



ROAD MAP UPDATE FOR CARBON CAPTURE, UTILIZATION, AND STORAGE DEMONSTRATION AND DEPLOYMENT IN THE PEOPLE'S REPUBLIC OF CHINA

AUGUST 2022

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Foreword

The earth is at a crossroads. It is in a race against time to reduce greenhouse gas emissions so that the ultimate objective of keeping the temperature increase to below 1.5°C by 2100 can be achieved. This requires all hands on deck, and means all tools have to be used. One needs to be imaginative—not only in exploring the solutions available today, but also solutions that are yet to be developed and implemented widely.

The People's Republic of China (PRC) has been fighting climate change and plays a key role in the uptake of energy efficiency and the renewable energy revolution. It is also the world leader in solar and wind energy. The PRC has long recognized carbon capture, utilization, and storage (CCUS) as a promising technology solution, and has been working on this with the Asian Development Bank (ADB) since 2009. ADB has been a partner in raising awareness on CCUS through knowledge products, workshops, and in establishing CCUS Centers of Excellence. ADB also helped in increasing the technical expertise of the PRC through study tours, technology evaluation, and feasibility studies. In 2015, ADB partnered with the PRC to create a road map for CCUS.

Since the release of the road map in 2015, a number of developments have taken place in policies, technology, and financing. Some of the important developments are as follows:

- The PRC has declared an ambitious goal to be carbon neutral by 2060.
- The role of CCUS has been recognized by industry in its effort to decarbonize operations.
- The PRC has implemented CCUS technologies like preparing food grade carbon dioxide (CO₂) and making ethanol from the tail gas of steel plants.
- The PRC has started implementation of the CO₂ hub project.

In light of these developments, ADB and the Government of the PRC decided to review the road map to ensure that these developments are captured in the PRC's future development path.

I hope that this publication will be useful in advancing CCUS technology in the PRC.



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Abbreviations

ADB	Asian Development Bank
BFG	blast furnace gas
CCER	China Certified Emission Reductions
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CDM	Clean Development Mechanism
CER	certified emission reduction
CNPC	China National Petroleum Company
EOR	enhanced oil recovery
EPS	emission performance standard
EU	European Union
ETS	Emission Trading System
FYP	five-year plan
GCCSI	Global Carbon Capture and Storage Institute
IEA	International Energy Agency
IGCC	integrated generation of combined cycle
IPCC	Intergovernmental Panel on Climate Change
PRC	People's Republic of China
R&D	research and development
SOE	state-owned enterprise
UK	United Kingdom
US	United States

Units and Measurements

GW	gigawatt
GWh	gigawatt-hour
km	kilometer
Mtpa	million tons per annum
Mt	million tons
tce	ton of coal equivalent
tCO ₂	ton of carbon dioxide
tpa	ton per annum

Executive Summary

The People's Republic of China (PRC) has made significant progress on carbon capture, utilization, and storage (CCUS) technology research and development and is carrying out several CCUS demonstration projects. The PRC has over 30 CCUS projects, with a cumulative carbon dioxide (CO₂) injection of 0.5 million~2 million tons until 2020.

During the 13th Five-Year Plan period, two post-combustion CO₂ capture pilot facilities were constructed: one by the Conch Group Baimashan Cement Plant and the other in China Resources Power Haifeng Power Plant. Shaanxi Guohua Jinjie Powerplant commenced operation in May 2021. However, its development has remained far lower than the development goal set in the original ADB carbon capture and storage (CCS) road map that was published in 2015. As a result of which, the expected low-cost CCS demonstration has not yet been realized at scale. Few projects were actually built CCS-ready, a design consideration for CCUS retrofit in the future.

In the PRC, many policies relevant to CCUS have gradually been issued and improved. The related scientific and technical capacity and level have been improved day by day, the scale of pilot and demonstration projects has been growing, and the overall competitiveness has been further enhanced, showing good development momentum. However, obstacles to CCUS development include a high energy penalty, lack of regulatory and standards frameworks; concerns over leakage risk, safety, and liability; lack of public awareness; the absence of an evaluation system; knowledge gaps in relation to some core technologies; and the unbalanced development of the existing CCUS technology chain.

To meet the needs of the PRC's low-carbon development in the long term, it is necessary to further strengthen confidence and strive to speed up the application range of CCUS from the coal chemical industry and thermal power plants to iron and steel, cement, hydrogen production, and other sectors. Based on the PRC's carbon peak target and carbon-neutrality vision, the CCUS development goals are set and categorized by sectors in this report. Enhanced oil recovery (EOR) is considered as an important tool by the PRC in its CCUS strategy. However, it may be noted that the new energy policy of ADB does not allow ADB to engage with EOR projects.*

The following principles are suggested to further develop CCUS in the PRC:

- (i) Through source and sink matching, identify priority areas and storage sites and early projects in CCUS technology development;
- (ii) Further promote the application of enhanced oil recovery in the 14th Five-Year Plan period to drive the successful demonstration of capture projects;
- (iii) Promote commercialization within 10–15 years through large-scale CCUS demonstration projects; and
- (iv) Accelerate infrastructure-sharing and promote CCUS clusters.

* Asian Development Bank. 2021. *Energy Policy Supporting Low-Carbon Transition in Asia and the Pacific*. <https://www.adb.org/sites/default/files/institutional-document/737086/energy-policy-r-paper.pdf>.

To speed up CCUS technology research and development and project demonstration and realize deployment in the near and medium term, some suggestions are provided:

- (i) Establish a trial regulatory framework for CCUS.
- (ii) Establish a method to measure CO₂ emissions and assess the abatement cost of CCUS technologies.
- (iii) Integrate CCUS into the PRC's carbon market and provide other carbon pricing signals for sectors with high concentration emission sources not included in the emission trading system.

In addition, there is a need to accelerate the construction of the CCUS industrial cluster and gradually integrate CCUS technology into the energy, mining, and other green development technology support system.

1 Introduction

Carbon Capture and Storage and Carbon Capture, Utilization, and Storage are Critical Carbon Mitigation Technologies¹

The Intergovernmental Panel on Climate Change (IPCC) defines carbon dioxide (CO₂) removal as “anthropogenic activities removing CO₂ from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO₂ uptake not directly caused by human activities” (IPCC 2018). Carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) are important CO₂ removal technologies.

The IPCC estimates that without CCS, the cost of the 2°C emission reduction target would increase by 138% (IPCC 2014). The IPCC also concluded that CO₂ removal measures will undoubtedly be necessary to limit the increase in average global temperatures to within 1.5°C and will likely be essential to limit the increase to within 2°C. Carbon removal measures may also be critical to returning the atmosphere to lower concentrations of CO₂, particularly if the world initially overshoots the 1.5°C target. The Government of the People’s Republic of China (PRC) has positioned CCUS as one of the most important means of tackling climate change and achieving its carbon peak and carbon-neutrality goal. The PRC will support major energy conservation and low-carbon technology industrialization demonstration projects during the 14th Five-Year Plan period, and carry out demonstration of major projects such as near zero energy consumption buildings, near zero carbon emissions, and CCUS.

As a technology, CCUS involves the following steps:

- (i) CO₂ capture,
- (ii) CO₂ utilization,
- (iii) CO₂ transportation,
- (iv) CO₂ storage, and
- (v) CO₂ monitoring.

Each of these steps involves different technologies that are at different levels of readiness and costs (Ritchie and Roser 2020).

History and Changes in the 2015 ADB Road Map

The Asian Development Bank (ADB) has been working with the PRC to develop CCUS as a low-carbon technology for almost 10 years. One of the critical projects was the publication of a road map of CCUS in the PRC, which was led by the National Development and Reform Commission. The publication was released during the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (ADB 2015).

¹ CCUS and CCS refer to the industrial process in which carbon dioxide is separated from industrial emission sources or directly used or stored to prevent it from entering the atmosphere and achieve CO₂ emission reduction. CCS is an internationally accepted definition of carbon capture and storage. CCUS in this report includes the resource utilization of CO₂. Direct air capture is another technology that can reduce past CO₂ emissions and is at an early stage of development.

Subsequently, there have been substantial changes in the CCUS field:

- Additional challenges of achieving more ambitious goals of emission reduction arising out of the commitments under the Paris Agreement;
- A technical breakthrough in CCUS technologies; and
- Experience in future planning, feasibility consideration, and engineering test gained in “hard-to-abate” sectors such as iron and steel, cement, and petrochemicals; and the emergence of hydrogen as a new vector of energy.

Objectives of This Study

The objective of this study is to conduct an assessment of the development and deployment of CCUS, provide an outlook of CCUS technologies since the release of the road map in 2015, support the development of CCUS in the PRC's 14th Five-Year Plan (FYP), and update and formulate a road map for the development of the PRC's CCUS industry, in combination with the PRC's carbon-neutrality target and the 13th FYP period CCUS development reality.

Current updates in this report will cover the following aspects:

- (i) Overview of the CCUS development in the PRC during the 13th FYP;
- (ii) Discussion of the contribution of CCUS in the decarbonization of hydrogen production from fossil fuels;
- (iii) Addition of CCUS readiness analysis in the steel, cement, refineries, and CO₂ industrial utilization;
- (iv) Updating of the long-term goal of the PRC's CCUS development; and
- (v) Proposition of CCUS deployment recommendation in the 14th FYP period and beyond.

2 Overview of Carbon Capture, Utilization, and Storage Development during the 13th Five-Year Plan

At present, in the PRC, many CCUS relevant policies have been gradually issued and improved. The related scientific and technical capacity and level have been improved day by day, the scale of pilot and demonstration projects has been growing, and the overall competitiveness has been further enhanced, showing a good development momentum. The PRC has the engineering capacity of large-scale capture, utilization, and storage of CO₂, and is actively preparing for the whole process of CCUS industrial clusters. CCUS projects are distributed in 19 provinces of the PRC, and the industries of capture sources and types of storage and utilization are diversified. Remarkable progress has been made in all technical links of CCUS in the PRC.

Major Projects during the 13th Five-Year Plan Period

According to Cai et al. (2019) and the Ministry of Science and Technology (2019), the PRC has conducted over 20 CO₂ capture demonstration projects, of which approximately 10 CO₂ geological utilization and storage projects, including over 10 full-chain demonstration projects as of 2020. The cumulative storage capacity for all CCUS projects is approximately 2 million tons of CO₂. A list of major projects is provided in Annex 1.

During the 13th FYP period (2016–2020), there was significant progress in CO₂ capture. Two post-combustion CO₂ capture pilot facilities were constructed in the Conch Group Baimashan Cement Plant and in the China Resources Power Haifeng Coal Power Plant. Another facility in Shaanxi Guohua Jinjie Coal Power Plant has been in operation in May 2021.

Two more chemical process projects are under construction. The first one is Dunhua Petroleum Company's 100,000 tons/year coal to chemical processing CO₂ capture facility at Ningxia Ningdong Coal Chemical Industrial Zone. The gas source comes from the Shenhua coal methanol plant. The other one is Yulin Shenghui Hengtong Gas Technology Co. Ltd.'s 500,000 tons/year coal to chemical process CO₂ capture facility at Shaanxi Yulin High Technique Zone (Phase I is under construction), where the gas is sourced from China Coal Group Shaanxi Yulin Energy and Chemical Co., Ltd.

One CO₂-enhanced oil recovery (EOR) project (CNPC Changqing Oil Company CCUS Project) was added to the new list of full-chain CCUS projects in the PRC in 2017. CO₂ is captured by chemical processing CO₂ capture facility at Ningxia, which is transported by tank trucks. It is expected to inject 50,000 tons of CO₂ per year in 2021, though the actual CO₂ purchased by CNPC Changqing Oil Company and the injection amount will fluctuate depending on the oil price.

Implementation Status of Carbon Capture, Utilization, and Storage Road Map for the 13th Five-Year Plan

Targets in the Carbon Capture, Utilization, and Storage Road Map for the 13th Five-Year Plan

As suggested by the Road Map for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China (ADB 2015), 10 million–20 million tons of carbon dioxide would have been abated with CCUS, and 30 million barrels of crude oil would have been increased through EOR between 2016 and 2020. The corresponding road map actions for 13th FYP were as follows:

- (i) Select and implement 5–10 large CCUS demonstration projects in the coal chemical industry and 1–3 large-scale coal-fired power plants CCUS demonstration projects to overcome technical barriers.
- (ii) Significantly reduce the cost of carbon capture technology in the first-generation coal-fired power plant.
- (iii) Plan CCS projects for million-ton coal-fired power plants in Shaanxi, Ningxia, Inner Mongolia, Xinjiang, and other regions, and build CCS-ready power plants.

