zero-level electricity prices, hydrogen production costs could still be around USD 6.4 to 7.1/kg H_2 due to the low utilisation factor of electrolysis equipment.[13]

Curtailment of wind, solar and hydropower in China, 2016-2021



Note: Total renewable power generation in 2021 was 2 480 TWh.
Sources: NEA (2017), Grid-connected operation of wind power in 2016; China Energy News (2017), Nearly 110 TWh of electricity was abandoned in 2016; NEA (2018a*), Grid-connected operation of wind power in 2017*; NEA (2018b), In 2018, we will continue to reduce the abandonment of wind power, photovoltaic and hydropower; NEA (2019), *Grid-connected operation of renewable energy in 2018*; NEA (2020), *Grid-connected operation of renewable energy in 2019;* NEA (2021), Transcript of the online press conference of the National Energy Administration in the first quarter of 2021; NEA (2022), *Grid-connected operation of renewable energy in 2021.*

Another option is to use dedicated off-grid renewable energy sources to supply electricity for electrolysers. Electrolytic hydrogen could also be produced from dedicated nuclear energy, which would ensure an electricity supply for electrolysers that is both firm and decarbonised. In fact, the China National Nuclear Corporation has already launched some demonstration projects (Energy Iceberg, 2020), and demonstration projects are also ongoing in Japan and Canada.

Recovery of by-product hydrogen

Around one-fifth of China's hydrogen supply, or 7.1 Mt/yr, is by-product hydrogen from facilities and processes designed primarily to produce something other than

[12] Based on a specific electricity requirement of around 51 kWh/kg H_2.
[13] Based on a utilisation factor of 10% for curtailed electricity.

hydrogen. The main sources of by-product hydrogen are refining, iron and steel manufacturing, and chemical production. Around half of the by-product hydrogen is used as fuel for heat generation, while the other half is recovered and distributed for use elsewhere. This exported by-product hydrogen often needs dehydrating or other types of cleaning before it can be used in a variety of hydrogen-using processes and facilities. A small share of by-product hydrogen is vented to the air.

In oil refining, by-product hydrogen comes largely from catalytic naphtha reforming, a process that produces blending components for high-octane gasoline and generates hydrogen at the same time. Refineries with integrated petrochemical operations also derive by-product hydrogen from steam cracking. All this by-product hydrogen is consumed onsite for desulphurisation and hydrocracking of oil fractions (see Hydrogen in Oil Refining) and cannot be diverted to alternative uses.

Meanwhile, the iron and steel sector produces a large quantity of hydrogen mixed with other gases as a by-product. These off-gases include coke oven gas, blast furnace gas and basic oxygen furnace gas, all generated from coal and other fossil fuels. Coke oven gas is made up of hydrogen (55-60%), methane (23-27%), carbon monoxide (5-8%) and a small amount of CO_2 (1.5-3%). A share of these off-gases can be used onsite for ancillary processes such as heating furnaces in rolling mills, while the remainder is used for on- or offsite steam generation.

Today, coke oven gas, owing to its high hydrogen content, is already used as a feedstock to produce methanol in China. Hydrogen in coke oven gas can be recovered using pressure swing adsorption. Based on a domestic coke output of 471 Mt in 2019 (National Bureau of Statistics, 2019), over 7 Mt/yr of by-product hydrogen from coke oven gas could be technically recovered. This hydrogen is currently used as a feedstock in steelmaking and methanol production, as well as for district heating. (Implicit in this is supplementation of the diverted coke oven gas currently used within the sector with low-emissions fuels.)

The chemical industry is the other major potential source of by-product hydrogen. In this sector, steam cracking and propane dehydrogenation to produce high-value chemicals (HVCs) – the precursors of most plastics – generate considerable by-product hydrogen, as does chlor-alkali electrolysis in chlorine and caustic soda production. Importantly, this is the only source of pure by-product hydrogen, as other processes produce hydrogen in a mixture of gases. In fact, chlor-alkali electrolysis in chlorine and caustic soda manufacturing generates by-product hydrogen of high purity.

China's caustic soda output is relatively stable at 30 to 35 Mt/yr, and by-product hydrogen is 750 to 875 kt/yr. Some 60% of this hydrogen is used to produce other chemicals, with the remaining 280 to 340 kt/yr available for other purposes. While HVC manufacturing via steam cracking and propane dehydrogenation could produce roughly 460 kt/yr of by-product hydrogen, other processes such as styrene production generate smaller volumes of by-product hydrogen.[14]

China's by-product gas is mostly distributed in developed coastal areas, mainly in the Yangtze River Delta, Bohai Rim and Pearl River Delta regions. These regions also have high-tech industries, including fuel cell manufacturing, which could be an important source of demand for hydrogen.

Harnessing by-product hydrogen could allow China to expand its market for pure hydrogen at low cost. Compared with dedicated hydrogen production, recovering by-product hydrogen demands little investment and low fossil fuel input, and most hydrogen-rich off-gases require just some dehydration or other types of cleaning. Thus, tapping into this potential could not only improve resource efficiency, but reduce GHG emissions. Although hydrogen-rich gases are not likely to present growth opportunities for low-emission hydrogen production in the future, exploiting them could launch the hydrogen market.

Approximately 100 kt of by-product hydrogen could be available for FCEVs per year. Based on hydrogen consumption of 3 to 4 kg per 100 km and a daily running mileage of 200 km for fuel cell trucks, and 1 to 1.3 kg H_2 per 100 km and 100 km daily mileage for fuel cell passenger vehicles, available by-product hydrogen could fuel around 35 000-45 000 fuel cell trucks or around 210 000-270 000 fuel cell passenger vehicles.

Hydrogen from biomass

The complexity of processing biomass means that it is generally a more expensive way to produce low-emission hydrogen than solar- or wind-based electrolysis. The potential for large-scale biomass-based hydrogen production will also be limited by the availability of sustainable, low-cost biomass. Competition to obtain sustainable biomass for use in other hard-to-decarbonise sectors (such as aviation, for which biokerosene constitutes one of few low-emission options) could also arise. Combining hydrogen production from biomass with CCUS could, however, be a possible means of carbon removal, which may be important for China to achieve its carbon neutrality target.

The carbon intensity of hydrogen produced from biomass may vary considerably, depending on the type of feedstock used, transport needs, conversion processes and CCUS application.

Hydrogen can be produced from various biomass sources, through several production routes. In biochemical methods, microorganisms break down organic material to produce biogas (a process referred to as anaerobic digestion) or a

[14] Based on total propane dehydrogenation (PDH) unit capacity of 7.76 Mt/yr in 2020, an average operating rate of 80%, and hydrogen yield of 38 kg H_2/tonne of PDH. By-product hydrogen of the ethane steam cracking industry is estimated at 220 kt H_2/yr.

combination of acids, alcohols and gases (fermentation). Thermochemical routes include gasification, pyrolysis, and hydrothermal treatment. Gasification of biomass is the most advanced of the three (TRL 5) and works much like coal gasification to convert biomass into a mixture of carbon monoxide, CO_2, hydrogen and methane.

Anaerobic digestion is a fully commercialised technology (TRL 9-10) and is therefore the most mature biochemical production route, but it can be used only to process sewage sludge; agricultural, food processing and household waste; and some energy crops. Enzymatic fermentation can process the non-edible cellulosic part of some plants, but it is still at the prototype stage (TRL 5). The main benefit of biological conversion is its low energy consumption.

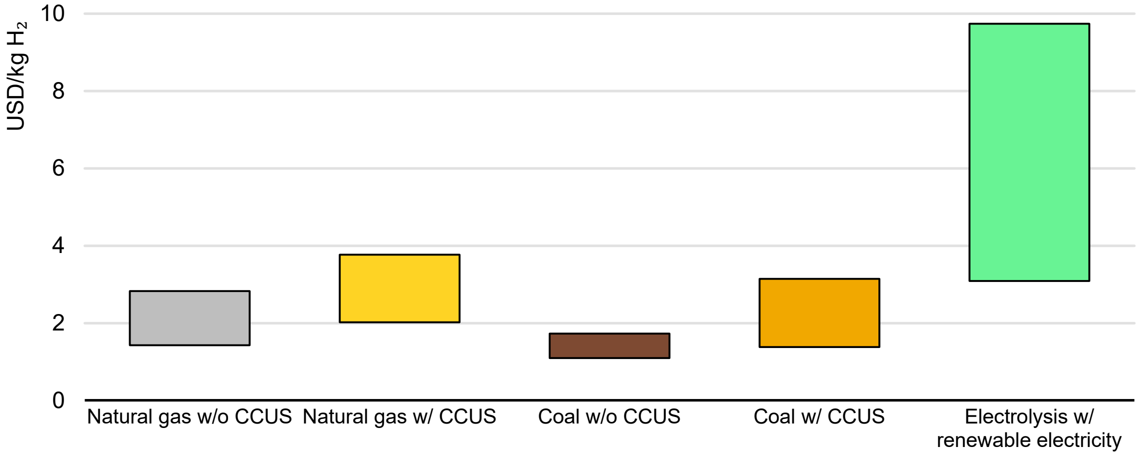
Gasification can potentially convert all organic matter into gases, including the lignin component of biomass, which is the most difficult compound to extract. Although small-scale biomass gasification (<200 kWe) to generate power and heat has already been commercially developed and deployed, large-scale biomass gasification is not yet mature. Although no bio-FT plants are yet operational in China, several biomass gasification ventures are in the project pipeline, though none will produce hydrogen. One in Heilongjiang province, a 40-MW co-generation plant, uses waste and residues, while in Jilin province a 20-MW biomass gasifier is being co-fired with coal at a 660-MW pulverised-coal-fired power plant.

Comparisons of hydrogen production routes

Costs

Coal gasification is currently the most cost-effective hydrogen production method in China, mainly owing to the availability of low-cost coal and China's extensive experience in gasification. The cost of producing hydrogen through coal gasification in China is estimated at USD 1.1 to 1.7/kg H_2 (CNY 7 to 11/kg H_2) (IEA, 2021a; Wang et al., 2021; Li et al., 2021; Fan et al., 2022). Depending on coal prices, fuel can make up around half of total production costs, followed by operational costs and capital expenditures. Adding CCUS could increase hydrogen generation costs to USD 1.4 to 3.1/kg H_2 (CNY 9 to 20 /kg H_2), assuming dedicated storage in a saline aquifer. Although there is potential for cost reductions, it may be more limited than for electrolysis.