The Implementation Status during the 13th Five-Year Plan

- (i) CCUS deployment partly achieved its prospective target:
 - (a) The expected low-cost CCS demonstration has not yet been realized. CO₂ capture in the coal chemical industry has been developing rapidly, mainly owing to the contribution from private companies, with the cost of capture still higher than \$20/ton of CO₂ (tCO₂), which is equivalent to the cost of CO₂ for EOR in the Weyburn field, Canada. In addition, the total cost of CO₂ (which is transported by truck from the capture facility) to the injection wells is \$0.17~\$0.22/(tCO₂·km) (CNY1.1~CNY1.4/[tCO₂·km]). At the same time, the CO₂-EOR experiment carried out in the PRC is still at an early stage, and both miscible and immiscible flooding experiments have not achieved a high effect compared with that in the United States (US) and Canada. The scale of CO₂-EOR projects is still small. Although CO₂-EOR and storage is a proven technology globally, the performance of CO₂-EOR in the PRC is still lower than that in the US or Canada and is not stable, which makes oil and gas companies hesitant to buy more CO₂ and to implement commercial-scale CO₂ storage projects.
 - (b) Due to the mismatch between CO₂ utilization or storage sites and emission sources, CO₂ capture facilities have not reached its full production capacity.
 - (c) The 13th Five-Year Plan road map proposed that CCS-ready projects would be widely developed, but only several CCS-ready projects were actually implemented.
- (ii) It is worth noting that the development was not as good as expected for the following reasons:
 - (a) No incentives from the government for CCUS.
 - (b) The possibility of low-cost capture of CO₂ (less than \$20/tCO₂) in the PRC's vast coal-chemical industry has not been realized, partly because the focus of carbon capture technology was on coal-fired power plants. In contrast, minor government support has been made for coal chemical CO₂ capture. There are no large low-cost demonstrations even for those high-concentration CO₂ capture technologies.
 - (c) The performance of CO₂-EOR did not reach the expectation in the demonstration projects. High effect enhanced oil recovery and large-scale CO₂ storage through CO₂-EOR projects have not been achieved.

- (iii) The gaps compared with the advanced economies in CO₂ capture from coal-fired power plants:
 - (a) At present, the scale of CO₂ capture in power plants is much smaller than that of the US and Canada. The capacity of carbon capture demonstration projects from coal-fired power plants in operation in the PRC is generally around 100,000–150,000 tons per year, while the capacity of operational carbon capture projects from the sector in the US and in Canada have reached more than 1 million tons per year.
 - (b) CO₂ capture costs in a domestic power plant are higher than those abroad, although the stated or estimated capture cost from experts or in feasibility reports is lower than that of abroad. For instance, the operation cost of an additional CNY140~CNY600 (\$20~\$90) per ton for CCS facilities will directly lead to a substantial increase in power generation costs (Mi et al. 2019).
 - (c) Oil companies are reluctant to purchase CO₂ for EOR at high prices when oil prices are low. Selling CO₂ to oil fields for EOR use can hardly be the main driver for CCUS investment in the power sector.

Technology Development Status

The PRC's CCUS technology has developed rapidly in recent years, with impressive results achieved (Cai et al. 2019). The PRC has developed a variety of CCUS technologies and has the design capability of a large-scale full-process system. The chemical absorption method, truck and offshore pipeline transportation, CO₂-EOR, and other vital technologies have achieved industrial or commercial maturity.

The PRC's various types of CO₂ storage technologies, including storage in deep saline aquifers, CO₂ use to improve oil recovery rate, CO₂ enhancing coal bed methane, and other CCUS key technologies have accumulated valuable experience for the PRC and the global CCUS development, promotion, and management (MOST 2019).

CCUS capture technology has become more mature in the PRC. Several key technologies of geological utilization and storage have made major breakthroughs. CO₂-EOR has been used to improve the oil recovery rate commercially.

The development of CO₂ utilization technology in the PRC has made great progress, and overall most technologies are still at the research and development (R&D) and demonstration stage. In terms of utilization, theoretical and key technology research has been carried out around different utilization methods such as CO₂ flooding, coal bed methane flooding, CO₂ biotransformation, and chemical synthesis. Industrial experiments of CO₂ flooding have been carried out, and pilot testing and small-scale production lines of biodegradable plastics from microalgae have been built.

In summary, the technical level of some aspects of CCUS in the PRC still needs to be improved. The existing CCUS pilot demonstration projects mainly focus on demonstrating carbon capture technology and EOR technology. However, the technical demonstration cases in saline aquifer storage, CO₂ storage monitoring, reporting and verification, and large-scale CO₂ transportation remain inadequate, and the size of demonstration projects is small compared with the advanced international level.

CCUS deployment is expected to follow the path as described in the following paragraphs:

- (i) The PRC is expected to reduce the cost and energy consumption of CO₂ capture technology by 10%–20% by 2030 through the orderly promotion of CCUS technology R&D and demonstration; break through large-scale CO₂ compression (equipment) technology and build a long-distance land pipeline with a single pipe transportation capacity of 2 million tons per annum (tpa); and realize the commercial operation and industrialization ability of the existing utilization technologies of CO₂ flooding and synthetic gas.
- (ii) By 2035, new technologies will be put into operation on a large scale; the cost and energy consumption of capture technology will be reduced by 15%–25% compared with the current situation; the new utilization

technology will have the ability to reach commercialization; the geological storage safety guarantee technology will have made a breakthrough, and large-scale demonstration projects will have been completed, which also has potential for industrialization.

- (iii) By 2050, CCUS technology will be widely deployed, and multiple CCUS industrial clusters will be built (MOST 2019).

Cost Performance

At present, the cost and energy consumption of the first-generation capture technology is still high, and there is a lack of extensive large-scale demonstration engineering experience. The second generation of capture technology is still in the laboratory R&D or small trial stages, and it needs to achieve intergenerational convergence around 2035.¹

The transport cost of CO₂ by tank truck is about CNY1.1–CNY1.4/ton-kilometer (km) (\$0.17–\$0.21 per ton-km) in the PRC. The cost of the key CO₂ transport and storage technologies is a function of the topography of land and offshore conditions. In complex mountainous areas and offshore areas, the cost increases compared with plain areas for the same technology. Low power consumption and high-efficiency CO₂ compressor facilities need to be developed.

For CO₂-EOR and CO₂ storage, the cost mainly depends on CO₂-EOR efficiency, recycled CO₂, and monitoring technologies. The cost of EOR technology varies greatly depending on the technical level, reservoir conditions, gas source, source distance, etc. EOR can improve the recovery rate of oil, effectively compensating for CCUS costs.

The cost of monitoring technologies will be cheaper, which is similar to aquifer storage monitoring. It is expected that new technologies may improve EOR, especially in a tight reservoir. The optimized monitoring technologies and lower-cost monitoring equipment will reduce the cost of the CO₂ storage operation. Nevertheless, the global oil price will be a critical factor to the viability of CO₂-EOR and storage operation and the application of monitoring technologies.

Based on the current level of technology, and taking into account the monitoring costs of 20 years after the closure of the well, the storage costs in 2020 prices are CNY60/ton of CO₂ (\$8.4) for onshore saline aquifers, CNY300/ton of CO₂ (\$43) for offshore saline aquifers, and CNY50/ton of CO₂ (\$7.1) for depleted oil and gas fields.

Key Policies and Regulations

The Government of the PRC has carried out a series of systematic deployments and demonstrations around CCUS and other related basic research, technology research, and development. Especially after the State Council's institutional reform in 2018, the government committed to adopting a more coherent environmental management approach, combining CO₂ emission reductions with air pollutant control. The PRC has identified CCUS as a key technology in climate change (the PRC has also mentioned CCUS as one of the greenhouse gas mitigation technology in its nationally determined contribution), actively promoted the construction of CCUS demonstration projects and related technologies, and strengthened environmental protection for carbon capture demonstration projects.

¹ For the definition of the first-generation technology and the second-generation technology, please refer to the road map of the Ministry of Science and Technology in 2019: the first-generation capture technology refers to technology that has been able to carry out large-scale demonstration at this stage, such as amine absorbent, atmospheric oxygen enriched combustion, etc.; the second-generation capture technology refers to technology whose energy consumption and cost can be reduced by more than 30% compared with the mature first-generation technology, such as new membrane separation technology, new absorption technology, and new technology. This paper introduces the technology of type-I adsorption, pressurized oxygen enriched combustion, chemical looping combustion, etc.

National policies and regulations on CCUS since 2015 are shown in Table 1. The main policy effects are reflected in three aspects.

- (i) First, CCUS is restated as the key technology to deal with climate change.
- (ii) Second, the PRC has actively accelerated the construction of CCUS demonstration projects and the promotion of related technologies.
- (iii) Third, the PRC has strengthened the environmental protection of carbon capture demonstration projects.

The policies and regulations mainly focus on the science and technology innovation of CCUS. They are not the kind of incentive policies and regulations for the deployment of commercial-scale CCUS projects such as the 45Q Tax Credit in the US. These still show a lack of incentive policies or effective policies to solve the barriers in deploying CCUS projects. Some policies should be set to reduce the cost of CO₂ capture and CO₂ transport, and require CO₂ emitters to pay the price for their carbon emissions.

Table 1: Major Policies and Regulations Related to Carbon Capture, Utilization, and Storage during the 13th Five-Year Plan, 2016–2020

No.	Agency	Year	Name of Document
1	National Development and Reform Commission (NDRC)	2015	Catalogue of National Key Low-Carbon Energy Technologies for Promotion (Second Batch)
2	Ministry of Ecology and Environment (MEE)	2016	Technical Guide for Environmental Risk Assessment of Carbon Dioxide Capture, Utilization and Storage (Trial)
3	The State Council, PRC	2016	National Science and Technology Innovation Plan of the 13th Five-Year Plan
4	The State Council, PRC	2016	The 13th Five-Year Plan for Greenhouse Gas Emission Control
5	NDRC	2016	The 13th Five-Year Plan for Petroleum Development, and the 13th Five-Year Plan for Natural Gas Development
6	NDRC	2017	Directive Catalog of Key Products and Services for Strategic Emerging Industries (2016 Edition)
7	Ministry of Science and Technology (MOST), MEE, China Meteorological Administration	2017	The 13th Five-Year Special Plan for Climate Change Science and Technology Innovation
8	Ministry of Housing and Urban-Rural Development	2018	Design Standard of Flue Gas Carbon Dioxide Capture and Purification Engineering
9	MOST	2019	The Roadmap for Carbon Capture, Utilization, and Storage Technology in China (2019)

Source: Cai et al. (2019).

Major Obstacles

Economies of Scale Not Achieved

Costs of CCUS projects vary widely with the concentration of CO₂ and the size of the project. In all aspects of CCUS capture, transportation, utilization, and storage technology, economies of scale were not achieved. The PRC's CCS demonstration projects are small in both number and scale.

The PRC has carried out a small number of CCUS demonstration projects in the 10,000- to 100,000-ton capacity. To achieve the carbon-neutrality target, there is an urgent need to carry out large-scale CCUS demonstration projects, on a scale of a million or even tens of millions of tons. The current 100,000-ton CCUS equipment

can be scaled in a modular approach, for example, 10 units of 100,000-ton grade equipment in-union can achieve a million-ton effect. This co-linked application is less economical and will increase the cost of CCUS, where its commercial development will become an economic obstacle. The current level of technology and the equipment size can meet the needs of a million tons, but the technical parameters and economic parameters need to be further analyzed. In addition, the scope of the current demonstration project costing is not consistent. The boundary demarcation is not reasonable and fails to reflect the project cost-effectively.

The GCCSI (2017) shows that the additional cost of CO₂ capture from power plants has been declining globally since 2005. The PRC's cost distribution across CCUS technology routes is at the top of the global cost range. In the future, the number of CCUS demonstration projects should be further increased. Projects should be shifted from demonstration-oriented to commercial-oriented projects in particular to increase the scale of projects and reasonably define cost boundaries.

Lack of a Carbon Capture, Utilization, and Storage Regulatory and Standard Framework

Formal regulatory or approval process for CCUS projects and the legal liability of CO₂ storage need to be well defined. In the course of CCUS project practice in the PRC, some problems need to be solved, such as unclear ownership, unclear jurisdiction and approval procedures, and lack of relevant technical specifications. There are applicable laws and regulations for reference in all aspects of the whole process of CCUS demonstration projects in the PRC as Table 1 shows. Still, there are no specific laws and regulations, which leads to enterprises' low enthusiasm to carry out CCUS demonstration projects at present. From the point of view of existing policies, the PRC encourages the development of CCUS, but mainly through guidance documents, and does not have dedicated fiscal or taxation support for the development of CCUS. There is also a lack of relevant laws and regulations on site selection, construction, operation, and geological utilization of demonstration projects, as well as environmental risk assessment and monitoring after the closure of storage sites.

Concerns on Environmental Risks

The product captured by CCUS is liquefied CO₂ with high concentration and high pressure. CO₂ leakage risk is very low and in case leakage occurs during transportation, injection, and storage, the ecological environment near the accident will be affected and would endanger personal safety. The geological complexity of CCUS seriously restricts the government and the public's cognition and acceptance of CCUS. In fact, the risk of geological storage is far lower than that of other flammable goods. This needs to consider the whole process and the entire stage of developing an effective plan for site characterization in the CCUS project as well as adopt a rigorous approach in environmental monitoring and risk prevention and control.