Hydrogen production cost ranges for different technology options in China, 2020



Notes: Assumptions for techno-economic parameters available from IEA, 2021a. Fuel price assumptions: natural gas USD 24 to 48/MWh (CNY 152 to 312/MWh); coal USD 9 to14/MWh (CNY 59 to 91/MWh); electricity USD 25 to 86/MWh (CNY 161 to 550/MWh). CO_2 price assumption for 2020: USD 0 to 11/t CO_2 (CNY 0 to 72/t CO_2). Efficiency assumptions: 73-76% for SMR; 66-69% for SMR + CCUS; 60-64% for coal; 56-58% for coal + CCUS; 51-65% for electrolysis. CO_2 transport and storage cost: USD 18 to 26/t CO_2 (CNY 119 to170/t CO_2).
Sources: IEA (2021a*), An Energy Sector Roadmap to Carbon Neutrality in China*; Fan et al. (2022), A levelised cost of hydrogen (LCOH) comparison of coal-to-hydrogen with CCS and water electrolysis powered by renewable energy in China; Wang et al. (2021), Cost analysis of different hydrogen production methods in China; Li et al. (2021), Study on cost and carbon footprint of hydrogen production from coal in China.

In hydrogen production from natural gas, gas costs have the largest impact on production costs, accounting for over 70% of the total, with capital expenditures coming next. The price of natural gas in China is considerably higher than in the Middle East, North America or the Russian Federation, where hydrogen production costs are consequently lower. The cost of producing hydrogen from natural gas in China is thus estimated at USD 1.4 to 2.8/kg H_2 (CNY 9 to 18/kg H_2) without CCUS, and USD 2 to 3.8 (CNY 13 to 24/kg H_2) with CCUS (IEA, 2021a; Wang, 2021).

Producing hydrogen from electricity is currently more expensive than from coal or gas with CCUS in most regions. In China, the cost of hydrogen production from renewable electricity is estimated at USD 3.1 to 9.7/kg H_2 (CNY 20 to 62/kg H_2) depending on the electricity source (IEA, 2021a; Fan et al., 2022; Wang et al., 2021). However, with solar PV- and wind-based generation becoming less costly, renewable electricity-powered electrolysers could become increasingly competitive in the future. Although hydrogen could conceivably be produced for USD 1.3 to 1.5/kg H_2 (CNY 8.4 to 9.7/kg H_2) in areas with favourable solar and wind resources (IEA, 2021a), renewable energy resources must be consistently available to ensure that electrolyser load factors remain high enough to amortise the capital costs.

The cost of industrial by-product hydrogen depends mainly on the price or economic value of the hydrogen-rich off-gas. Hydrogen recovery from coke oven gas costs around USD 2.2 to 3.8/kg H_2 (CNY 14 to 24/kg H_2), assuming a coke oven gas price of USD 3.5 to 6.6/GJ (CNY 21 to 42/GJ)[15] (Wang et al., 2021).

Greenhouse gas emissions

The lifecycle GHG emissions of different hydrogen production technologies vary widely. Direct process CO_2 emissions from hydrogen production from natural gas without CCUS (8.9 to 9.8 kg CO_2/kg H_2) are currently estimated to be around half those of coal without CCUS (17.8 to 21.6 kg CO_2/kg H_2) (IEA, 2019b; Wang et al., 2021; Li et al., 2021; Zhang et al., 2021b). However, applying CCUS can reduce process CO_2 emissions to an estimated 1.0 to 2.2 kg CO_2/kg H_2 for coal with 90-95% capture, 4.3 to 5.4 kg CO_2/kg H_2 for natural gas with partial CO_2 capture (56%) and 0.5 to 0.6 kg CO_2/kg H_2 for natural gas with full CO_2 capture (95%). High capture rates (>90%) and low upstream emissions will be essential to minimise residual emissions from fossil fuel-CCUS hydrogen production routes.

Depending on how fuels and materials are sourced, indirect GHG emissions (not only of CO_2 but also of methane and nitrous oxide) can significantly increase the hydrogen-GHG balance. For coal, lifecycle emissions depend mainly on the mining process used (opencast or shallow), transport distance and upstream methane emissions. Upstream GHG emissions of coal supply in China could contribute an additional 1.8 to 3.4 kg CO_2-eq/kg H_2 (IEA, 2019b; Zhang et al., 2021b; Li et al., 2021). While this increases the carbon balance of hydrogen from unabated coal only marginally, it more than doubles that of hydrogen from coal with capture.

Upstream natural gas GHG emissions vary significantly from one region to another, depending on methane leakage and value chain configuration. In China, accounting for upstream GHG emissions associated with natural gas supply can increase the carbon footprint of hydrogen from natural gas by 2.0 to 2.2 kg CO_2/kg H_2.

By Chinese standards, hydrogen production qualifies as “clean” if total direct and indirect GHG emissions are below 4.9 kg CO_2-eq/kg H_2. Emissions deriving from the electricity or fuel supply (from both extraction and transport), and from the hydrogen production process, form the system boundaries (CHA, 2020c). While hydrogen produced from both coal or gas with CCUS could meet China’s clean hydrogen standard, lower thresholds could be implemented over time to support carbon neutrality goals and/or comply with international export market requirements, which are also likely to become more stringent.

[15] Based on a calorific value of 20 MJ/Nm^3 for coke oven gas.

Reducing upstream emissions and ensuring that carbon capture is applied to all process streams at a high capture rate will be critical to meet tighter standards and minimise methane emissions from gas-CCUS production. Biomass sourcing can also be associated with high lifecycle emissions, with biomass upstream emissions varying considerably depending on feedstock type, origin and transport distance.

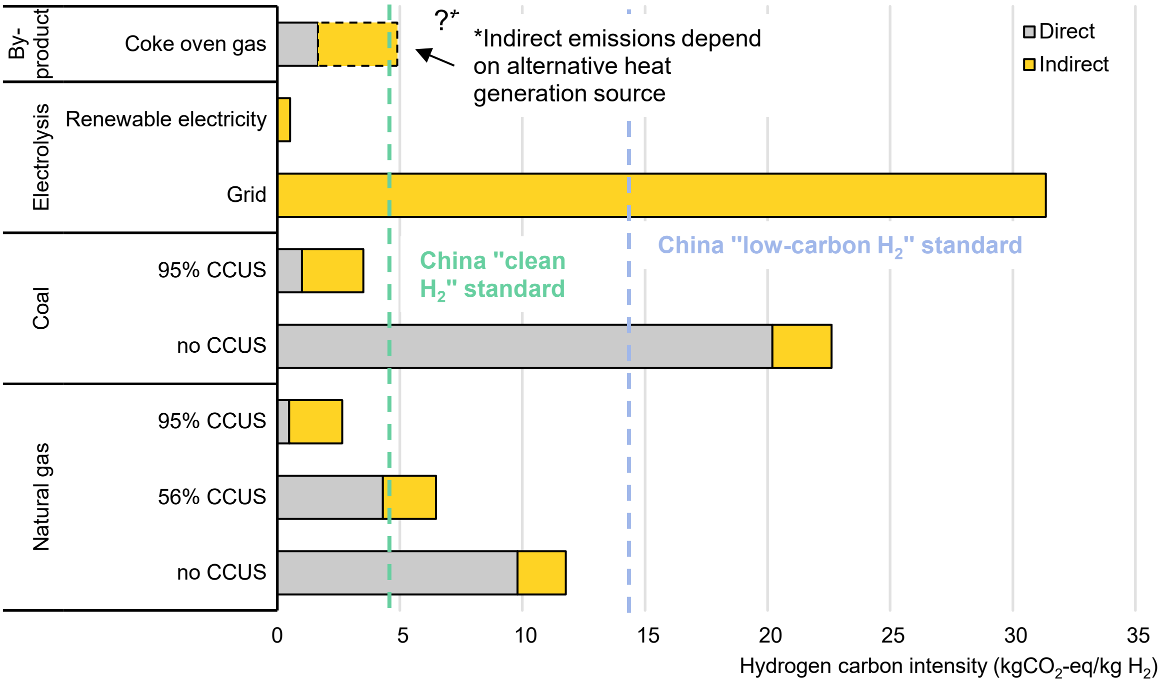
The GHG emissions intensity (CO_2 only) of electrolysis depends on the GHG intensity of the electricity input. Using renewable electricity can result in 0.3 to 0.8 kg CO_2/kg H_2 if emissions associated with manufacturing and building the production assets are included (Wang et al., 2021). Hydrogen produced from renewable electricity can therefore be considered close to zero-emission, as these emissions are typically not considered within the boundaries of the lifecycle assessment of fossil-based routes.

Using grid electricity in China can yield around 29 to 31 kg CO_2/kg H_2 – well over the emissions of coal-based hydrogen production without CCUS (Wang et al., 2021). This is because close to 70% of China's electricity currently comes from coal-fired power plants, and conversion losses during electricity generation mean that using coal-based electricity would be more CO_2-intense than using natural gas or coal directly for hydrogen production.

Achieving close to zero lifecycle emissions will therefore require further decarbonisation of the power supply mix or the use of dedicated renewables. Switching to electrolysis would offer benefits beyond CO_2 emissions reductions, as renewables-based electrolysis consumes four to nine times less water than coal gasification. Growing concern about water stress in China thus reinforces the importance of electrolysis-based hydrogen production in the long term.

Meanwhile, recovering by-product hydrogen from coke oven gas can generate up to 2.0 kg CO_2/kg H_2 during the hydrogen purification process, assuming grid electricity is used for hydrogen purification. Diverting these hydrogen streams for alternative uses also means that high-grade process heat requirements must be met with another energy source. These sources would have to be low-emission to ensure that diverting by-product hydrogen to other uses results in avoided carbon emissions relative to using by-product hydrogen directly. Having a holistic view of the energy system is thus essential to decide whether to use by-product hydrogen for onsite industrial heat generation or for other applications instead, and industry type and the availability of other low-emission heat generation alternatives will have to be considered.

GHG emissions intensity of hydrogen production routes in China, year



*Indirect emissions depend on alternative heat generation source.
Notes: Coal indirect emissions total 12.1 kg CO_2-eq/GJ and cover mining, transport and methane emissions in China for 2018. Natural gas indirect emissions cover the world average natural gas supply non-methane emissions (6.2 kg CO_2-eq/GJ) and upstream and downstream methane emissions associated with natural gas supply in China (6.2 kg CO_2-eq/GJ). Grid electricity carbon intensity is 610 g CO_2/kWh. Lifecycle emissions do not include coal and gas plant construction. Renewable lifecycle emissions include construction.
Sources: IEA (2019a), *The Future of Hydrogen*; IEA (2019b), *World Energy Outlook 2019*; IEA (2021d), Methane Tracker 2021; IEA (2021a), *An Energy Sector Roadmap to Carbon Neutrality in China.*

Chapter 4. Fostering hydrogen-CCUS synergies

HIGHLIGHTS

- Utilising low-emission hydrogen and CCUS will be important for China to become carbon-neutral by 2060. Together, hydrogen and CCUS account for around 13% of the cumulative emissions reductions achieved in China to 2060 in the Announced Pledges Scenario (APS).

- Significant synergies exist between hydrogen and CCUS, with potential for their deployment to be mutually beneficial and reinforcing. Being one of the least-cost opportunities for CO_2 capture, applying CCUS to hydrogen production can support early CCUS scale-up. Similarly, CCUS-equipped hydrogen production is likely to be a cost-effective way for China to acquire low-emission hydrogen in the near term.

- Co-locating hydrogen production and CCUS in industrial clusters could help achieve economies of scale and reduce the cost of infrastructure needed to transport and store hydrogen and CO_2. The availability of this infrastructure could in turn unlock new investment opportunities and provide a focal point for the scale-up of low-emission hydrogen production. Much of China's existing hydrogen supply and demand come from industrial hubs, with close to 80% of methanol plants, ammonia plants and refineries within 100 km of CO_2 storage.

- Opportunities to use CO_2 captured from CCUS-equipped hydrogen production could generate an additional revenue stream for these facilities and help close the commercial gap with conventional production. Current and emerging markets for CO_2 use in China include enhanced oil recovery (CO_2-EOR), fuel and chemical production, and building material manufacturing. However, CO_2 use is not always associated with emissions reductions. For CCUS-equipped hydrogen production to be considered low-emission, the CO_2 will typically need to be permanently stored.

- Producing hydrogen from biomass with CCUS can generate negative emissions, serving to counterbalance emissions in other parts of the energy system that are technically difficult or prohibitively expensive to abate directly. Biogenic CO_2 can also be used as a carbon-neutral feedstock for synthetic fuel fabrication. Today, biomass-based production routes for hydrogen are at an early stage of development, with innovation and early demonstration needed to understand their costs and potential in China. Careful consideration must also be given to constraints on sustainable biomass availability and potential competition for biomass use.

Potential synergies between hydrogen and CCUS

Producing hydrogen from fossil fuels with CCUS could be pivotal to establish China's hydrogen economy. It is a cost-effective (or sometimes the sole) technology option to decarbonise existing hydrogen production assets in the refining and industry sectors. In the short to medium term, it will also likely be the most competitive option for new low-emission hydrogen production capacity in areas with low-cost coal and CO_2 storage capacity. In other regions with ample solar and wind resources, electrolytic hydrogen may be the more cost-effective pathway in the future. Therefore, strategies that support the scale-up of both electrolytic-based and fossil-based hydrogen production combined with CCUS should underpin China's strategy to exploit hydrogen opportunities.

The several synergies that exist between hydrogen and CCUS can be fostered to mutually reinforce one another. For instance, revenue streams from CO_2-EOR and other commercial end uses can support investment in CO_2 capture at existing and future hydrogen plants. Furthermore, as hydrogen production from coal and natural gas offers low-cost CCUS opportunities, this application could serve as a stepping-stone to CCUS deployment in other sectors. Industrial clusters and ports are ideal places to develop shared transport and storage infrastructure for both CO_2 and hydrogen.

In the longer term, several other synergies can also be exploited. Captured CO_2 can be used to convert hydrogen into synthetic transport fuels for applications in which direct hydrogen use is extremely challenging, such as in aviation. CCUS can also be applied to biomass-based hydrogen production for carbon removal, which will be an important part of the transition to carbon neutrality by 2060. Both applications are currently still at early stages of development.

Co-locating hydrogen and CCUS in industrial clusters

Clusters of industrial activity are ideal places to ramp up low-emission hydrogen production and CCUS application. The principal benefit of developing H_2 and CCUS in industrial clusters is the prospect of creating transport and storage hubs, as low-emission H_2 and CO_2 demand and supply would be located at the same site. Greater efficiency and less duplication of infrastructure could thus achieve economies of scale and reduce unit costs.

Decarbonising China's existing hydrogen capacity within industrial clusters could also offer several advantages and opportunities. It would allow established infrastructure and supply chains to continue operating, maintaining employment and attracting new investment. For example, industrial clusters offer promising locations for the expansion of hydrogen supplies to meet new demand, including for transport. Industrial clusters with shared infrastructure can also support CCUS-equipped hydrogen production from smaller industrial facilities for which dedicated hydrogen and/or CO_2 transport and storage infrastructure may be impractical or uneconomic. The availability of hydrogen and CO_2 infrastructure may also attract new outside industries seeking to decarbonise their activities, thus offering economic growth opportunities for the region.

China is particularly well placed to develop hydrogen clusters and CCUS hubs:

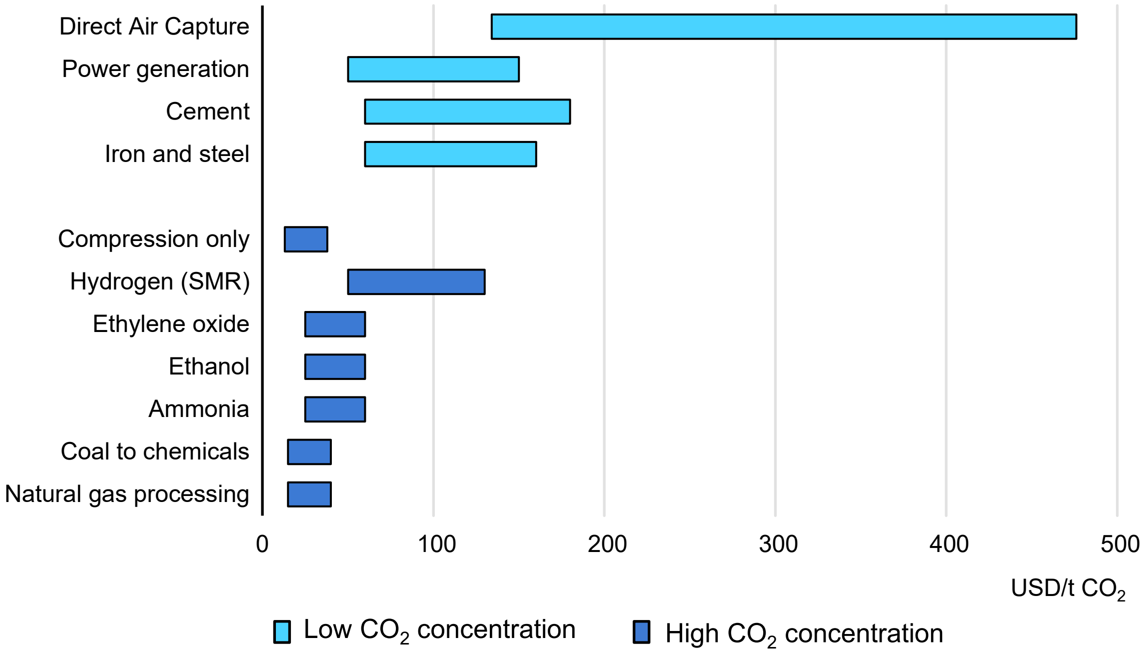
- Existing sources of hydrogen demand in China are already concentrated in industrial clusters, as is nearly all the dedicated hydrogen and pipeline infrastructure. The ammonia industry is located mainly in the Henan, Shandong and Shanxi provinces, while the methanol industry is concentrated in Inner Mongolia, Shandong, Ningxia, Shannxi and Henan. Oil refineries are situated predominantly along China's coast and near some inland oilfields (IEA, 2021a).
- Existing hydrogen demand and supply sources are already near potential CO_2 storage facilities, with an estimated 63% of ammonia plants, methanol plants and refineries within 50 km of potential CO_2 storage sites, and close to 80% within 100 km (IEA, 2021a).
- Many industrial clusters are in regions with CO_2-EOR opportunities, offering a potential revenue stream for captured CO_2. These include the eastern coastal provinces of Shandong and Liaoning, and inland northern provinces such as Heilongjiang, Inner Mongolia, Ningxia, Henan, Jilin, Shaanxi and Xinjiang.
- Industrial clusters along the coast have port facilities that could support international hydrogen trade by ship, the use of hydrogen and synthetic fuels as maritime and inland shipping fuels, and offshore storage of CO_2. China's first offshore CO_2 storage project was announced in August 2021.

Low-cost CO_2 capture opportunities

The cost of CO_2 capture is a function of CO_2 concentration at the point source. Natural gas processing and bioethanol fermentation plants that release highly concentrated CO_2 streams are among the least-cost CCUS applications, at USD 15 to 25/t CO_2 for natural gas processing and USD 25 to 35/t CO_2 for bioethanol fermentation. In coal gasification, the CO_2 stream for pre-combustion capture is also relatively concentrated (over 80% after acid gas removal) compared with post-combustion capture on flue gas (~12-15% for a coal-fired boiler and 4-6% for a gas boiler).