In addition to the above, CCUS also faces some ideological issues on application of different aspects of the technology. Few of them are as follows:

- (i) While EOR is an important technology from the perspective of energy security, one of the main concerns against EOR is that while it takes in CO₂, it releases CO₂ back in the form of fossil fuel. So the net advantage to the environment is much less. The technology does not take CO₂ out of the atmosphere completely, although compared with the conventional fossil fuel exploration, the net CO₂ emissions is much less. As a matter of fact, the new energy policy of ADB approved in September 2021 has specifically mentioned that it will support CCUS but, not enhanced oil recovery.²
- (ii) While implementing EOR and sealed storage projects, care should be taken to ensure stable geological storage (such as CO₂ mineralization in underground rock formations, etc.). A review of these geological

² Asian Development Bank. 2021. *Energy Policy Supporting Low-Carbon Transition in Asia and the Pacific*. <https://www.adb.org/sites/default/files/institutional-document/737086/energy-policy-r-paper.pdf>.

aspects should be carried out during the implementation of this road map, along with any other such emerging CCS/CCUS technologies.

- (iii) Direct air capture is one more technology wherein CO₂ is removed from the air and sequestered or used to make a product like fuel or concrete. Currently, direct air capture is estimated to cost \$94 to \$232 per ton of CO₂ captured (Temple 2021). This technology may be employed once it is cheaper or when all the point sources are dealt with.
- (iii) One more concern expressed in the case of amine-based CO₂ capture is the possible leakage of solvent in the atmosphere.

Lack of Public Awareness

At present, CCS technology is still a novel term for most of the public in the PRC. It is necessary to raise awareness through the introduction and promotion of some successful cases at home and abroad, to reduce the public's concern about the risk of CO₂ leakage, consolidate public support for CCS technology, and prepare for later development of the CCS technology.

Lack of a Well-Developed Evaluation System

Many aspects of CCS technology need to be evaluated. For example, the location of CO₂ geological storage needs to be decided based on the existing evaluation system for the overall assessment.

Gap in Some Core Technical Knowledge

The development of CCUS in the PRC needs to overcome key technicalities to reduce the cost of CCUS deployment and prove the safety of CO₂ storage. There are gaps in some core technical knowledge, including second-generation capture technology, pipeline transmission technology, CO₂ high-efficiency oil drive technology, geological storage, and safety monitoring technology and equipment.

Unbalanced Development of Existing Carbon Capture, Utilization, and Storage Technology Chain

In regard to the CCUS technology chain, the development of utilization and storage of CO₂ is not enough and did not form a market demand for CO₂. In the North American region, which has developed well in CCUS, the long-term development of CO₂-EOR has formed the demand for CO₂. In the PRC, because the development of CO₂-EOR and storage has not yet formed a stable demand for CO₂, the capture end on the one hand to promote the enthusiasm is not enough, and even if capture projects are developed, they are often small scale.

3 Carbon Capture, Utilization, and Storage is a Key Carbon Dioxide Emission Reduction Technology in the People's Republic of China

Carbon Dioxide Emissions of Major Industries in the People's Republic of China

Energy and Industry-Related Carbon Dioxide Emissions in the People's Republic of China

The PRC's energy and industry-related CO₂ emissions are enormous, and the pressure to reduce CO₂ emissions increases. For the PRC, the total primary energy consumption in 2019 was 4.86 billion tons of coal equivalent (tce), with a rise of 3.3% over the previous year. The coal consumption increased by 1.0% compared with that of the previous year, but its share of the overall primary energy consumption was 57.7%. The contribution of coal in the overall primary energy consumption mix was 1.5% below that of the previous year (National Bureau of Statistics 2020). The long-term existence of the PRC's coal-based energy structure in the future highlights the importance of CCUS technology. Also, oil and gas will take a significant share of primary energy consumption in the country in the future. The corresponding energy-related CO₂ emissions need to be substantially reduced.

In 2019, the PRC's industrial end-user primary energy consumption was 42.89 million terajoules, accounting for 48.94% of the total terminal energy consumption; industrial energy consumption mainly resulted from six high energy-consuming industries, including electricity, steel, cement, petrochemical, chemical industry, and nonferrous metals. In 2017, the six high energy-consuming industries accounted for 75.1% of the total industrial primary energy consumption.

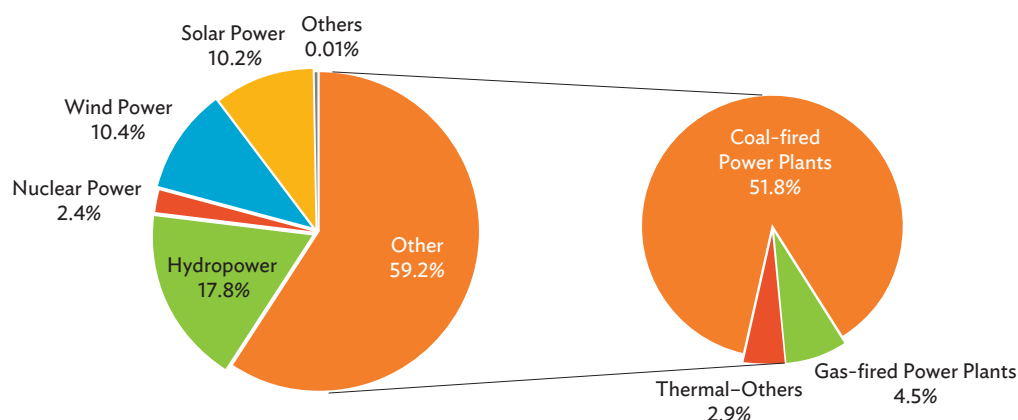
In 2019, the PRC's total CO₂ emissions were 9.88 billion tons, accounting for 29.39% of the total CO₂ emissions in the world (about 33.622 billion tons of CO₂e). About 9.876 billion tons of CO₂ emissions from energy activities remain the largest source of CO₂ emissions in the PRC.³

Power Sector

In 2019, the CO₂ emissions of the PRC's thermal power industry were 4.23 billion tons.

As of the end of 2019, the PRC's full-caliber installed capacity of power generation is 2,010 gigawatts (GW). Among them, hydropower 358 GW, accounting for 17.8%; thermal power 1,190 GW, accounting for 59.2%; nuclear power 48.74 GW, accounting for 2.4%; grid-connected wind power 210 GW, accounting for 10.4%; grid-connected solar power generation 200 GW, accounting for 10.2%. In thermal power, coal-fired power generation 1,040 GW, accounting for 51.8% of the total installed power generation; gas-fired power generated 90.24 GW, accounting for 4.5% of the total installed power generation (Figure 1).

³ International Energy Agency. *Data & Statistics* (accessed 30 August 2021).

Figure 1: Power Generation Installed Capacities by Fuel in the People's Republic of China

Source: China Electricity Council. Briefing of power industry operation in May 2020.

In 2019, the PRC's full-caliber power generation reached 7,326.6 terawatt-hours (TWh), increasing 4.7% over the previous year. Of this, thermal power generation was 5,046,500 gigawatt-hours (GWh), which increased 2.5% from a year earlier. In thermal power generation, coal-fired power generation was 4,553,800 GWh, 1.6% over the previous year, and gas-fired power generation was 232,500 GWh, 7.9% from a year earlier (CEC 2020).

Iron and Steel Sector

The steel industry is one of the primary industrial sources of CO₂ emissions in the PRC. The country's iron and steel industry emitted about 1.399 billion–2.057 billion tCO₂ in 2014, accounting for 15%–22% of the total carbon emissions in the PRC (Qingshi, Yongjie, and Guojun 2017). The CO₂ emissions of the steel industry accounted for 15% of the PRC's total emissions in 2017 (Menglan 2017). Therefore, controlling CO₂ emissions of the steel industry is essential to achieve the greenhouse gas emission targets.

The PRC's steel industry has made significant progress in energy savings until 2005, which has reduced air pollution and reduced CO₂ emissions. However, this downward trend tends to be flat after 2000 (Yin, Lianshui, and Ning 2011). Currently, the CO₂ emission intensity of the PRC's steel industry is around 2 tCO₂/t of steel. Studies have shown that the CO₂ emission density of some steel plants can be as low as 1.5, such as Shanxi Taigang Stainless Steel Co. Ltd., Sansteel Minguang Co. Ltd. Fujian, etc. (Ganggang 2018). Although the emission intensity is stable, for the annual increase in steel production, carbon emissions also increase, such as crude steel production reached 1,065 million tons in 2020, which resulted in about 2.1 billion tons of carbon emissions in the steel industry.

According to the development of domestic per-ton steel emission level, domestic steel industry technology level, and other international steel industry situations, the emission level per ton of steel for the long process should be maintained around 2 tCO₂/t in the short and medium term. In the long-term steel production capacity, the proportion of new processes will increase in recent years.

The total carbon emissions of the steel industry is mainly affected by the steel production, and the changing trend is close to that of the steel production.

Cement Sector

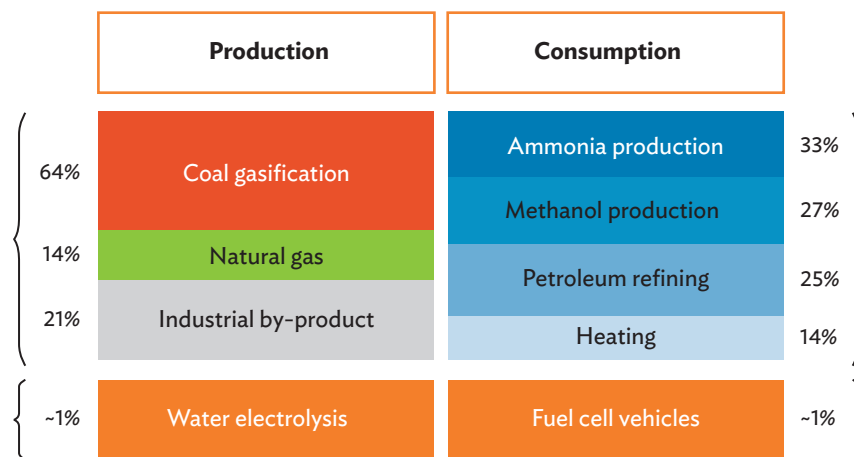
According to the latest data released by the International Energy Agency (IEA), the total global CO₂ emissions in 2019 has reached 33.621 billion tons, and the CO₂ emissions of the cement industry accounts for about 7.0%–7.3% of total emissions (IEA 2021). The CO₂ emissions of the cement industry mainly includes energy consumption emissions and industrial process emissions. Energy consumption emissions include direct emissions caused by fossil fuel combustion and indirect emissions caused by power consumption, while the cement industrial process emissions refer to emissions generated by carbonate decomposition in the cement clinker production process.

The output of cement and energy consumption per unit product are the two main factors affecting the CO₂ emissions of the cement industry. The judgment of the inflection point is concentrated in 2015–2020, when the inflection point occurs, the per capita cumulative cement consumption is 16–22 tons, and the annual per capita consumption is 1.5–2 tons.

Hydrogen Production Sector

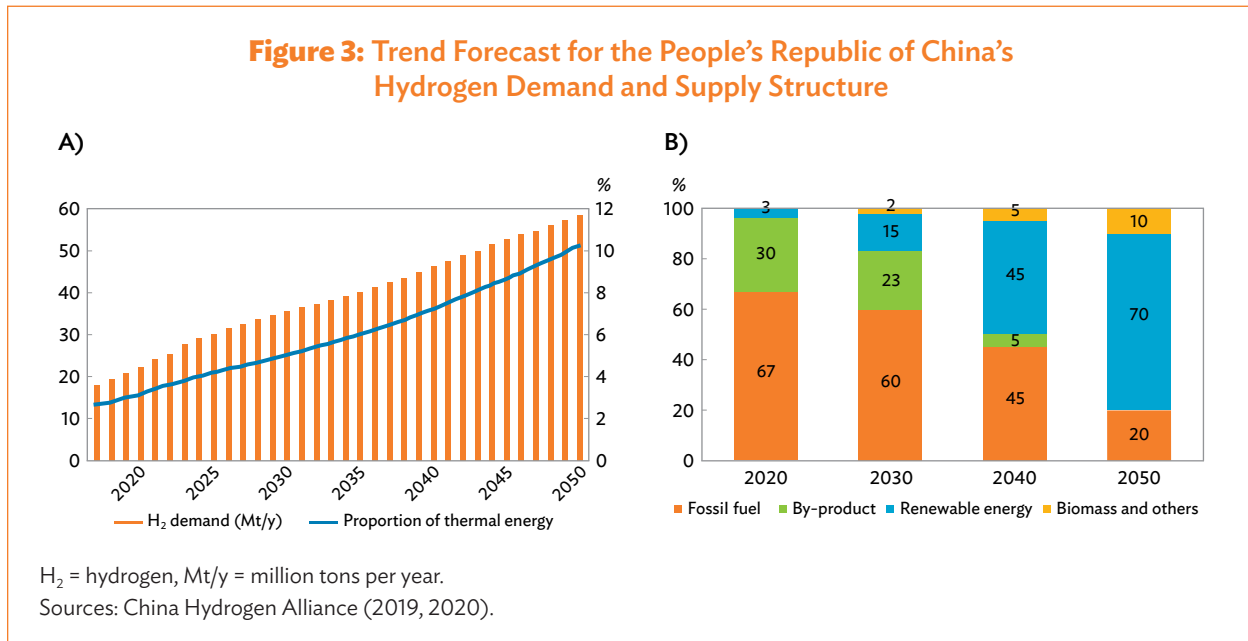
The PRC is the world's largest hydrogen producer, with more than 25 million tons of hydrogen gas produced each year, accounting for about one-third of the world's production volume. As Figure 2 shows, coal is the main raw material for industrial hydrogen production in the PRC, accounting for up to 64%, which is in line with the country's resource structure characteristics of using large amounts of coal. Natural gas takes second place in hydrogen production, about 14%. The remainder is mainly industrial by-product hydrogen, while hydrogen produced via electrolysis by renewable energy is less than 1%, nearly 2 million tons per year. Therefore, the total amount of high carbon-hydrogen is about 23 million tons per year. Around 2050, as the scale of renewable energy continues to grow, hydrogen production from renewable energy is expected to become the main source of hydrogen supply in the PRC. At present, the country's hydrogen is mainly used for ammonia and methanol production, as well as petroleum refining. The hydrogen consumption for ammonia production accounts for about 33%; methanol production accounts for about 27%, and consumption in the petroleum refining process accounts for about 25%; the consumption in the transportation sector is less than 1%, but the transportation sector will have vast application in the following decade.