Prioritising lower-cost capture opportunities such as hydrogen production could help funnel investments towards CCUS and support early development of CCUS infrastructure. Indeed, early CCUS project development has been focused primarily on natural gas processing (over 60% of the world's operating capture capacity), bioethanol synthesis (e.g. the ADM plant in Illinois) and hydrogen production (e.g. the Quest project in Canada).

Global levelised cost of CO_2 capture by sector and initial CO_2 concentration, 2019



Note: SMR = steam methane reforming.
Source: IEA (2020c), *CCUS in Clean Energy Transitions.*

Generating revenues from CO_2 use

Demand for CO_2 can be an important driver for investment in CCUS-equipped hydrogen production while supporting widespread deployment of CCUS. China already consumes large amounts of CO_2 in various commercial applications: indeed, it used around 60 Mt of CO_2 in 2015, which equates to around a quarter of global demand (IEA, 2019c). The bulk of the CO_2 China uses is consumed by the fertiliser industry to produce urea, while smaller amounts are used in CO_2-EOR, food and beverage production, water treatment and other applications. In its 2019 CCUS roadmap, the Chinese government expressed its ambition to develop commercial opportunities for CO_2 use, particularly for CO_2-EOR and for novel methods to convert CO_2 into fuels, chemicals and building materials (ACCA21, 2019).

However, CO_2 use does not always lead to emissions reductions. It provides climate benefits when CO_2 usage displaces a product with higher lifecycle emissions (for example chemicals) or when the captured CO_2 is permanently stored through usage (for example in building materials). Quantifying the climate benefits of CO_2 use can be complex, and comprehensive lifecycle assessment is required.

CO_2-EOR

CO_2-EOR is a well-established commercial technology that involves injecting CO_2 into oilfields to enhance production. Estimated annual global consumption of CO_2 is 70 to 80 Mt (in 2017), primarily in North America (IEA, 2019c) From 2010 to 2017, China used more than 1.5 Mt CO_2 for EOR (ACCA21, 2019).

Over 70% of operating CO_2 capture capacity around the world rely on revenue from selling CO_2 for EOR. While recent CCUS project announcements suggest a shift away from EOR towards dedicated geological storage (dedicated storage is envisioned for more than 50% of planned CO_2 capture capacity), EOR is still expected to play a role in CCUS project development in China. For instance, at least three commercial-scale CCUS projects currently being developed in China are planning to use CO_2 for EOR.

CO_2-EOR can also provide a means of storing CO_2 permanently, as over the lifetime of a project a significant proportion of the injected CO_2 is retained in the reservoir. For a CO_2-EOR project to be considered a genuine climate mitigation measure, the CO_2 must come from an anthropogenic source, such as a power station or natural gas processing plant, or the atmosphere. Additionally, further site characterisation, emissions and subsurface monitoring and changes to field closure may be required (IEA, 2015).

China has considerable CO_2-EOR potential. An assessment of 296 onshore oilfields, accounting for about 70% of total mature onshore oilfields in China, showed that onshore CO_2-EOR can recover approximately 7.7 billion barrels of crude oil (1.1 Gt) at a net positive revenue, with the potential to trap 2.2 Gt CO_2 underground in the process (Wei et al., 2015). Most of these opportunities are in China's northwest (Xinjiang), centre (Gansu, Ningxia, Shaanxi) and northeast (Heilongjiang, Jilin). The net cost per tonne of CO_2 used ranges from USD -100/t (CNY 645/t) to higher than USD 0/t, depending on oilfield quality (e.g. oil recovery rate, oil viscosity, residue oil saturation) (Wei et al., 2015).

Thirty-four CO_2-EOR projects of various types have reportedly been conducted in China. The main petroleum basins hosting CO_2-EOR projects are in the northeast (Songliao Basin); the east (Bohai Sea region) and south of Beijing (Bohai Basin); the centre-north (Ordos Basin); off the coast of eastern Shandong province (South Yellow Sea Basin); and in northwestern Xinjiang province (Junggar basin). Most of the CO_2 used for EOR is delivered by truck, but there are also several short pipelines in operation, for instance as part of the CNPC's Jilin CCUS project.

Geological basins in China with EOR activity and CCUS hub potential

Basin	Province(s)	CO_2 sources	Existing EOR activities
Junggar and Turpan-Hami Basins	Xinjiang (northwest China)	Power, chemical, cement, iron and steel production; refining	Dunhua methanol EOR Xinjiang CCUS Hub
Ordos Basin	Shanxi, Shaanxi, Ningxia, Gansu (north China)	Power, chemical, cement, iron and steel production; refining	CNPC Changqing methanol EOR project Yanchang coal-to-chemicals CO_2 capture demonstration
South Yellow Sea Basin	Shandong (offshore)		Sinopec CCUS full-chain demonstration project of Huadong oilfield
Bohai Basin	Beijing, Tianjin, Hebei, Shandong (north China)	Power, chemical, cement, iron and steel production; refining	Sinopec Shengli oilfield coal plant EOR Sinpoec Zhongyang oilfield fertiliser EOR
Songliao Basin	Heilongjiang, Jilin (northeast China)	Power, chemical, cement, iron and steel production; refining	Daqing natural gas processing EOR

New pathways for transforming CO_2 into products

New technologies to use or recycle CO_2 are emerging, potentially boosting demand for CO_2. New CO_2 uses that involve chemical and biological technologies are still at initial development stages, but early opportunities are already being captured. The three main categories of CO_2-based products are fuels, chemicals and building materials.

Most CO_2 applications are not currently competitive with conventional processes, so prospects for these products will largely be determined by policy support that recognises their mitigation potential. However, some applications, such as certain CO_2-based plastics and building materials, can already be competitive and generate revenues.

Fuels

The carbon in CO_2 can be used to convert hydrogen into a fuel that is as easy to handle and use as gaseous or liquid fossil fuels, including methane, methanol, gasoline and aviation fuel. CO_2-based fuels can be important in applications in which the direct use of electricity or hydrogen is extremely challenging, such as in aviation. However, producing these synthetic fuels is highly energy-intensive and their climate mitigation value depends strongly on the origin of the CO_2 and the carbon intensity of the hydrogen. As emissions regulations become more stringent over time, the CO_2 used in the production process must increasingly be sourced from biogenic sources or the air to provide carbon-neutral CO_2 feedstock.

The most technologically mature conversion routes are direct conversion of CO_2 (through hydrogenation) into methanol and methane, and indirect conversion whereby the CO_2 is first transformed into carbon monoxide, followed by synthesis into a CO/H_2 gas mixture (syngas), which is then used to produce a range of other fuels.

Hydrogenation technology is being demonstrated at a 1-kt/yr liquid fuel facility in Lanzhou (Gansu province). Meanwhile, the Hebei-based company Xinao Group has built a 20-t/yr biodiesel pilot plant that will use microalgae to absorb 110 t CO_2/yr from coal-based chemical plants and convert it into bio-oil and then biodiesel (China, MOST, 2010). An estimated 61 to 87 Mt of CO_2 could theoretically be used per year through 2050 for syngas, liquid fuel and methanol production (Huang et al., 2022).

The first demonstration facility producing synthetic liquid fuels from renewable energy and CO_2 in China

In January 2020, the Dalian Institute of Chemical Physics, Chinese Academy of Science, commissioned a facility in Lanzhou (Gansu province) with a capacity of 1 kt/yr to demonstrate the production of liquid fuels from renewable energy. The plant uses dedicated renewable electricity capacity (solar PV) for the electrolysis of water to generate hydrogen, which is then reacted with captured CO_2, to produce methanol. This pathway enables the use of renewables-based electricity to produce fuels and provides electricity grid services by reducing loads during periods of low supply (ramping down) and absorbing surplus electricity during periods of high supply (ramping up). Around 1.4 kt CO_2 per year is captured from a coal-to-ammonia plant and used in the process.

The project combines two innovative technologies developed by the Dalian Institute of Chemical Physics, Chinese Academy of Sciences: 1) large-scale, low-cost water-splitting to produce hydrogen using a new electrocatalyst; and 2) low-cost hydrogenation of CO_2 into methanol using a new, more efficient ZnO-ZrO_2 solid-solution catalyst.

This project uses alkaline water electrolysis technology to produce hydrogen. While alkaline electrolysers have long been used commercially in industry, their industrial applications are small in scale (50 to 200 Nm^3/hr or 1.6 to 6 MW) and have high specific energy consumption of 4.7 to 5.0 kWh/Nm^3 H_2 (~60-65% LHV efficiency). The electrolyser technology used in this demonstration plant has a capacity of 1 000 Nm^3/hr (30 MW) and uses a novel catalyst, reducing energy consumption to 4.0 to 4.2 kWh/Nm^3 H_2 (~72-76% LHV efficiency). This is the world's highest reported conversion efficiency of a large-scale alkaline electrolyser.

Total project investment is around CNY 140 million (USD 22 million), of which some CNY 50 million (USD 8 million) is for the 10-MW solar PV installation, while the electrolyser and CO_2 conversion equipment account for the rest (Liu, Wang and Liu, 2020).

Chemicals

The carbon in CO_2 can also be used as an alternative to fossil fuels to produce plastics and intermediate chemicals such as methanol, olefins and aromatics, which are the main building blocks of the petrochemical industry. Some chemicals will continue to require carbon to provide their structure and basic properties, and hydrogen and energy needs will vary according to production method and chemical.

As with CO_2-based fuels, converting CO_2 into methanol and methane is the most technologically mature pathway. CO_2-based methanol can then be processed into various olefins and aromatics. Other conversion methods are still at earlier stages of development, such as dry reforming of CO_2/methane gas mixtures to produce methanol, and biological conversion of CO_2. China has made considerable progress in developing CO_2 conversion technologies and demonstration projects in recent years (see box below).

The potential to use CO_2 to produce fuels and chemicals in China in 2050 is projected at 96 to 138 Mt/yr, with an additional 8 to 12 Mt/yr of CO_2 used in biological conversion processes (Huang et al., 2022). The purchase price of hydrogen and CO_2, and the selling price of methanol, have a decisive influence on the economic performance of methanol production from CO_2. Thus, using CO_2 captured from hydrogen production plants to produce methanol could be profitable under favourable pricing conditions only. Globally, profits from hydrogen-derived methanol production could range from around USD -230/t CO_2 today (production costs are currently higher than methanol's market value) to USD 4/t CO_2 in the long term (IEA, 2019c).[16]

[16] Based on a methanol market value of USD 350/tonne and a CO_2 feedstock cost of USD 30/t CO_2.