Figure 2: Hydrogen Production and Consumption Status in the People's Republic of China



Sources: China Hydrogen Alliance (2019, 2020).

As Figure 3 shows, at the initial stage of the PRC's hydrogen energy market, from 2020 to 2025, the annual demand for hydrogen will be about 22 million tons (China Hydrogen Alliance 2019, 2020). The fuel increase will be limited, and the cost of industrial by-product (chlor-alkali, propane dehydrogenation, etc.) hydrogen will become much cheaper. It will become the main body of hydrogen supply. Some regions will accelerate the demonstrations of renewable energy hydrogen production projects.



In the midterm development of the hydrogen energy market, around 2030, the average annual demand for hydrogen is about 35 million tons. Coal gasification for hydrogen production combined with CCS technology, renewable energy electrolysis for hydrogen production will become the main hydrogen supply, and new technologies such as biomass hydrogen production and solar water splitting for hydrogen production are under this demonstration. Green hydrogen will provide up to 17% of the hydrogen supply, and CCUS demonstration projects will be in their initial stage. Hydrogen can use long-distance and large-scale transportation.

For the long-term development of the hydrogen energy market, around 2050, the average annual demand for hydrogen will be about 60 million tons, and the PRC's energy structure will change from a fossil energy-based to a renewable energy-based structure. The hydrogen production with renewable energy electrolysis and hydrogen produced by coal gasification combined with CCS technology will become the main body of hydrogen supply. Biomass hydrogen production and solar water splitting for hydrogen production technologies have become an effective composition, such that the surplus hydrogen could reach 10 million tons annually for export. Green hydrogen will constitute up to 80% in the hydrogen supply. All CO₂ emissions will be captured and consumed by CCUS to achieve carbon neutrality.

In 2050, hydrogen energy will account for 10% of the PRC's final energy system. By then, the hydrogen demand will be close to 60 million tons annually, which can reduce about 700 million tons of carbon dioxide. The transportation sector consumes 24.58 million tons of hydrogen, accounting for 19% of the energy consumption in this sector; the industrial field consumes 33.7 million tons of hydrogen, and hydrogen consumption in the building sector and other fields is about 1.1 million tons (China Hydrogen Alliance 2019, 2020).

The People's Republic of China's Nationally Determined Contribution, Carbon-Neutrality Goals, and Commitments

On 28 October 2021, the PRC submitted to the United Nations a plan of action titled China's Achievements in Implementing Nationally Determined Contributions and new goals and measures. Based on its prevailing national conditions, its current stage of development, its strategy for sustainable development, and the international responsibilities it bears, the PRC has made a set of commitments it aims to achieve. This set of commitments include

- (i) achieving its peak CO₂ before 2030 and endeavoring to reach carbon neutrality before 2060;
- (ii) lowering CO₂ emissions per unit of gross domestic product to more than 65% from 2005 levels;
- (iii) increasing the share of nonfossil fuels in primary energy consumption to around 25%; and increasing its forest stock by around 6.0 billion cubic meters against the 2005 level; and
- (iv) installing wind and solar power plant with total capacity of 1.2 billion kilowatts at least.

The PRC announced an ambitious climate pledge to achieve carbon neutrality by 2060.⁴ At the Climate Ambition Summit on 12 December 2020, the PRC announced that it will increase its national independent contribution: by 2030, its CO₂ emissions per unit of gross domestic product will drop by more than 65% compared with that in 2005, the proportion of nonfossil energy in primary energy consumption will reach about 25%, the forest stock will increase by 6 billion cubic meters compared with 2005, and the total installed capacity of wind power and solar power will reach over 1.2 billion kilowatts.

Carbon Dioxide Emission Trajectory and Carbon Price in Achieving Carbon Neutrality by 2060

The Carbon Dioxide Emission Trajectory to Achieve Carbon Neutrality in 2060

The energy-related CO₂ emissions trajectories from 2020 to 2060 under the 2060 carbon-neutrality scenario are shown in Figure 4. It is worthwhile mentioning that the 2060 carbon-neutrality scenario reflects the policy recently proposed by the PRC government to achieve the goal of “peaking carbon emissions by 2030” and “reaching carbon neutrality by 2060.”

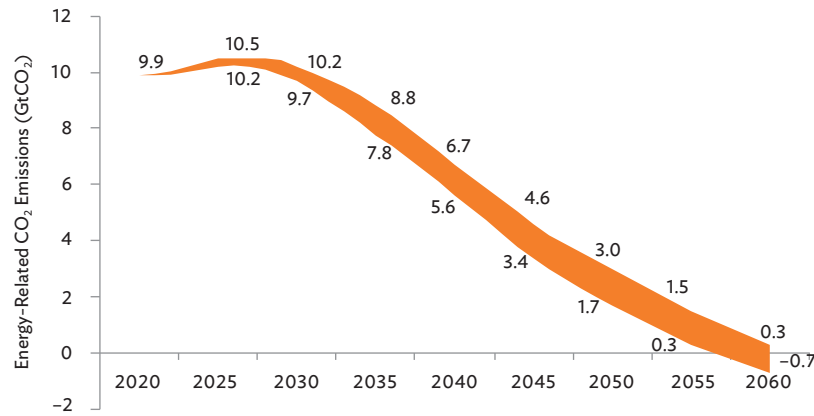
Energy-related CO₂ emissions will peak at around 10.5 gigatons of carbon dioxide (GtCO₂) before 2030 under the 2060 carbon-neutrality scenario. With the development of renewable energy technology, large-scale electrification, improvements in energy efficiency, and other technological breakthroughs, the speed of CO₂ emission reductions will accelerate year by year. CO₂ emissions will decrease from 7.8~8.8 GtCO₂ in 2035 to 1.7~3.0 GtCO₂ in 2050 and finally achieve carbon neutrality by 2060.

The Trajectory of the Carbon Prices

Figure 5 shows the carbon price (analyzed by the authors), reflecting the marginal mitigation cost, under the 2060 carbon-neutrality scenario to achieve deep decarbonization. With the strengthening of the carbon constraints, the carbon price increases from about \$8 in 2020 to \$25~\$33 in 2035 and \$390~\$415 in 2060 under the 2060 carbon-neutrality scenario.

⁴ “China will scale up its intended NDC by adopting more vigorous policies and measures. We aim to have carbon dioxide (CO₂) emissions peak before 2030 and achieve carbon neutrality before 2060,” President Xi Jinping said at the United Nations General Assembly on 22 September 2020.

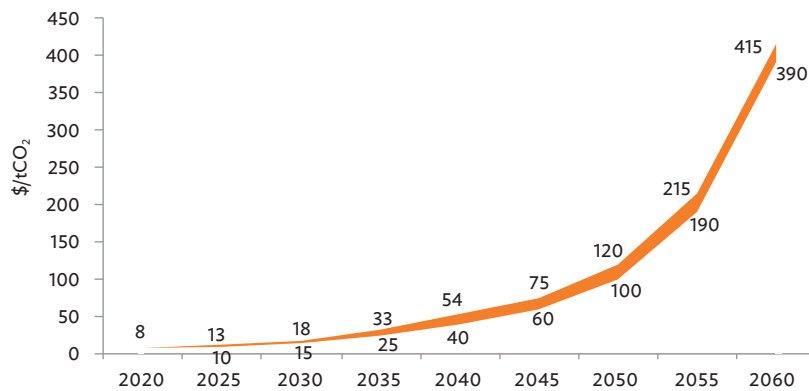
Figure 4: The People's Republic of China's Energy-Related Carbon Dioxide Emission Trajectory



CO₂ = carbon dioxide, GtCO₂ = gigaton of carbon dioxide.

Source: Generated by the authors.

Figure 5: Carbon Price, 2020 (\$/tCO₂)



tCO₂ = ton of carbon dioxide.

Source: Generated by the authors.

Contribution of Carbon Capture, Utilization, and Storage in the People's Republic of China

The Application of Carbon Dioxide Capture Technology in Various Industries

To achieve its carbon neutralization target, the PRC needs to establish a net zero carbon energy system through nonfossil energy, and decouple economic development from carbon emissions. As an important part of the PRC's technology portfolio to achieve carbon neutralization, CCUS technology is the only technical option for low-carbon utilization of fossil energy in the PRC and the main technical means to maintain the flexibility of the

power system, but also a feasible technical scheme for hard-to-abate industries such as iron and steel and cement. In addition, the negative emission technology coupled with CCUS and renewable energy is the technical guarantee to offset the inability to reduce carbon emissions and achieve the goal of carbon neutrality.

CO₂ sources can be divided into high-concentration sources of more than 40% (e.g., coal chemicals, natural gas purification plants) and low-concentration sources (e.g., coal-fired power plants, steel mills, cement plants, etc.).

The PRC's CO₂ capture is mainly concentrated in the coal chemical industry, followed by the thermal power industry. CO₂ capture technology is also gradually implemented in natural gas purification and petrochemical and cement industries. A few projects have been implemented in the thermal power industry, methanol, cement, fertilizer, and other industries. Projects are mainly distributed in eastern PRC and northern PRC.

Coal-Fired Power Plant

There are 10 CO₂ capture demonstration projects in the thermal power industry, with an annual capacity of 450,000 tons of CO₂ captured.

The PRC's post-combustion capture technology is mainly in coal-fired power plants using chemical absorption method to capture CO₂ in the flue gas.

The country's pre-combustion capture technology includes integrated generation of combined cycle (IGCC) and industrial separation. Domestic IGCC projects include the Huaneng Tianjin GreenGen IGCC project and Lianyungang clean energy power system research facilities. The Huaneng Tianjin GreenGen IGCC project was put into operation in November 2012, and its CO₂ capture facility (60,000–100,000 tons of CO₂ per year) was put into operation in 2018.

Up to 14 large-scale demonstration projects are in preparation at different stages, and all of them contain capturing, utilization, storage, etc. full processing.

Coal Chemical Industry

At present, emissions of high concentration CO₂ from the PRC's coal chemical industry is 200 million tons per year. Some coal chemical projects in the PRC adopt CO₂ capture technology, and the captured CO₂ is used or stored. The three domestic low-cost EOR projects (the Zhongyuan oil field, Changqing oil field, and Yanchang oil fields) use CO₂ captured from coal chemical factories.

The largest CCUS project is the CO₂-EOR project in Zhongyuan Oilfield with CO₂ captured from the Xinxiang Xinlianxin Fertilizer Plant in Xinxiang, Henan Province, which amounts to 350,000 tons/year (Cai et al. 2019). CO₂ capture in coal chemical and fertilizer production processes has developed rapidly in the past 5 years, and due to the low cost of building facilities, it has become the mainstream of the PRC's CO₂ utilization market, with a capture capacity of millions of tons.

Cement Industry

In the cement industry, the demonstration production line of CCUS was launched in the PRC. Anhui Conch Group Co. Ltd. in 2018 in the Wuhu Baimashan cement factory built a set of cement kiln flue gas carbon capture purification demonstration line.

Due to the particularity of the cement production process, the concentration of CO₂ produced is less than 20% (generally 18% to 20%), and there are many harmful components brought in by raw materials and fuels.

The composition of flue gas from cement kiln is complex, so it is difficult to capture and purify, and the production cost is relatively high.