Technological developments in converting CO_2 to chemicals

China has made steady progress as well as several breakthroughs in recent years in developing CO_2 conversion technologies to produce chemicals.

Biodegradable plastics: Researchers from the Changchun Institute of Applied Chemistry, Chinese Academy of Sciences, have developed a CO_2-based biodegradable plastic film and put it on 330 hectares of farmland in China to create greenhouses. This plastic, which took twenty years of research and development to achieve industrial production with an annual output of 50 kt/yt over the last 20 years, can also be used in the preparation of plastic bags and packaging, as well as in other applications (Science and Technology Daily, 2018).

Production line for CO_2-based plastics and materials: Zhongke Jinlong Environmental Protection New Materials Co. Ltd. from Jiangsu has designed a polypropylene carbonate production line to produce plastics and other materials with an output capacity of 50 kt/yr. The core technology comes from a collaboration between the Guangzhou Institute of Chemistry, Chinese Academy of Sciences, and other research institutes, and the main output products are various CO_2-based plastics, materials and coatings (Jiangsu Zhongke Jinlong Environmental Protection Nez Material Co. Ltd., 2021).

Facility producing syngas via methane autothermal reforming with CO_2: In 2017, the Lu'an Group in Shanxi succeeded in producing H_2/CO syngas from CO_2 and methane at full load using autothermal reforming technology. The plant can convert 60 t CO_2 into 200 000 Nm^3 of syngas per day (Chinese Academy of Sciences, 2017).

Building materials

CO_2 can also be reacted with minerals or waste streams such as iron slag to form carbonates for high-value building materials. This conversion pathway is typically less energy-intensive than for fuel and chemical production and involves storing CO_2 permanently in the materials.

China has initiated a number of projects to demonstrate the use of CO_2 in building materials. Among them are a 100 kt/yr plant converting the industrial waste product phosphogypsum into ammonium sulphate (fertiliser), a 5 kt/yr plant converting potassium feldspar into potassium compounds (fertiliser) and calcium carbonate (building material), and a 50-kt/yr plant converting steel slag into aggregates (building material) (China, MOST, 2017).

The potential to use CO_2 in building materials in China in 2050 is estimated at 85 to 115 Mt/yr (Huang et al., 2022). Based on existing demonstration projects in China, converting steel slag into aggregates could generate a profit of approximately USD 30/t CO_2.[17]

Combining bioenergy-based hydrogen production with CCUS for carbon removal

In the IEA Announced Pledges Scenario (APS), China requires CO_2 removal by 2060 to compensate for residual emissions from hard-to-abate sectors. Removal technologies begin to be deployed in 2035 with 60 Mt CO_2 removed per year, increasing almost tenfold to 570 Mt CO_2/yr in 2060. Bioenergy with carbon capture and storage (BECCS) delivers 80% of the removal, while direct air capture takes care of the remainder.

Bioenergy is currently the fourth-largest energy source in China after coal, oil and gas, accounting for 4% of final energy consumption in 2020 (IEA, 2021a). Indeed, the country has been developing its vast bioenergy resource base at a rapid pace in recent years. According to the IEA, China added 7 GW of biomass-based power generation capacity in 2020, primarily through energy-from-waste projects, with these additions accounting for around 60% of the global total. According to the China National Renewable Energy Centre, total installed capacity of biomass-based power could increase to 55 GW_e by 2035 (ERI/CNREC, 2019).

Producing hydrogen from bioenergy with CCUS (BECCS) could be an important carbon removal option. A wide range of raw materials can be converted into hydrogen, including straw and forestry residues, pulp and paper, bio-refining waste, municipal solid waste (MSW), and livestock and poultry manure. The collectable amount of biomass resources in the form of waste and residue (corn stover, rice straw, wheat straw, forestry residues and animal manure) in China in 2020 was 10 to 18 EJ/yr[18] (Kang et al., 2020; Nie et al., 2018).

This could correspond to 7-12% of China's total primary demand in 2020. Thus, unlocking this potential could theoretically produce 40 to 75 Mt of hydrogen per year,[19] and equipping this production capacity with CCUS could deliver negative emissions in the range of 0.4 to 1.6 Gt CO_2/yr.[20] If other raw materials such as MSW and waste from pulp and paper and bio-refining are also included, hydrogen potential could be even higher.

[17] Assuming CO_2 utilisation of 0.25 t CO_2 per tonne of steel slag.

[18] Waste and residue use is influenced by both the technical feasibility of collection and by the need to use residues for other non-energy purposes, such as maintaining the soil's organic carbon content.

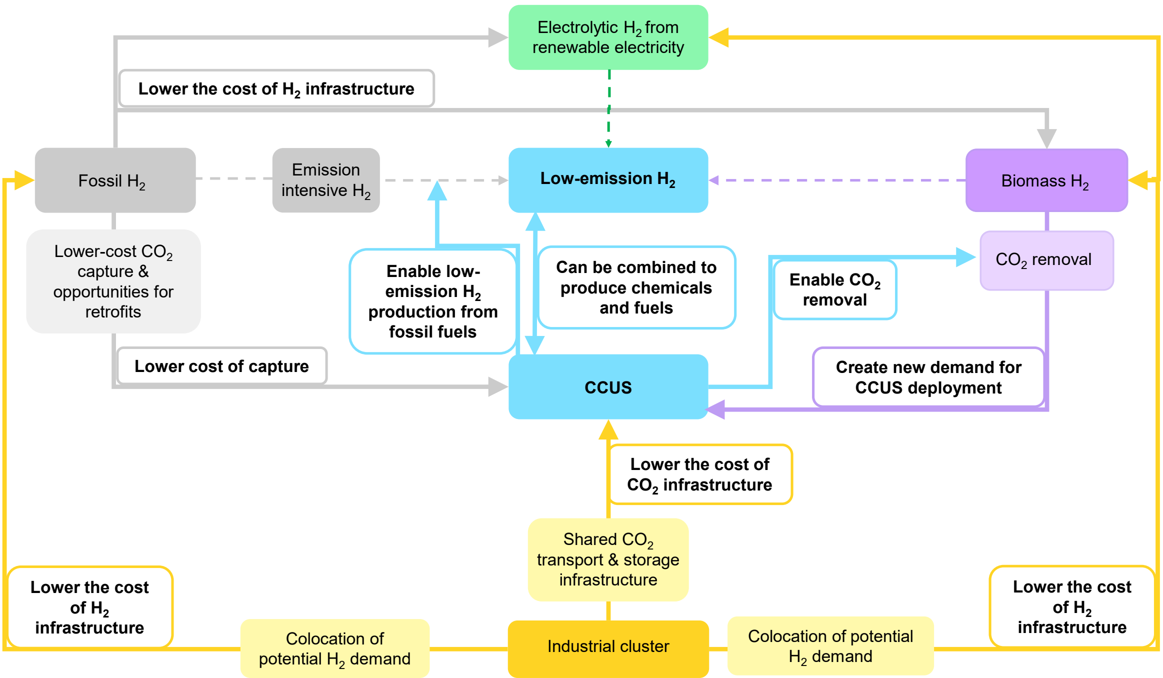
[19] Based on an average biomass-to-hydrogen conversion efficiency of 50% LHV.

[20] Lower boundary based on a lifecycle assessment of hydrogen produced from corn stover pyrolysis combined with chemical looping (only ~30% of the corn stover's initial carbon is captured) (Heng, Xiao and Zhang, 2018). The upper boundary is based on a biomass emissions factor of 100 kg CO_2/GJ and an overall CO_2 capture rate of 90%.

China has made considerable progress in developing and demonstrating biomass conversion technologies, particularly biomass-based power and ethanol plants. In 2019, the City of Jixian (Heilongjiang province) and the Jin Tong Ling Technology Group Co., Ltd. signed a contract to develop a biomass-to-hydrogen gasification plant. The facility will produce 200 million Nm^3 H_2/yr from 750 kt of raw materials such as forestry and agricultural waste and manure (Shuangyashan People's Government Network, 2019).

Given the highly concentrated stream of CO_2 generated during this process, projects such as these are ideal opportunities to apply CCUS technology, but China's RD&D activities on CCUS have so far focused primarily on conventional power and coal-to-chemical plants. While BECCS development and demonstration has been lagging, it is expected to gain traction in upcoming years because of its importance in achieving carbon neutrality by 2060.

CCUS and hydrogen industry synergies in China, 2022



Policy recommendations

Hydrogen and CCUS are both cross-cutting technologies that have the potential to interact in many subsectors of the energy system. They also share some innovation needs, such as demonstrator scale-up and commercial-scale integration into industrial processes. It is thus an opportune time for the Chinese government to implement policies that encourage hydrogen and CCUS development in tandem, to support deployment of less-carbon-intensive fuels and products. Key targets for policy support to boost hydrogen deployment with CCUS include:

- **CCUS retrofits of existing hydrogen capacity.** Policy support is needed to take advantage of CCUS retrofit potential, as current incentives to equip plants with CCUS are insufficient. In the absence of revenues or cost rebates associated with CO_2 capture, policies such as direct funding for initial projects, operational subsidies and regulatory requirements will be necessary to encourage CCUS deployment at established hydrogen facilities. Regulations can also ensure that new installations are designed to be compatible with CCUS development, which would lower the cost of retrofits.
- **CO_2 management infrastructure.** Large-scale CCUS deployment hinges on the timely rollout of CO_2 transport, storage and utilisation infrastructure. The locations of emissions sources and potential storage sites need to be considered in all provincial and regional infrastructure planning. As industrial clustering can create economies of scale and opportunities to share transport and storage infrastructure, initial planning could focus on developing these hubs. The government's role in co-ordinating and planning investment among all potential stakeholders (emitters, landowners and storage developers), as well as across all provinces, will be very important.

  According to China's Guidelines on Establishing a Green Financial System, which covers all types of clean energy investment, public-private partnerships could be appropriate for operating CO_2 management infrastructure. Meanwhile, the transmission service operator model could be well suited to pipeline CO_2 transport. Repurposing existing infrastructure for hydrogen, hydrogen-derived fuel and CO_2 transport could also help reduce costs. Finally, the government will need to further explore and assess potential CO_2 storage resources, making the resulting survey available to potential developers and researchers.
- **Hydrogen infrastructure.** Producing and using hydrogen, ammonia and hydrogen-based synthetic fuels will require changes to the existing supply infrastructure as well as the development of new production and distribution facilities such as dedicated refuelling stations and terminals and ships for potential exports. China's infrastructure plan of February 2021, its Outline of National Comprehensive Three-Dimensional Transportation Network Planning, could be extended to the provision of low-emission fuels. Holistic infrastructure planning also needs to be adopted to foster synergies with CCUS.
- **Low-emission hydrogen market and financing.** Various policy instruments can help create and enlarge markets for low-emission hydrogen. Market-pull measures, such as labelling, public procurement and sales tax rebates, can help create demand for low-emission hydrogen. For example, mandatory quotas on low-emission hydrogen shares or on shares of near-zero-emissions products in refining, steel and ammonia could help establish the use of low-emission hydrogen in industrial processes (these quotas could increase over time). In the new "city

cluster" competition, policies could include a carbon intensity ceiling on hydrogen, along with an ambitious schedule and the awarding of points for low-emission hydrogen. China's recently launched emissions trading scheme (ETS) could also have an important influence, provided that CO_2 prices are sufficiently high and stable enough to reduce project risks and secure the considerable capital investments required for hydrogen and CCUS projects.

The government can also set a strong example by introducing regulations to optimise lifecycle emissions. Supporting international efforts to develop harmonised standards and carbon accounting methodologies for hydrogen production, transport and distribution will be key to ensure that hydrogen production is consistent with net-zero goals. The government could also help industries raise funds for low-emission technologies by offering them access to sustainable debt and transition-finance markets. CCUS was included in China's green bond standards in 2020, which could be a key lever for obtaining CCUS project financing. Applying lessons learnt about financing structures from earlier-funded projects can help optimise financing mechanisms and benefit later projects.

- **Innovation.** Boosting innovation in both CCUS and hydrogen technologies is an important stimulant for their deployment. In China, state-owned enterprises (SOEs) with experience in oil and gas, chemicals, and iron and steel have the expertise and resources to deploy CCUS. The government can support these entities by co-ordinating the various stakeholders with different incentives. CCUS development can also benefit from China's Innovation Fund for Technology-based Firms. Indeed, devising and validating novel technologies and techniques (especially for CO_2 capture) could be done rapidly with establishment of a CCUS innovation centre. While demonstration projects can help test and validate various technologies, they are not sufficient to accelerate the pace of CCUS innovation.

  To move from innovation to commercial-scale deployment, the government needs to consolidate potential markets for rapid scale-up by co-ordinating companies across sectors in exploring common challenges and policy mechanisms to support investment. For hydrogen, innovation needs to be encouraged at all stages of the value chain, including supply, distribution and use. Leading SOEs in the chemical and steel industries can have a crucial role in tackling R&D challenges. Commercial-scale projects in existing hydrogen industries (e.g. steel, ammonia and methanol) would help scale-up low-emission hydrogen production in industrial clusters, where a significant share of hydrogen demand will be located. This, in turn, could boost the development of technologies and business models for hydrogen use in heavy-duty fuel cell trucks, following a similar approach to that of the cluster-based model for China's rapid deployment of light FCEVs. China also has a prime opportunity to lead international projects to ensure that technological developments and lessons are available for the benefit of all countries.

References

ACCA21 (Administrative Centre for China's Agenda 21) (2019), Roadmap for Carbon Capture, Utilization and Storage Technology in China 2019, Science Press, https://www.las.ac.cn/front/book/detail?id=321299b0229f36916ae9edbc02c8ca5c.

CAEP (Chinese Academy of Environmental Planning) (2020), China Status of CO_2 Capture, Utilization and Storage (CCUS) 2019, 10.13140/RG.2.2.19465.88168.

CHA (China Hydrogen Alliance) (2020a), China Hydrogen Energy and Fuel Cell Industry Development Report, https://item.jd.com/13451504.html.

CHA (2020b), China Hydrogen and Fuel Cell Industry Handbook. (in Chinese), https://www.chinah2data.com/#/client/database/ReportBaseListhttp://h2cn.org.cn/en/publicati/295.html.

CHA (2020c), Standard and Evaluation of Low-Carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen, http://www.ttbz.org.cn/Pdfs/Index/?ftype=st&pms=42014.

China Energy News (2017), Nearly 110 TWh of electricity was abandoned in 2016, https://news.bjx.com.cn/html/20170329/817264.shtml.

China, MOF (Ministry of Finance) et al. (2020), Notice on the Development of Fuel Cell Vehicle Demonstration Applications, http://www.gov.cn/zhengce/zhengceku/2020-09/21/content_5545221.htm.

China, MOST (Ministry of Science and Technology) (2017), The national science and technology support plan project of "carbon dioxide mineralisation and utilisation technology research and development and engineering demonstration" of the 12th Five-Year Plan passed the acceptance, http://www.most.gov.cn/kjbgz/201707/t20170714_134077.htm.

China, MOST (2010), China's clean energy in progress, http://losangeles.china-consulate.gov.cn/eng/hzjl/tech/corpration/201006/P020210814221452616283.pdf.

China, NDRC (National Development and Reform Commission) (2022), Medium and long-term plan for the development of hydrogen energy industry (2021-2035), http://zfxxgk.nea.gov.cn/2022-03/23/c_1310525630.htm (in Chinese).

Chinese Academy of Sciences (2017), 10 000 cubic meter unit of methane and carbon dioxide autothermal reforming to syngas realized stable operation, http://www.cas.cn/zkyzs/2017/08/114/kyjz/201708/t20170814_4611126.shtml.

Energy Foundation China (2020), China's New Growth Pathway: From the 14th Five Year Plan to Carbon Neutrality, Energy Foundation China, https://www.efchina.org/Reports-en/report-lceg-20201210-en.

Energy Iceberg (2020), Ten Chinese Green Hydrogen Companies Poised to Lead. https://energyiceberg.com/ten-chinese-green-hydrogen-companies/.

ERI/CNREC (Energy Research Institute/China National Renewable Energy Centre) (2019), China Renewable Energy Outlook 2019, https://www.thinkchina.ku.dk/documents/CREO-2019-EN-Final-0316.pdf.

Fan, J.-L. et al. (2022), A levelized cost of hydrogen (LCOH) comparison of coal-to-hydrogen with CCS and water electrolysis powered by renewable energy in China, Energy, Vol. 242, 123003.

GCCSI (Global CCS Institute) (2021), CCS Facilities Database, https://co2re.co/ (accessed 18 October 2021).

Heng, L., R. Xiao and H. Zhang (2018), Life cycle assessment of hydrogen production via iron-based chemical-looping process using non-aqueous phase bio-oil as fuel, International Journal of Greenhouse Gas Control, Vol. 76, pp. 78-84.

Huang, J. et al. (2022), National Assessment Report on Development of Carbon Capture Utilization and Storage Technology in China, Science Press.

IEA (2021a), An Energy Sector Roadmap to Carbon Neutrality in China, https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china.

IEA (2021b), Global Hydrogen Review 2021, https://www.iea.org/reports/global-hydrogen-review-2021.

IEA (2021c), Key Word Energy Statistics 2021, https://www.iea.org/reports/key-world-energy-statistics-2021.

IEA (2021d), Methane Tracker 2021, https://www.iea.org/reports/methane-tracker-2021.

IEA (2020a), Energy Technology Perspectives 2020, https://www.iea.org/reports/energy-technology-perspectives-2020.

IEA (2020b), Iron and Steel Technology Roadmap, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

IEA (2020c), CCUS in Clean Energy Transitions, https://www.iea.org/reports/ccus-in-clean-energy-transitions.

IEA (2019a), The Future of Hydrogen, https://www.iea.org/reports/the-future-of-hydrogen.

IEA (2019b), World Energy Outlook 2019, https://www.iea.org/reports/world-energy-outlook-2019.

IEA (2019c), Putting CO_2 to Use, https://www.iea.org/reports/putting-co2-to-use.

IEA (2015), Storing CO_2 through Enhanced Recovery, https://www.iea.org/reports/storing-co2-through-enhanced-oil-recovery.

Jiangsu Zhongke Jinlong Environmental Protection New Material Co. Ltd (2021), Company profile, http://www.zhongkejinlong.com.cn/bk_23012596.html.

Kang,Y. et al. (2020), Bioenergy in China: Evaluation of domestic biomass resources and the associated greenhouse gas mitigation potentials, Renewable and Sustainable Energy Reviews, Vol. 127.

Li, J. et al. (2021), Study on cost and carbon footprint of hydrogen production from coal in China, Energy of China, Vol. 43, pp. 51-54, https://www.cnki.com.cn/Article/CJFDTotal-ZGLN202101013.htm (in Chinese).

Liu, W., J. Wang and T. Liu (2020), The world's first large-scale solar fuel synthesis demonstration project was successfully commissioned, China Science News, http://news.sciencenet.cn/htmlnews/2020/1/434933.shtm.

National Bureau of Statistics (2019), http://www.stats.gov.cn/tjsj/ndsj/2019/indexeh.htm (accessed October 2020).

NEA (National Energy Administration) (2022), Grid-connected operation of renewable energy in 2021, http://www.gov.cn/xinwen/2022-01/29/content_5671076.htm.

NEA (2021), Transcript of the online press conference of the National Energy Administration in the first quarter of 2021, http://www.nea.gov.cn/2021-01/30/c_139708580.htm.

NEA (2020), Grid-connected operation of renewable energy in 2019, http://www.nea.gov.cn/2020-03/06/c_138850234.htm (in Chinese).