At present, the main problem is that if the emission reduction policies required by the state are not implemented, the enterprises have no enthusiasm for emission reduction. Second, most cement plants are far away from the oil field, and there is no place to store CO₂. Therefore, priority should be given to promoting enterprises close to the oil field to carry out CO₂ capture. If there are no coal chemical capture facilities around the cement plant, the CO₂ captured by the cement plant can be sold to the food industry, and there is a way out.

Steel Sector

For the steel sector—one of the most important hard-to-abate sectors for the future—adopting CCS technology is considered an important alternative for the future.

The report Adjustment and Upgrading Plan of Iron and Steel Industry (2016–2020) issued by the Ministry of Industry and Information Technology of the PRC in 2016 also prospectively incorporated CCUS technology into the cutting-edge energy-saving and emission reduction technologies.

In the iron and steel sector of the PRC, CCUS is basically still at the research stage. Some steel plants (e.g., Shougang Jingtang Iron and Steel Co. Ltd.) have carried out a feasibility study of CCUS. But no substantive project has been implemented. Shougang has a pilot project under construction, and the feasibility study of CCS and CO₂ utilization in steelmaking has been carried out (LanzaTech 2018). The commercial chemical plant using the tail gas of the steel plant to produce liquid fuel in the Shougang compound in Caofeidian was successfully put into operation in May 2018. The annual output of 46,000 tons of fuel ethanol is supplied to Sinopec, PetroChina, and Shell in the Hebei and Shandong markets.

Generally, the application conditions of capture technology in the iron and steel industry are not mature. During the 13th FYP, the domestic steel industry is still mainly carrying out the treatment of conventional pollutants (particulate matter, sulfur dioxide [SO₂], nitrogen oxide [NO_x]). CCUS is basically still at the research stage in the steel sector, and some steel plants have carried out the feasibility study of CCUS.

In 2021–2025, a high concentration CO₂ capture demonstration should be carried out on a hot blast stove and rotary kiln of ironmaking.

Hydrogen Production Sector

CCUS technology in the hydrogen production process has also attracted much attention due to its economic attractiveness compared with electrolysis-based green hydrogen. More than 96% of hydrogen produced from fossil fuels and hydrogen from renewable sources will not increase to more than 15% by 2030 (China Hydrogen Alliance 2019).

CCUS will provide an early opportunity to transit to the hydrogen economy. The early availability of hydrogen will ensure that the downstream hydrogen infrastructure is ready by the time electrolysis-based green upstream infrastructure is cost-effective by around 2035 or so. One should emphasize enough the importance of efficient hydrogen production and CO₂ capture. In the PRC, with the established coal mining infrastructure and the lack of cheap domestic natural gas, coal-based hydrogen equipped with CCUS is likely to be, in the short and medium term, the most affordable option for low-carbon hydrogen production.

Box: Carbon Capture in Steel Plants

There are two possible carbon capture methods in steel plants: carbon capture from flue gas or gas (including blast furnace gas, coke oven gas, and converter gas). The concentration and impurity of different flue gas outlets, such as sintering and blast furnace, are not the same, which is slightly higher than that of the power plant. The concentration of carbon dioxide (CO₂) in the flue gas of iron and steel plants ranges from 5% to 30%. However, it is possible to adopt a similar decarburization process to that of power plants.

It can draw on the more mature post-combustion carbon capture technology in the power industry. The advantage is that it does not affect the steel production process, it is easy to promote and use, and can be quickly deployed to achieve carbon emission reduction in a short period. It should be noted that although the desulfurization facility removes the acid gas in the flue gas of the steel plant, it still needs to be further removed to eliminate the adverse effects on the CO₂ absorbent.

The gas of conventional iron and steel plants is mainly blast furnace gas (BFG), coke oven gas, and converter gas (also called basic oxygen furnace gas or Linz-Donawitz converter gas). It is true that CO₂ exists in the three kinds of gas, but it should be mainly from BFG. In the typical long process steel plants in the People's Republic of China (PRC), the magnitudes of the above three types of gas flow are 1 million cubic meters; 100,000 cubic meters; and 10,000 cubic meters. The CO₂ concentration is also the highest in BFG which is 8–10 times of coke oven gas, so if we compare the amount of CO₂ in different gases in the steel industry, the CO₂ of the steel industry mainly exists in BFG.

Absorption method, pressure swing adsorption, vacuum pressure swing adsorption, and other technologies can be used for BFG decarbonization. The use of gas after decarburization also needs to be carefully considered, such that it can be injected into the blast furnace after reprocessing.

At present, the proportion of long process production is too high in the PRC, far higher than the average level of other countries globally. The application of a short process mainly needs scrap resources and low electricity price. Although direct reduced iron can be used in electric furnaces instead of scrap steel, it will not lead to carbon emission reduction. The blast furnace–basic oxygen furnace process is the main process of the PRC's steel industry. For example, in 2020, the PRC's crude steel production of the BF–BOF process accounted for 90.8%, while the world average for the same period was 73.2%. The European Union (28 countries) and the United States were 57.6% and 29.4%. The BOF and electric arc furnace (EAF) processes use iron ore and scrap steel (or direct reduced iron) as raw materials. Due to the lack of scrap steel resources, the BOF process using iron ore as a raw material is the primary steel process in the PRC. The carbon emission intensity of BF–BOF is much higher than EAF, which is about 1.5t CO₂/t steel higher than EAF. Due to the high proportion of the BF–BOF process, the PRC's carbon emission intensity is high, so are that of Japan and the Republic of Korea.

At present, CCUS has been demonstrated in the foreign steel industry, such as the CCS + EOR demonstration project of Iron and Steel Company of the United Arab Emirates. The country bears all the economic and technical risks. The United Arab Emirates is building the first large-scale application of a CCS steel project in the world. CO₂ is captured from the direct reduction iron process and transported to the oil field by pipeline for oil displacement. The Al Reyadah project in the United Arab Emirates is the first fully commercial carbon capture project in the world's iron and steel industry. It started operation in 2016. After being compressed and dehydrated in the Mussafah plant, CO₂ is transported to the Abu Dhabi National Oil Company (ADNOC) onshore at the Habshan oilfield for injection.

^a World Steel Association. 2021. World Steel. Beijing.

^b Energy Transition Commission. 2018. *The Circular Economy: A Powerful Force for Climate Mitigation*. Stockholm.

^c World Steel Association. 2019. *Steel Statistical Yearbook 2019*. Beijing.

^d Sakaria, D. 2017. Review of Project Proposed for CSLF Recognition. Powerpoint presentation for BDM–Abu Dhabi Carbon Capture Company–Al Reyadah. United Arab Emirates. 30 April.

Source: Authors.

Carbon Dioxide Transportation

From the viewpoint of CO₂ transportation, CO₂ truck transport has matured. The PRC's truck transportation cost is currently about CNY1.1~CNY1.4/ton-km (\$0.16~\$0.20/ton-km as in 2020 prices) (Cai et al. 2019).

CO₂ pipeline transportation technology is the most economically viable solution in the country when this kind of technology is applied in large scale. The operation cost of CO₂ transportation through pipelines is low. However, the investment in pipeline infrastructure is quite expensive. Differing from oil and gas transportation, CO₂ must be dried and compressed into a supercritical state before transportation, to avoid pipeline and tank corrosion and reduce the volume of CO₂. The PRC has completed the preliminary design of the 1 million tons/year pipeline project; and it is developing relevant design specifications. The offshore pipeline transmission technology is still in the conceptual research stage. There are no technical barriers to demonstrating supercritical CO₂ pipeline infrastructure.

One of the primary reasons why CO₂ pipeline planning and construction has not started is that the cost of laying pipelines in the PRC is more than several times that of the US. The other reason is that the CCS project cannot afford pipeline investment if it is not profitable. In the case of the pilot CCS projects under implementation in the PRC, the pipeline laying leads to an increase in the costs.

It is worth learning from global experiences. The Saskpower Boundary Dam project is 3.4 km from the aquifer storage site (about 10 km in pipeline length) and about 80 km from the oil pipeline (only 4 km from the 330 km US-Canada CO₂ pipeline, which has rebuilt a 80 km length separate pipeline partly due to the saturation of the pipeline and the different CO₂ concentrations). The Petra Nova pipeline is also about 80 km. The experience that can be learned includes reasonable source and sink matching, appropriate CO₂ transportation distance, and appropriate pipeline construction start time.

The CCUS hub or cluster is considered internationally to be the most important CCUS business model for large-scale emission reduction in the future. The concept of a 3 million tons per year CCUS hub has been put forward in the Xinjiang oil field in the PRC and needs to be further refined to implement the enterprise.

The IEA considers that “the development of CCUS hubs—industrial centers with shared CO₂ transport and storage infrastructure—could play a critical role in accelerating the deployment of CCUS (IEA 2020). CCUS hubs or clusters indicate that in CO₂ high-emission zones, or dense areas of high-emission enterprises, capture, transportation, and storage facilities can be built in accordance with the respective responsibilities of enterprises, and then through the sharing of transport (pipeline), shipping, and geological storage facilities, to achieve the most economical large-scale emission reduction.

Carbon Dioxide Utilization

Recently, CO₂ utilization is taken as a process, extending the source of CO₂ to the fixed CO₂ in a biological process or land process, and has been called unconventional CO₂ utilization. According to this definition and classification, the current mainstream traditional and nontraditional utilization technologies include items, as Table 2 shows.

First, EOR is the direction of national key support and provides a lot of financial support. At the same time, large state-owned enterprises such as PetroChina and Sinopec have relatively high enthusiasm, and in the process of oil and gas industry development, they have accumulated a lot of technical and operational management experience in exploration, reservoir description, simulation, capacity evaluation, drilling and production and water injection, formation monitoring, pipeline equipment, and so on. The knowledge of the reservoir cap system can be directly applied to EOR project location, project operation, and management.

Table 2: Traditional and Nontraditional Carbon Dioxide Utilization Technologies

Traditional Utilization	Nontraditional Utilization
Chemicals	Enhanced weathering
Fuels	Forestry techniques
Microalgae	Land management
Concrete building materials	Biochar
Enhanced oil recovery	

Source: Generated by the authors.

The chemical utilization of CO₂ has made great progress, and more CO₂-use technologies have been incorporated into the CCUS system as a whole due to the pilot phase.

Currently, CO₂ hydrogenation to chemical fuels is the most promising way to consume the abundant CO₂, and the main products (such as carbon monoxide [CO], methane [CH₄], methanol [CH₃OH], and other gaseous or liquid hydrocarbons) are important chemical feedstock and could be used as fuels. In this regard, the products from CO₂ hydrogenation could be good alternatives for the depleting nonrenewable energy source.

In addition to CO₂-EOR, CO₂ is mainly used for CO₂ hydro synthetic methanol (approximately 42%), CO₂ and methane reorganized syngas (31%), CO₂ synthetic methylphthalate (8%), CO₂ synthetic biodegradable polymer material (0.23%), welding, food addition, etc.

At present, the CCUS demonstration projects carried out in the PRC focus on CO₂ capture in the chemical industry and CO₂-EOR utilization. Among them, the extension of the petroleum CCUS integration project and the cooperation between universities and research institutions play an essential role in demonstration in the PRC. CO₂ utilization plays an important role in guiding and demonstrating the success of CCUS commercialization.

Carbon Dioxide Storage

The PRC has completed the national assessment of the theoretical storage potential of CO₂. The total theoretical capacity of onshore geological utilization and storage technology is 1.21 trillion~4.13 trillion tons. The potential of CCUS emission reduction in the PRC is vast, and the theoretical storage potential of CO₂ geological storage is huge. The theoretical storage potential of the deep saline aquifer layer alone is more than 2.42 trillion tons (Cai et al. 2021).

The PRC's CO₂ storage technology is still in the R&D or small-scale demonstration stage. Deep saline aquifers have the largest potential storage capacity for CO₂. However, CO₂ geological utilization technology is relatively mature. CO₂-EOR has been applied to improve oil recovery in a number of demonstration projects. The projects are mainly around several oil and gas basins, including the Songliao Basin in northeast PRC, the Bohai Bay Basin in north PRC, and the northwest Ordos and Junggar Basin.

CO₂-EOR effect in the country is still low and not stable, making oil and gas companies hesitant to buy CO₂ and implement commercial-scale CO₂ storage projects. There is still a large gap with the advanced international level, mainly because the CO₂-EOR technology is not widely used and due to the country's complex reservoir characteristics. Those reservoirs that meet the requirements of CO₂ miscible flooding, which has higher efficiency than immiscible oil flooding, need to be developed first.

The enthusiasm of enterprises is high, which is the driving force of CO₂-EOR development. It is necessary to expand the low-cost CO₂ capture source-based further EOR demonstration area, giving priority to the selection of miscible and near miscible oil reservoirs for CO₂ injection experiments; improve the monitoring and verification technology supporting oil recovery; and gradually realize the large-scale production and demonstration of CO₂-EOR.

Refer to Annex 2 for more details on this section.

Development Trend

A phased approach to CCUS technology development and demonstration is needed.