NEA (2019), Grid-connected operation of renewable energy in 2018, http://www.gov.cn/xinwen/2019-01/28/content_5361939.htm#1 (in Chinese).

NEA (2018a), Grid-connected operation of wind power in 2017, http://www.gov.cn/xinwen/2018-02/02/content_5263096.htm (in Chinese).

NEA (2018b), In 2018, we will continue to reduce the abandonment of wind power, photovoltaic and hydropower, http://www.gov.cn/xinwen/2018-01/25/content_5260301.htm (in Chinese).

NEA (2017), Grid-connected operation of wind power in 2016, http://www.gov.cn/xinwen/2017-01/28/content_5164027.htm (in Chinese).

Nie, Y. et al. (2018), Spatial distribution of usable biomass feedstock and technical bioenergy potential in China, GCB Bioenergy, Vol. 12, pp. 54-70.

Science and Technology Daily (2018), Mass production of new carbon dioxide-based biodegradable plastics, http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/html/2018-10/25/content_406436.htm?div=-1.

Shuangyashan People's Government Network (2019), Jixian County has attracted 1.32 billion yuan to build the largest hydrogen base in Northeast China, https://shuangyashan.dbw.cn/system/2019/08/07/058242732.shtml.

Tu, K.J. (2020), Prospects of a Hydrogen Economy with Chinese Characteristics, Études de l'Ifri, October 2020, https://www.ifri.org/sites/default/files/atoms/files/tu_china_hydrogen_economy_2020_1.pdf.

Wang, Y. et al. (2021), Cost analysis of different hydrogen production methods in China, Energy of China, Vol. 43, No. 05, pp. 29-37, https://www.cnki.com.cn/Article/CJFDTotal-ZGLN202105008.htm (in Chinese).

Wei, N. et al. (2021), Decarbonizing the coal-fired power sector in China via carbon capture, geological utilization, and storage technology, Environmental Science & Technology, Vol. 55, pp. 13164-13173, doi:10.1021/acs.est.1c01144 (2021).

Wei, N. et al. (2016), Budget-type techno-economic model for onshore CO_2 pipeline transportation in China, International Journal of Greenhouse Gas Control, Vol. 51, pp. 176–192, https://doi.org/https://doi.org/10.1016/j.ijggc.2016.05.010.

Wei, N. et al. (2015), Economic evaluation on CO_2-EOR of onshore oil fields in China, International Journal of Greenhouse Gas Control, Vol. 37, pp. 170–181, https://www.sciencedirect.com/science/article/pii/S1750583615000304.

Yue, M. and C.N. Wang (2020), Hydrogen: China's progress and opportunities for a Green Belt and Road Initiative, Green Belt and Road Initiative Center, https://green-bri.org/hydrogen-chinas-progress-and-opportunities-for-a-green-belt-and-road-initiative.

Zhang, X. et al. (2021a), Development of carbon capture, utilization and storage technology in China, Strategic Study of CAE, Vol. 23, No. 6, pp. 70-80, https://www.engineering.org.cn/en/10.15302/J-SSCAE-2021.06.004.

Zhang, X. et al. (2021b), Carbon footprint assessment of China's coal-to-hydrogen coupled CCUS technology based on full-process analysis, China Population, Resources and Environment, Vol. 31, No. 12, pp. 1-11 (in Chinese).

Appendices

Appendix A. Hydrogen projects in China

Selected R&D hydrogen projects in China, 2018-2020

Year	Project description
2018	Basic research on solar photocatalysis, photoelectrocatalysis and thermal decomposition of water for hydrogen production
	Basic research on high-density hydrogen storage based on hydrogen storage materials
	Research on degradation mechanism and life extension strategy of high-efficiency solid oxide fuel cells
	Research on new fuel cell based on low-cost material system
	MW-grade hydrogen production technology using solid polymer electrolyte electrolysis of water
	Engineering preparation technology of proton exchange membrane fuel cell long-life stack
	Engineering development of solid oxide fuel cell stack
	Fuel cell stack and auxiliary system component testing technology
	Research and demonstration of key technologies for large-scale wind-/solar-based complementary hydrogen production
2019	Fuel cell membrane electrodes for vehicles and batch preparation technology
	Research and development of fuel cell air compressor for vehicles
	Research and development of fuel cell hydrogen recirculation pump for vehicles
	70-Mpa vehicle-mounted high-pressure hydrogen storage bottle technology
	Vehicle-mounted liquid hydrogen storage and supply technology
	Hydrogen purification technology for fuel cell vehicles
	High-safety solid hydrogen storage and supply technology for hydrogen refuelling stations
	Key 70-Mpa equipment for pressurised filling of hydrogen refuelling station
	Safety performance testing technology and equipment for key hydrogenation components

Year	Project description
	High-temperature and low-humidity-resistant proton membrane and film-forming polymer batch preparation technology for vehicles
	Preparation technology and application of alkaline ion exchange membrane
	Batch preparation and technical application of carbon paper for diffusion layer
	Batch preparation technology for fuel cell catalysts for vehicles
2020	Development of special substrates for proton exchange membrane fuel cell plates
	Material and component durability test technology and specifications for fuel cell stacks and air compressors for vehicles
	High-pressure, large-capacity tube bundle container hydrogen storage technology for road transportation
	Research on key equipment and safety of liquid hydrogen production, storage, transportation and filling
	Fuel cell system integration technology for hydrogen production from alcohol reforming and combined cooling, heating and power

Source: CHA (2020b), *China Hydrogen and Fuel Cell Industry Handbook*.

Appendix B. Case study on a CCUS-equipped coal-to-chemical plant in China

Hydrogen production in China is dominated by coal, with a production fleet composed of relatively young assets. It is therefore important to explore the possibility of retrofitting these facilities with CCUS. Professor Ning Wei of the Wuhan Institute of Rock and Soil Mechanics prepared this case study, which evaluates the cost distribution of a coal-to-hydrogen plant retrofitted with CCUS in the Ningdong region, one of the priority regions for CCUS demonstration.

CCUS hubs in China

Five coal-to-hydrogen production hubs featuring storage sites with similar geological characteristics have been identified in China. As one of the priority regions for CCUS demonstration and CCUS cluster development, the Ningdong region (eastern area of Ningxia province) was selected for this case study. Key assets of Ningdong include its concentration of CO_2 emission sources within an industrial cluster; proximity to the Ordos Basin with suitable potential storage sites; and access to relatively low-cost coal, which is transported from nearby shallow mining sites.

The ITEAM-CCUS framework

This study was performed using the integrated techno-economic assessment method for CO_2 capture, geological utilisation and storage (ITEAM-CCUS) model. The framework combines GIS-based spatial analysis with process-level techno-economic modelling to assess the economic viability of a wide range of coal-based industries.

Source-sink matching of suitable CO_2 injection sites with CO_2 emissions sources was used to determine optimal CCUS value chains.

Techno-economic evaluation captures the entire CCUS value chain, including CO_2 capture, compression, pipeline transportation and injection for enhanced water recovery (EWR), EOR and geological storage. For each stage, capital expenses (CAPEX), operations and maintenance (O&M) costs and potential revenue streams were considered. For example, revenues associated with CO_2 utilisation (including the sale of additional crude oil for EOR) and water sold after desalination for EWR are included.

Background on hydrogen production from coal

Coal gasification is the leading hydrogen production process in China. The bulk of these plants' CO_2 emissions (66-78%) occur during the acid gas removal (AGR) process at a high CO_2 concentration. Most of this CO_2 stream is of high purity (>99%) and can be sent directly for compression, while a small fraction is of lower purity (80%) and needs to undergo low-temperature distillation to reach 95% purity. Remaining plant CO_2 emissions (22-34%) occur at the syngas combustion stage at a lower concentration (12-15%), and the exhaust gas needs to undergo post-combustion capture before compression.

Assuming capture efficiencies of 90% for post-combustion, a net process capture efficiency of 90% can be reached. Without capture, the process emits 17 to 19 kg CO_2/kg H_2. With capture, emissions may be reduced to 1.7 to 1.9 kg CO_2/kg H_2. The total cost of producing hydrogen from coal is estimated at USD 1.2 to 2.1/kg H_2 (CNY 7.7 to 13.5/kg H_2).

Technical assumptions

The plant configuration modelled within the framework consists of a coal gasification plant with pre-combustion CO_2 capture and amine-based post-combustion capture on an auxiliary syngas boiler, with CO_2 being compressed, transported and stored, or used for EOR/EWR. The plant has a capacity of 0.18 Mt/yr, with annual output of 0.01 Mt/yr (i.e. an overall capacity factor of 55%).

Based on fuel composition and process efficiency, direct CO_2 emissions per unit of hydrogen are calculated as 17.8 kg CO_2/kg H_2, which results in 1.75 Mt of CO_2 emitted per year. Process configuration is such that 66% (i.e. 1.15 Mt per year) of the CO_2 is emitted at the H_2-CO_2 separation stage at high purity, and the remainder (i.e. 0.6 Mt CO_2 per year) from the syngas boiler exhaust at a lower purity. The overall capture rate is 90%.

CO_2 from the auxiliary boiler is captured with an amine-based post-combustion capture system to reach 95% purity, and it is mixed with high-purity CO_2 (>99%) from the syngas methanol-based AGR unit (the Rectisol process).

A five-stage compressor system is used to raise CO_2 pressure from 0.15 MPa to 7.38 MPa. A one-stage booster pump then increases CO_2 pressure to the specified pipeline's inlet pressure, assumed to be 12 MPa.

Supercritical CO_2 is transported to storage sites and oilfields for EOR within a 50-km radius of the facility. GIS-based spatial analysis identified the Yanchang Formation, the Heshanggou Formation, the Liujiagou Formation and the Shiqianfeng Formation in the Ordos Basin as suitable storage reservoirs. The Yanchang and Liujiagou formations were selected for CO_2 injection and storage in this case study.

While indirect emissions resulting from upstream energy and material consumption at the coal mining and transport stages are also accounted for, emissions from plant construction, equipment manufacturing and transport are considered out of the scope of this study. Overall indirect emissions are estimated at 1 to 3 kg CO_2/kg H_2. Direct and indirect emissions relating to the additional power/heat requirements for CO_2 capture and compression were also accounted for.