- (i) First, targeting low-cost CCUS applications in refineries, coal-chemical plants, and natural gas purification plants with CO₂-EOR can prove the feasibility of the CO₂ off-take arrangement and provide much-needed confidence in the CCS application.
- (ii) Second, when oil and gas companies reach the capacity to use million tons of CO₂-EOR and CO₂ storage, investment may gradually transfer into the power sector and low CO₂ concentration sources. Of course, intensive R&D activities, including limited CCUS application in coal-based power plants, cement, steel plants, and hydrogen production with saline aquifer storage nearby, could bring down the capture costs and provide new insights and experiences. This will stimulate further research to drive down the CO₂ capture costs.

This dual-track approach of accelerated demonstration and more intensified R&D of capture technologies until 2025 can pave the way for wider deployment of cost-competitive CCS from 2030 onward.

4 Carbon Capture, Utilization, and Storage Development Outlook

Carbon Dioxide Capture Outlook by Sector

Power Sector

The key period of CCUS technology transformation in the PRC's coal-fired power plants is around 2030. From the perspective of intergenerational technology, the second-generation capture technology with low-energy consumption can greatly improve the economy of CCUS technology, but the commercialization time of the second-generation capture technology is too late, which may lead to the risk that the first-generation capture technology locks in the PRC's coal-fired power plants. The study finds that 2025–2035 can be the best window period for the commercial deployment of CCUS technology (Fan et al. 2018).

With the progress and large-scale development of carbon capture technology, carbon capture's cost and energy consumption in the future thermal power industry will show a downward trend. The related forecast data are shown in Table 3.

Table 3: Projections of the Carbon Dioxide Mitigation Cost of Key Carbon Capture, Utilization, and Storage Technologies

Technologies	Costs and Energy Consumption	2025	2030	2035	2040	2050/2060
Pre-combustion capture	Costs (CNY/tCO ₂)	160~210	130~190	110~170	90~150	70~130
	Efficiency Loss (%)	6~9	6~8	5~7	4~7	3~7
Post-combustion capture	Costs (CNY/tCO ₂)	230~330	190~250	160~200	150~180	120~150
	Efficiency Loss (%)	7~12	7~11	7~10	6~9	5~8
Oxy-fuel combustion capture	Costs (CNY/tCO ₂)	230~310	210~280	160~210	130~180	90~150
	Efficiency Loss (%)	7~10	7~9	6~9	6~8	5~7

tCO₂ = ton of carbon dioxide.

Note: \$1 = CNY6.5.

Source: Administrative Center for China's Agenda 21 (2019).

The deployment and application progress of CCUS technology in the thermal power industry will be uncertain, mainly depending on the following aspects. The first is the sustained and effective support policies and degree of CCUS technology cost decline. Second, its cost competitiveness with other low-carbon technologies (such as nuclear and renewables). The third is the additional income generated in the process of CO₂ utilization.

The PRC has currently deployed CCUS demonstration projects in coal-fired power plants to generate about 450,000 tons of CO₂ emission reduction capacity per year (Annex 1). The CCUS project, which should be built and put into operation during the 14th FYP period, is expected to form a CO₂ emission reduction capacity of about 7 million tons of CO₂ per year. Considering the ambitious plan to replace fossil fuel power with renewable energy

and referring to the results of other relevant studies, the authors forecast the development paths of deployment and application of CCUS technology for CO₂ emission reduction in different thermal power industry stages in the PRC as follows.

By 2030, the cumulative CO₂ emission reduction capacity of the thermal power industry will reach about 10 million–50 million tons of CO₂ emission reduction per year through the implementation of CCUS demonstration projects.

Between 2031–2040 is the most favorable period for large-scale deployment of CCUS technology in the thermal power industry. Because more than half of the coal-fired generating units in service in the country were built between 2005 and 2015, according to the operating life of about 30 years, the existing units will be replaced at a peak during this period, which is conducive to large-scale deployment and application of CCUS technology with the opportunity of unit retrofit. At the same time, the second-generation CCUS technology with low-cost and low-energy consumption will become more and more mature and industrialized in this stage. It will lead to a significant reduction in the overall cost and energy consumption of CCUS technology and greatly enhance CCUS technology competitiveness compared with other CO₂ emission reduction technologies. It is expected that by 2040, the cumulative CO₂ emission reduction capacity of the thermal power industry through the implementation of CCUS projects will reach 366 million tons per year. By then, the penetration rate of CCUS technology in thermal power plants will reach about 48%.

In 2050, in the face of more stringent CO₂ emission constraints, CCUS technology will become the main choice for the thermal power industry to reduce CO₂ emissions. The authors expect that the thermal power industry's cumulative CO₂ emission reduction capacity will reach 550 million tons per year through the implementation of CCUS projects. By then, the penetration rate of CCUS technology in thermal power plants will reach nearly 100%.

By 2060, the capture capacity of CO₂ capture devices installed in thermal power plants will mostly keep stable. It is predicted that the annual CO₂ capture capacity will be 600 million tons, and all coal-fired power plants and gas-fired power plants in service will be equipped with CO₂ capture devices.

Coal Chemical Industry

Coal chemical industry should closely integrate CCUS technology to achieve low-carbon transformation. As the coal chemical industry's development strategic positioning is not clear, especially under the carbon peak and carbon-neutrality target. Strategic positioning of the coal chemical industry has brought new uncertainty, which has led to policy uncertainty. In this sense, the coal chemical industry must integrate CCUS technology to achieve low-carbon transformation, solve the characteristics of high carbon emissions, and gradually clarify its position and development direction under the vision of carbon neutrality.

The PRC should make full use of the advantage of high concentration of CO₂ by-product in the coal-based energy chemical process and actively develop CCUS technology. From the perspective of CCUS development strategy, we are currently facing the pressure of high cost. In the cost composition of CCUS, the capture cost occupies a relatively high proportion. However, coal chemical and other projects have high flue gas CO₂ concentration and low capture cost, which is of great significance to solve the cost reduction in the development of CCUS. Unconventional means should be used to deploy efficient CCUS, CO₂ flooding, CO₂ to olefin and other cutting-edge CCUS technology R&D, to expand CO₂ utilization.

At present, the high-concentration CO₂ emitted by the coal chemical industry in the PRC is 200 million tons/year, which should not be increased in the future. Therefore, it should capture 200 million tons by 2050. It is also possible that the coal chemical industry will go bankrupt early without such high emissions. The cost of CO₂ capture is predicted as follows:

- (i) 2020–2025: high-concentration CO₂ capture in the coal chemical industry, strive to achieve the wellhead price of CNY400/ton by 2020–2025, that is, by the end of the 14th FYP.
- (ii) 2025–2030: the price of high concentration CO₂ capture in the coal chemical industry would reach CNY350/ton from 2025 to 2030.
- (iii) 2030–2060: the price of high concentration CO₂ capture in the coal chemical industry would reach CNY250/ton in 2030–2050.

Steel Sector

During the 14th FYP period, the PRC's steel industry will conduct more extensive R&D and pilot tests on blast furnace gas (BFG) decarbonization and flue gas decarbonization. Most steel plants are more likely to achieve CO₂ emission control by improving energy efficiency and strengthening waste heat and energy recovery, and a few steel plants may deploy CCUS demonstration projects. On cost, many of the capture sources of steel plants have higher CO₂ concentrations than the flue gas of power plants, and steel plants have a lot of waste heat resources. These factors will reduce the cost of carbon capture. Based on the operating costs of CCUS pilot and demonstration projects in the international steel industry, considering the technological improvements, it is predicted that the carbon capture cost at this stage will be \$40–\$50/tCO₂. When not including the cost of waste heat in the steel plant, it can be reduced by \$10–\$15 /tCO₂.

On technology, with reference to the Opinions on Promoting the Implementation of Ultra-Low Emissions in the Steel Industry issued by the Government of the PRC, the PRC's steel industry is still mainly concerned about the emission control of conventional pollutants before 2025, even for a longer time (MEE Unpublished). At this stage, it is unlikely to implement CCUS demonstration and industrialization on a large scale. The PRC's steel industry will conduct more extensive R&D and pilot tests on BFG decarbonization and flue gas decarbonization, as well as a few demonstration projects. Considering factors such as the operation of the national carbon trading market, the technological progress of reducing gas utilization in blast furnace and the chemical utilization of gas, a small number of demonstration projects may occur in the BFG pressure swing adsorption decarbonization. With the development of CCUS in other industries and guaranteed stable and cheap sources of CO₂, it is possible to have demonstration projects of CO₂ utilization in the solid waste treatment of steel slag and other solid waste in the steel industry.

During 2026–2030, the estimated amount of CO₂ emission reduction will be about 2 million~10 million tons per year. It is estimated that the steel production capacity of CCUS deployment will not exceed 5% by 2030.

Applicability research and pilot tests of the second-generation CO₂ capture technology in the steel industry will be promoted. Second-generation CO₂ capture technology, when mature, can reduce energy consumption and costs by more than 30% compared with mature first-generation technologies. The second-generation CO₂ capture technology includes new membrane separation technology, new absorption technology, pressurized oxy-fuel combustion technology, and chemical looping combustion technology (MOST 2019).

The CO₂ transportation pipe network constructed by other industries should have a CO₂ transportation interface for the steel industry. Deployment of 10–20 CO₂ carbon capture projects of BFG and flue gas are expected to include 2 million~10 million tons of steel production capacity with a capture cost of \$25–\$40/tCO₂. Benefiting from the technology development of using reducing gas for blast furnaces, blast furnace oxygen blowing, HISARNA smelting reduction (Junjie 2017) and other technologies, the CO₂ concentration in coal gas will be greatly increased so that capture cost will be further reduced. With the government's increasingly stringent control on carbon emission reduction, the development of CCUS in other industries has established a shared CO₂ pipeline network. It is possible to carry out carbon capture demonstrations for high-concentration CO₂ flue gas such as hot blast stoves and lime kilns.

On policy, it is imperative to establish a long-term mechanism to ensure that the steel industry can continue to receive financial subsidies for carbon emission reduction. It is also important to adjust the carbon emission measurement standards in the steel industry in the carbon trading mechanism, such as appropriately adjusting the indirect emission calculation weights to promote the steel industry to reduce coal consumption and shift toward the use of electricity in steelmaking.

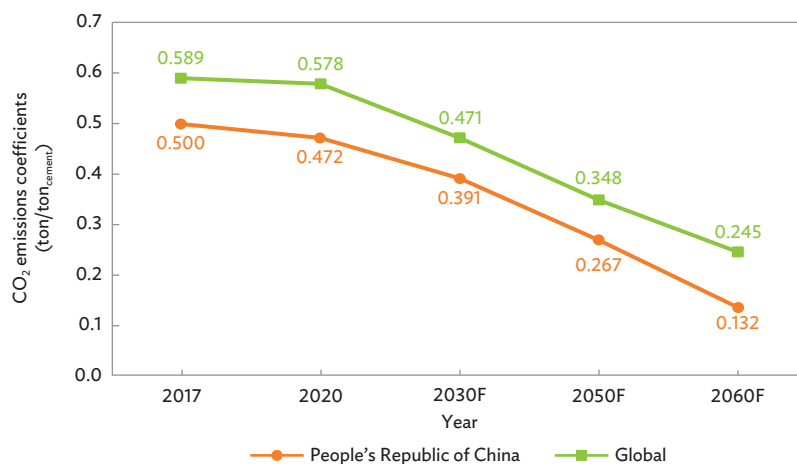
In the long term (2030–2060), the estimated CO₂ emission reduction will be about 90 million~290 million tons per year. It is estimated that the steel production capacity of CCUS deployment will exceed 30% by 2060. The second-generation CO₂ capture technology is mature and deployed on a large scale in the steel industry. Deployment of more than 100 CO₂ carbon capture projects of BFG and flue gas are expected, which will include 90 million~290 million tons of steel production capacity with a capture cost lower than \$20/tCO₂. With the advancement and maturity of capture technology, more projects will be deployed, and the scaling-up effect will lead to a decrease in design and equipment prices, and the carbon capture cost is expected to be further reduced. In the steel industry at home and abroad, the industrial application of flue gas and gas decarbonization increases. There is a need to promote the standardized design, complete equipment manufacturing, and specialized third-party operations to reduce investment and operating costs significantly.

Cement Industry

At present, the cement demand in the PRC has reached a high plateau from 2014 to 2020. After 2020, cement consumption in the country began to decline year by year, mainly because the infrastructure construction has matured. The demand for cement has not particularly increased. With the progress of society and the development of science and technology, new building materials will continue to emerge, and more substitutes for cement will inevitably be available. It is predicted that cement production will decline year by year after 2022, and it will reach a more significant decline after 2035, to 2060 and beyond.

With the improvement of the PRC's cement production technology and adoption of energy efficiency measures, the intensity of CO₂ emissions will become increasingly lower (Figure 6) (Gao 2019). The application of CCS technology in the cement industry in the future is expected mainly to capture the direct emissions from

Figure 6: The Amount of Carbon Dioxide Emitted per Ton of Cement Produced Each Year



CO₂ = carbon dioxide, F = fiscal.
Source: Gao (2019).

large-scale and high-efficiency new dry-process cement processes, such as the use of large-scale production lines with a scale of more than 4,000 tons per day (t/d). In the PRC, a capture demonstration in Anhui Baima Conch Cement Factory has already been implemented in October 2018.

As Table 4 shows, it is predicted that by 2021 and 2050, the world cement industry's CO₂ emissions per ton of cement will be 0.578 tons and 0.348 tons, respectively, a reduction of 39.8% in 2050 compared with that of 2021. In the PRC, these figures will be 0.472 tons for 2021 and 0.267 tons for 2050, a corresponding reduction of 43.4% in 2050 compared with 2021. It can be seen that this indicator in the PRC in 2060 should be much more advanced than that of the world average, mainly due to the development and application of CCS technology.

Table 4: Cement Production, Carbon Dioxide Emissions, and Forecast in the People's Republic of China, 2010–2060

Year	Cement Production (million tons/year)	CO ₂ Emissions from the Cement Industry (million tons/year)
2010	1,860	960
2011	2,060	998
2015	2,350	1,130
2020	2,250	1,080
2030 (Prediction)	1,600	690
2050 (Prediction)	850	230
2060 (Prediction)	800	210

CO₂ = carbon dioxide.

Source: Shi and Wang (2010).

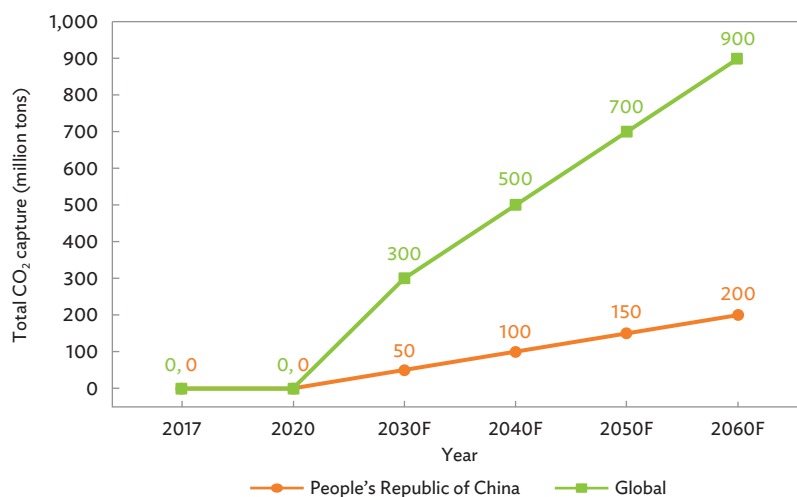
It is possible to carry out CCUS demonstrations for high-concentration CO₂ flue gas such as BFG from hot blast stoves and flue gas from lime kilns from 2021 to 2025. BFG decarbonization may shift from demonstration to industrialization at the same time.

According to predictions, in 2030, the world's cement industry will capture 300 million tons of CO₂, and the PRC will capture 5 million–10 million tons of CO₂ annually. In 2060, the world's cement industry will capture 900 million tons of CO₂ per year, and the PRC will capture 150 million–200 million tons of CO₂ per year. Both of them will start large-scale commercial operations after 2025, but the PRC has developed more rapidly, and the CO₂ capture will be widely used (Figure 7).

Hydrogen Production Sector

Although green hydrogen production and consumption should undoubtedly be a long-term goal, there must be a role for blue hydrogen as an enabler of a future hydrogen economy. CCUS is becoming more viable and could be a great accelerator for the expansion of blue hydrogen (IEA 2020).

Under the PRC's current climate policy and economic development (China Hydrogen Alliance 2019, 2020), low-carbon hydrogen will be around 5 million tons (Mt) between 2020 and 2025. With the application of hydrogen production from renewable energy combined with CCUS, low-carbon hydrogen production will reach 15 Mt around 2030. With the widespread application of CCUS technology in the hydrogen production industry, the output of low-carbon hydrogen will reach 57 Mt by about 2050.

Figure 7: Prediction of Trend Total Carbon Dioxide Capture in the Cement Industry Each Year

CO₂ = carbon dioxide, F = fiscal.

Source: Generated by the authors.

In the short term, CCUS is mainly applied in the coal-to-hydrogen industry, and the biomass hydrogen production industry will be dominant in the mid and long term around 2050. Currently, the total capture cost of CO₂ (including operating cost and capital cost) is around CNY180– CNY 250/t. The price will be reduced from about CNY100/t around 2035 to about CNY60/t around 2050. About 0.5~2, 10~80, and 40~100 Mt of CO₂ are estimated to be captured from the hydrogen production sector in 2030, 2050, and 2060, respectively, where more than about 60% of the CO₂ will be used for EOR.

Carbon Dioxide Utilization

CO₂ utilization could also act as a driver of technology learning and acceptance of CCUS. For example, the implementation of CO₂-EOR combined with measuring, monitoring, and verification can provide a technical experience that storage could use (GCCSI 2011). The deployment of CO₂-EOR will accelerate the clarification of the geological detail of the storage reservoir, enhance understanding of the CO₂ capture and transportation, and influence factors for CCUS development.

The projection of CO₂ utilization development is shown in Tables 5 through 8.

Table 5: Projection of Carbon Dioxide Utilization Development—Energy Recovery

		2025	2030	2050
Energy Recovery	Phase	Demonstration	Pre-commercial application	Commercialization
	Target scale, Mtpa	3.50+	>7	>55
Enhanced Oil Recovery	Target	Complete industrial demonstration of 1 million tons	Complete industrial demonstration of million tons of different types of reservoirs	Commercialization

Mtpa = million tons per year.

Source: Generated by the authors.

Table 6: Projection of Carbon Dioxide Utilization Development—Chemicals

		2025	2030	2050
Chemicals	Phase	Verify technical feasibility	Demonstration	Commercial application
	Target scale (10,000 t/a)	100	>400	>1,000
Syngas	Target (10,000 t/a)	20	50	200
Synthesis of methanol	Target (10,000 t/a)	40	100	500
Synthetic degradable polymer material	Target (10,000 t/a)	15	40	100

t/a = ton of carbon dioxide per year.

Source: Generated by the authors.

Table 7: Projection of Carbon Dioxide Utilization Development—Carbonated Materials

		2025	2030	2050
Mineralization and utilization of steel slag	Target (10,000 t/a)	50	200	1,500
Mineralization and utilization of phosphogypsum	Target (10,000 t/a)	30	100	500

t/a = ton of carbon dioxide per year.

Source: Generated by the authors.

Table 8: Projection of Carbon Dioxide Utilization Development—Microalgae

		2025	2030	2050
Microalgae	Stage	Verify technical feasibility	Pilot and demo	Commercial application
	Target	Kiloton pilot	10,000 ton scale demonstration	Commercialization

Source: Generated by the authors.

Capture and Storage Scale Outlook

CCUS technology carbon reduction will be significantly enhanced with more policy and investment support. The scale targets for the phased implementation of CCS technologies in the PRC during the 14th FYP period and beyond are proposed (Table 9).

During 2021–2025 (14th FYP period), it is proposed to carry out 5–10 CCUS demonstrations in the field of natural gas purification and coal chemical industry; 1–3 projects in the field of thermal power, cement, steel, and hydrogen production; and that the annual amount of CO₂ storage and geological utilization would reach 2–40 Mt by 2025, while increasing the production of 0.5–10 Mt of crude oil (EOR ratio is considered as 4 t_{CO₂}/t_{oil}) (Kuuskraa and Wallace 2014).

In 2025–2035 (medium term), the cost of carbon capture technology for second-generation coal-fired power plants will be significantly reduced, and commercial deployment in the natural gas purification and coal chemical industries will be achieved while entering a demonstration phase of widespread rollout. The annual amount of CO₂ storage and geological utilization would reach about 90–600 Mt by 2035.

Table 9: Projection of Carbon Capture and Storage Development Plan (Mtpa)

	2025	2030	2035	2050	2060
Total	2~40	30~120	90~600	850~2500	1300~2600
Coal power CCS	0.1~20	10~50	50~200	500~1000	500~1000
Gas power CCS	0~10	0~20	0~60	40~350	40~350
BECCS	0~0.1	0~0.1	0.1~20	100~500	300~700
Iron and steel CCS	0.1~5	2~10	10~20	50~210	90~290
Coal-chemical CCS	1~5	5~35	10~50	100~200	100~200
Cement CCS	0.1~2	5~10	10~80	10~150	150~200
H ₂ production CCS	0.1~1	0.5~2	2~10	10~80	40~100
DACCS	0	0	0~1	1~100	30~300

BECCS = bioenergy with carbon capture and storage, DACCS = direct air carbon capture and storage, CCS = carbon capture and storage, Mtpa = million tons per year.

Source: Generated by the authors.

Commercial deployment in the natural gas purification process, coal-chemical industry, and demonstration phase for wider CCS application will be achieved.

Planned large-scale coal-fired power plants in Shaanxi, Ningxia, Inner Mongolia, Guangdong, Xinjiang, among other regions, will be constructed CCS-ready, where there will be a larger contribution of second-generation technologies to the cost reduction curve in coal-fired power plants.

If the government supports the development and demonstration of carbon capture technology in the cement industry, several CCS industrial demonstration projects may be built in the PRC during 2020–2030.

After 2035, the decrease in capture costs would be accompanied by a rise in the carbon price to a certain level, triggering large-scale CCS applications. The annual amount of CO₂ storage and geological utilization would reach about 1,300 billion~2,600 billion tons by 2060.

The second-generation technologies will make a large contribution to the cost reduction in coal-fired power plants, cement, iron and steel plants, and hydrogen production. Capture cost reduction and carbon price reach a level to trigger a wider application of CCS.

Transport Technology Outlook

A cost-effective CO₂ transport system will connect large emission sources to the storage site so that CO₂ storage can be undertaken at a lower cost. Truck lines will provide an opportunity for small emission sources to capture CO₂. As such, it is also critical for the CCS deployment that the emission source must be close to the storage site. Then the cost of CO₂ transport will be greatly reduced, as well as the cost of the whole CCS project. Caution should be paid in designing and constructing long-distance supercritical CO₂ transport pipeline without confidence in large-scale CO₂ storage capacity and significant demand for CO₂-EOR.

At the current CO₂ injection scale, gaseous phase pipelines are possible to be built during 2020–2025. When the CO₂ injection amount exceeded 0.5 Mt/a for one CCS project during 2025–2030, then supercritical CO₂ transport pipelines or truck lines would be built as a long-term infrastructure. After 2030, more pipelines are expected to be constructed to transport a large amount of CO₂. When the transportation distance is less than 200 km, the pipelines

Table 10: Carbon Dioxide Transport Technology Outlook

Distance	Type of CO ₂ pipeline	Implementation timeline
Up to 200 km	Gaseous	Up to 2025
More than 200 km	Supercritical	Up to 2030
1,000–4,000 km	High pressure supercritical CO ₂	Up to 2050

CO₂ = carbon dioxide, km = kilometer.

Source: Generated by the authors.

may be designed for the gaseous phase. This is expected to be built by 2025. When the transportation distance is more than 200 km, high pressure supercritical CO₂ pipelines may be built. This is expected to be achieved by 2030, with 1,000–4,000 km high pressure supercritical CO₂ pipelines likely to be built by 2050 (Table 10).

Enhanced Oil Recovery Outlook

R&D funding should be more focused on CO₂-EOR and storage technologies, equipment, and demonstration. CO₂ source can be captured from natural gas coal chemical process and other high CO₂ concentration sources. Until the storage project reaches a large scale, for example, 0.5 Mt/a or larger, a high-pressure CO₂ pipeline would be built. The CCS project would gradually utilize CO₂ from a low-concentration emission source.

The PRC may start CO₂-EOR and storage by using cheap CO₂ sources, which comes from natural gas purification and coal chemical processes. Studies for CO₂-EOR technologies and monitoring technologies for safety storage must be prioritized and developed. As the terrestrial clastic reservoir in the PRC is more complex than marine carbonate reservoir in other countries such as the US, CO₂ is immiscible with crude oil and the efficiency of CO₂-EOR is lower than that in the miscible phase reservoir. It would take longer for the PRC to practice and reach higher CO₂-EOR efficiency.

Therefore, the government's policy should be to encourage research institutes, universities, and the oil industry to conduct CO₂-EOR study and pilot projects in all possible areas. Incentive policies can benefit from Saskatchewan, Canada, where the Weyburn project is conducted, and tax from CO₂ oil recovery is waived until the project starts to generate revenue (Ministry of Energy and Resources, Energy Policy Branch - Petroleum Royalties Group 2021).

Traditional crude oil recovery monitoring is designed to assess the efficiency of improved crude oil recovery technologies and address health and safety issues. To successfully introduce CO₂-EOR technology into CCUS projects, the injected and stored CO₂ amount should be fully counted. This requires (i) careful assessment of leakages and other risks prior to the start of the injection activity; (ii) the development of monitoring, reporting, quantification and auditing agreements, and compliance with the agreement during the implementation of the CO₂-EOR project; (iii) regular reporting to the government and the disclosure to the public of CO₂ injections, storage, and emission reductions during the implementation of the project; and (iv) establishing post-closing monitoring agreements and management responsibilities, and long-term liability guarantees.