Key modelling assumptions

CO_2 stream from H_2 plant	Fraction of total plant emissions	CO_2 Capture	CO_2 compression	CO_2 transport
Pure (99%) CO_2 separated from H_2-CO_2-rich shifted syngas	66%	Methanol washing AGR (capture rate 90%)	5-stage compressor train and 1-stage booster station to achieve 12 MPa pressure	50-km transport in pipeline (no booster pump station), inlet pressure at 12 MPa
Exhaust from syngas combustion	34%	Amine-based post-combustion (capture rate 90%)		

Scenarios

We explored two revenue scenarios for the end use of the CO_2: 1) 100% of the CO_2 is used for CO_2-EWR and storage; or 2) 40% is sold to oilfields for EOR and 60% is used for EWR and storage.

Techno-economic assumptions

CO_2 stream from H_2 plant	Scenario 1	Scenario 2
Capture capacity	1.75 Mt CO_2/year	1.75 Mt CO_2/year
CO_2 end use	100% EWR	60% EWR, 40% EOR
Overall capture rate	90%	90%
Capacity factor	80%	80%
Project period	25 years	25 years
Transportation distance	50 km	50 km
Discount rate	10%	10%
Electricity price	CNY 0.35/kWh	CNY 0.35/kWh[21]
Water price	CNY 5.5/t	CNY 5.5/t
Coal price	CNY 336/t	CNY 336/t[22]

[21] Electricity price is from Wei et al. (2021).
[22] The China Energy Group's crude coal price is about two-thirds the price in other provinces.

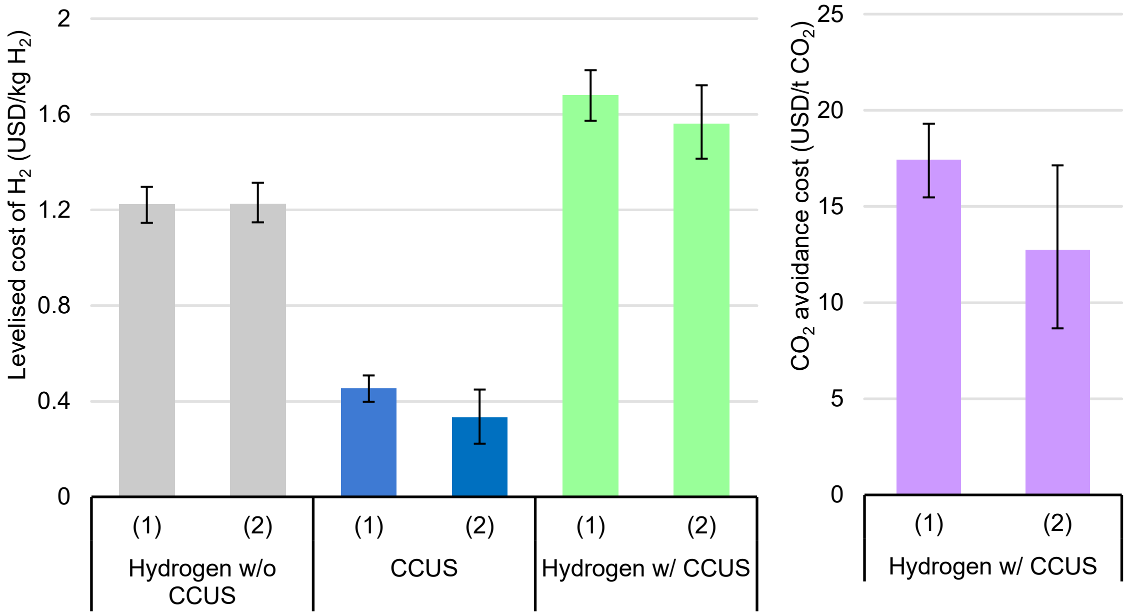
Cost distribution analysis

To capture input parameter variability, the oil price, capacity factor, discount rate, land cost, capital investment, and cost of CO_2 transport and storage were distributed around a mean value using 5% standard variation. Stochastic analysis was performed with all the variable combinations to obtain probability distribution curves for the levelised cost of hydrogen (LCOH) production, the levelised cost of CCUS retrofits, and the CO_2 avoidance cost of hydrogen from CCUS-equipped coal facilities.

The LCOH produced from coal without CCUS ranges from USD 1.1/kg (CNY 7.4/kg) to USD 1.3/kg (CNY 8.4/kg), with an average value of USD 1.2/kg (CNY 7.9/kg). Meanwhile, the cost of CCUS-equipped hydrogen production ranges from USD 1.6/kg (CNY 10.1/kg) to USD 1.8/kg (CNY 11.5/kg), with an average value of USD 1.7/kg (CNY 10.8/kg). This results in a levelised CCUS cost of USD 0.4 to 0.5/kg (CNY 2.6 to 3.3/t CO_2) and a CO_2 avoidance cost of USD 15.5 to 19.3/t CO_2 (CNY 100 to 125/t CO_2).

In Scenario 2, using 40% of the captured CO_2 for EOR improves the project economics. The cost of CCUS-equipped hydrogen production drops to USD 1.4 to 1.7/kg (CNY 9.1 to 11.1/kg), with an average value of USD 1.6/kg (CNY 10.1/kg). This results in a levelised CCUS cost of USD 0.2 to 0.4/kg (CNY 1.4 to 2.9/kg) and a CO_2 avoidance cost of USD 8.7 to 17.1/t CO_2 (CNY 56 to 111/t CO_2).

Levelised cost of hydrogen production and CO_2 avoidance cost under Scenarios 1 and 2



Notes: Scenario 1 = 100% EWR. Scenario 2 = 60% EWR and 40% EOR.

Analysis of carbon emission reductions

Coal in the Ningdong area is at a shallow depth, the transportation distance is short, and mining and transportation costs are low. The CO_2 emissions factor for the mining and transportation stage is thus estimated to be 1.0 to 3.0 kg CO_2/kg H_2, while for the hydrogen production stage it is assumed to be 17.8 kg CO_2/kg H_2 and the overall CO_2 capture rate is 90%. This results in total direct emissions of 1.8 kg CO_2/kg H_2 and total lifecycle emissions (including mining, transportation and production) of 3.0 to 5.0 kg CO_2/kg H_2.

Conclusion

This study presents levelised cost distributions for a coal-fired hydrogen production facility equipped with CCUS, but cost distributions for a base-case plant without CCUS are also provided for comparison. Two CO_2 injection scenarios are explored: 100% CO_2 storage for EWR demonstration in Scenario 1, and 40% CO_2 sold for EOR and 60% for EWR in Scenario 2.

Results show that the levelised cost of producing hydrogen from coal increases 37-38% when CCUS is applied. If a fraction of the captured CO_2 is used for EOR, the cost increase can be limited to 23-31%.

Although CCUS has significant potential to reduce direct emissions, indirect emissions remain high. With CCUS, direct emissions amount to 1.8 kg CO_2/kg H_2, while indirect emissions from coal mining and transport constitute the largest share of emissions at 1 to 3 kg CO_2/kg H_2.

We found the cost of producing hydrogen from coal with CCUS to be lower than from natural gas or water electrolysis. While coal-fired hydrogen production with CCUS costs roughly USD 1.7/kg H_2 (average value for CO_2-EWR), production from natural gas with CCUS is typically around USD 2.0 to 3.8/kg H_2, and from electrolysis is USD 3.1 to 9.7/kg H_2.

The Ordos Basin, where the Ningdong industrial cluster is located, offers prime opportunities for source-sink matching of suitable sites for CO_2-EWR storage and EOR utilisation, and for coal-to-chemicals production. A CCUS cluster in this area is therefore highly recommended, and the potential sharing of CCUS and hydrogen infrastructure could reduce CO_2 transport and storage costs.

Abbreviations and acronyms

ACTL	Alberta Carbon Trunk Line
AGR	Acid gas removal
APS	Announced Pledges Scenario
ATR	Autothermal reforming
BECCS	Bioenergy with carbon capture and storage
BF-BOF	Blast furnace-basic oxygen furnace
CAE	Chinese Academy of Engineering
CAPEX	Capital expenses
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CHA	China Hydrogen Alliance
CNPC	China National Petroleum Corporation
CNR	Catalytic naphtha reforming
DRI	Direct reduction of iron
DRI-EAF	Direct reduction of iron-electric arc furnace
EOR	Enhanced oil recovery
ETS	Emissions trading scheme
EWR	Enhanced water recovery
FCEV	Fuel cell electric vehicles
FYP	Five-Year Plan
GHG	Greenhouse gas
HVC	High-value chemicals
IGCC	Integrated gasification combined cycle
LCOH	Levelised cost of hydrogen
LHV	Lower Heating Value
MSW	Municipal solid waste
O&M	Operations and maintenance
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
RD&D	Research, development and demonstration
PV	Photovoltaics
SMR	Steam methane reforming
SOE	State-owned enterprises
SOEC	Solid oxide electrolysis cell
TRL	Technology readiness level

Glossary

bcm	billion cubic metres
bcm/yr	billion cubic metres per year
EJ	exajoule

Gt	gigatonne
$GtCO_2$	gigatonne of carbon dioxide
$GtCO_2$/yr	gigatonnes of carbon dioxide per year
CNY	Chinese yuan
GW_e	gigawatt electric
kg H_2	kilogram of hydrogen
kg CO_2-eq	kilogram of carbon dioxide equivalent
km	kilometer
kt	kilotonne
kWh	kilowatt hour
kWh_e	kilowatt hour electric
Mb/d	million barrels per day
mln	million
Mt	million tonnes
Mtce	million tonnes of coal equivalent
MW	megawatt
MW_e	megawatt electric
Nm^3	normal cubic meter
tCO_2	tonne of carbon dioxide
TWh	terawatt-hour

This publication is the result of a collaborative effort among the International Energy Agency (IEA) and The Administrative Center for China's Agenda 21 (ACCA21).

Typeset in France by IEA - November 2022
Cover design: IEA
Photo credits: © Shutterstock