In particular, it is recommended that coordination mechanisms for CCUS demonstration projects be established at the national level. Around 5–10 commercial-scale CCUS CO₂-EOR demonstration projects should be selected, each of which can capture, utilize, and store 100,000–500,000 tons/year as a flagship national project. These projects should be recognized by the national government and receive resources and financial support. After successful completion, it will become a knowledge-sharing platform for similar projects nationwide and internationally.

5 Suggestions on Carbon Capture, Utilization, and Storage Development and Deployment during the 14th Five-Year Plan and Beyond

Development Principles

1. Through source and sink matching, identify priority areas and storage sites, and early projects in CCUS technology development.

The government should support the storage capacity assessment and site selection. The geological characterization process will provide more detailed geological information and the best place for CO₂ geological sequestration. The current assessment of storage capacity and site selection is rough and in the scale of geological basin areas, for example, in Ordos Basin and Junggar Basin.

The Songliao Basin in northeast PRC, the Bohai Bay Basin in the eastern part of the PRC, the Pearl River Estuary Basin in southern PRC, the Ordos Basin in western PRC, the Junggar Basin, and the Tarim Basin are all oil fields suitable for CO₂-EOR operations. These areas also have large coal chemical plants and refineries that will be the main choice for low-cost CO₂ capture and will also be a source of cheap coin. These areas can be selected as priority areas for the construction of CCUS project clusters (Annex 2).

Detailed geological information will help the CCUS projects to reduce risk and the cost of drilling and CO₂ injection. This may also be useful for the government to shift the new infrastructure of high emissions enterprise to close to the best CO₂ storage sites. It will greatly reduce the cost of CCUS projects on pipeline building, mitigate drilling risk, and improve injection efficiency. Early projects in CCUS technology development have also been identified (Annex 3) to support large-scale demonstrations.

Under the premise of more mature technical and economic conditions, priority will be given to the early application of CO₂ chemical and bio-utilization technology in the eastern and southern regions; CO₂ geological utilization and storage technology will be applied in the early period in the midwest and northeast.

2. Further promote the application of EOR, and drive the successful demonstration of the capture project in the 14th Five-Year Plan period.

During the 14th FYP period, efforts should be made to improve the project scale, improve the business model, and expand the CCUS scale. The PRC will continue to promote low-cost demonstration projects with the coal chemical industry and other projects as the source and EOR oil fields as sinks. In the near future, there will still be unfavorable factors such as low oil price. However, from the perspective of long-term and energy and climate security, vigorously promoting CO₂-EOR is still the best choice. Activities to promote CO₂-EOR may include transfer investment from CO₂ capture project into CO₂ storage projects; form a CO₂ capture model driven by large-scale CO₂-EOR with storage or aquifer storage; and select and endorse priority regions such as the Ordos Basin, Songliao Basin in northeastern PRC, Junggar Basin in northwestern PRC, Bohai Bay Basin in eastern PRC, Pearl River Mouth Basin and Beibuwan Basin in southern PRC, and all offshore

and onshore basins, which have oil fields that are amenable to CO₂-EOR operations and are therefore good candidate regions. These regions are home to a large number of major coal-chemical plants and natural gas purification plants, which offer low-cost CO₂ capture options and a source for a large amount of inexpensive CO₂ supply (ADB 2015).

3. Promote commercialization in 10–15 years through large-scale carbon capture and storage demonstrations.

It is suggested that starting 2021, new and existing coal chemical plants should be required to assess the feasibility of their CCUS demonstrations. Hydrogen production enterprises, large high-efficiency coal-fired power plants, cement, steel, and other high-emission enterprises around the EOR storage site are encouraged to carry out the geological storage feasibility study of the saline aquifers and promote the CO₂ storage demonstration project in the near future. The PRC will enable companies to experiment flexibly and actively with CCUS technologies of 50,000 tons/year and over. R&D of new technologies and appropriate demonstration activities will be strengthened in coal-fired power plants, cement industry, steel industry, and hydrogen production processes, as well as bioenergy with CCS to reduce capture costs.

4. Accelerate infrastructure-sharing and promote the industrialization of CCUS clusters.

CCUS industrial clusters can enhance the feasibility of technology applications by reducing costs. The integration of CCUS and future energy systems is expected to become an essential component of new multi-energy systems. By constructing public infrastructure for CO₂ utilization and storage, the development of relevant projects can see greater certainty and lower costs, such as CO₂ transportation network, and benefits use and sink clusters.

Regions with favorable conditions for forming characteristic CCUS clusters include the Ordos Basin, Junggar–Turim Basin, Sichuan Basin, Songliao Basin, Bohai Bay Basin, and Pearl River Mouth Basin. Regions with high energy density and good utilization and storage potential can be selected, such as Northern Shaanxi, Xinjiang, and other regions.

Key Policy Suggestions

Building on the CCUS Technology Development Road Map proposed by the Ministry of Science and Technology and the findings of this study, the authors recommend the following measures to speed up the development of CCUS in the PRC:

- Consider the inclusion of CCUS in the scope of national key low-carbon technologies, including exploring the feasibility of including CCUS in the national carbon emission trading system.
- Develop a CCUS-specific best practice and standard system, and accelerate large-scale integration demonstration. Guided by the large-scale demonstration of CO₂ utilization technologies such as oil displacement/gas, solid waste mineralization and chemical utilization, actively support the construction of CCUS industrial demonstration zone in oil and gas, energy, chemical industry and other related industries, accelerate the construction of CCUS industrial cluster, and gradually integrate CCUS technology into the technical support system for green development of energy and mining.
- Strengthen the industrial chain cooperation mechanism and promote knowledge sharing and the distribution of social responsibility, and economic and social benefits.
- Support international cooperation and exchange of CCUS technology, and promote the establishment of an international technology transfer mechanism.
- Integrate the PRC's CCUS technology and business into the international market.

Policy makers have recognized the vital role of CCS and CCUS because of climate experts and the media in the last decade (Annex 4). CCUS-enabling policies should include (i) a CCUS ready policy;⁵ (ii) a CO₂-EOR incentive policy; (iii) a carbon pricing policy, i.e., government sets a price that emitters must pay for CO₂ emissions or CCUS operators to gain from emission reduction; and (iv) a CO₂ transport policy. The authors recommend the following:

- Develop and adopt a CO₂ capture incentive or mandatory policy for high concentration sources, coal chemical, and natural gas purification plants.
- Designate policy to charge a certain level of fees to emission firms, or paying certain pollution treatment fees to CO₂ capture companies.
- Provide policy incentives, such as grant and concessional loans to develop innovative CCUS technology and equipment to further reduce the CO₂ capture cost.
- Develop policy guidance and policy incentives for establishing CO₂ transport infrastructure and for encouraging third-party access to the infrastructure.
- Encourage oil companies to build CO₂ transport pipelines from their own natural gas purification plants to CO₂-EOR or other storage sites.
- Develop major CCUS clusters and hubs in the PRC.

The authors recommend the following objectives and policy incentives for the 14th FYP CCUS road map in the PRC:

- **There is an urgent need to develop large-scale integrated CCS demonstration projects in key sectors: power, steel, cement, and petrochemical.** Each project should be larger than 1 million tons of CO₂ in capacity with capture, transportation, utilization, or storage components. Although CCS is more important in the PRC based on the PRC's energy structure and the percentage of coal use in primary energy, the PRC is currently behind international progress in building large-scale CCS demonstration projects. The first group of large-scale integrated CCS demonstration projects should start construction at the end of the 14th FYP, i.e., 2024 to 2025.
- **It is beneficial to integrate CCUS into the PRC's carbon market: carbon pricing is an important driver for CCUS in Norway and Canada.** The PRC's emission trading system (ETS) could learn from Canada to allow CCS projects to generate multiple emission reduction credits linked with the PRC's China Certified Emission Reductions (CCER) scheme. The approach that allows 1 ton of CO₂ avoidance in the Canadian CCS project to generate 2 tons of credit could be a useful mechanism to accelerate CCS deployment in the PRC. The usage of auctioning revenue for financing CCS, such as the European Union (EU) NER300 and NER400 scheme, are also excellent examples.
- **Financial support to incentivize the PRC's CCS technologies to be applied abroad.** The PRC may learn from the Japanese model to incentivize Chinese firms to develop CCUS projects abroad and encourage Chinese oil companies to develop CO₂ storage sites overseas. It is beneficial to identify CCS early opportunities in belt and road countries, e.g., capture from high-concentration sources and apply CO₂ for EOR.
- **Adopt CCUS readiness design for all large stationary emission sources in the PRC and for state-owned enterprises (SOEs) development abroad.** CCS readiness design could avoid a carbon lock-in effect. A guidance document for promoting CCS readiness in the PRC and on overseas investments could reduce the climate transition risk (i.e., a high carbon price leads to stranded assets in the future).
- **Increase R&D policy support for CCS technologies.** The level of support in the 14th FYP should be increased given that major economies in the world are significantly increasing the level of support for CCS.
- **Mitigate CO₂ storage liability risk for early CCS demonstration projects.** Early-stage CCS demonstration projects are taking significant technology risks, e.g., failure of capture plant, transportation interruption,

⁵ The CCUS readiness of an industrial plant refers to plans and capabilities being in place to implement CCUS at a future time if the economic or regulatory environment changes; for example, tax credits for the capture of CO₂ or increased efficiency and reduced costs improving the financial viability of CCUS.

CO₂ storage site injectivity. Therefore, the government should create a risk mitigation mechanism to absorb most of the CO₂ storage long-term liability exposures, e.g., through a special and favorable insurance scheme. Government regulatory framework is needed to address long-term liability issues. Liability transfer to governments is a typical mechanism used in countries with commercial CCS projects.

- **Provide other carbon pricing signals on the sector with high-concentration emission sources not yet included in ETS.** Deploy CCS at high concentration emission sources (e.g., >70% CO₂ by volume) is significantly cheaper than capturing from other sources (e.g., power, cement, steel). The PRC is suggested to define and identify high concentration emission sources and develop a tailored policy incentive to trigger CCS from these early opportunities, such as carbon tax and mandatory internal carbon pricing for SOEs. The Form 45Q tax credit in the US sets an excellent example to enable the highest concentration CO₂ sources in the US to deploy CCUS technologies.
- **Establish a trial regulatory framework for CCS.** The complexity of the approval process for CCS projects and the number of administrative departments involved would increase the risks and costs of the project. It is suggested that the Climate Department of the Ministry of Ecology and Environment in the PRC should take the lead in designing a unified approval process to clarify the implementing organs, conditions, procedures, and deadlines of various approvals. Simultaneously, one should clarify the boundary of each regulatory department in the PRC and clarify their role explicitly to ease project developers.
- **Establish a method to measure CO₂ emissions and assess the abatement cost of CCS technologies.** There are inconsistent emission accounting and cost measurement methods for CCS in the world. Developers or technology vendors would usually adopt a method that is favorable to their interest. The key debate is on life cycle emissions and cost for CO₂ utilization such as CO₂-EOR and converting CO₂ to chemicals. It will help policy makers to understand the social benefits, costs, and potential opportunities of different technologies if a fair and uniform costing and carbon accounting method is in place.

ANNEX 1

Major Carbon Capture, Utilization, and Storage Research and Development and Demonstration Projects in the People's Republic of China

Table A1: Major Carbon Capture, Utilization, and Storage Research and Development and Demonstration Projects in the People's Republic of China

No.	Project	Capture Mode	Transport Mode	Storage/ Utilization	Capacity (CO ₂)	Year of Operation	Status
1	Xi'an Kewei Chemical Co. Ltd. of Shaanxi Weihe Coal Chemical Cooperation Group Ltd.	Capture from coal to fertilizer processing	By tank truck	Utilization in the food industry	30,000 t/a	2000	Operation on 16 October 2000
2	Research and demonstration of EOR in Jilin oil field of PetroChina	Natural gas purification	Pipeline (~50 km)	EOR	0.2 Mt/a	2007	In operation
3	Power Plant of Huaneng Gaobeidian	Post-combustion capture technology for coal-fired power plants	–	–	0.003 Mt/a	2008	Closed
4	Power Plant of Huaneng Shidongkou	Post-combustion capture technology for coal-fired power plants	–	–	0.12 Mt/a	2009	In operation
5	Sinopec Shengli Oilfield Coal-fired Power Plant Capture and EOR Demonstration	Post-combustion capture technology for coal-fired power plants	Truck (~80 km)	EOR	0.04 Mt/a	2010	In operation
6	CHINA Electric Power Chongqing Shuanghuai Power Plant	Post-combustion capture technology for coal-fired power plants	–	–	10,000 t/a	2010	In operation
7	Shaanxi Xinghua Group Co. Ltd.	Capture from coal to fertilizer processing	By tank truck	EOR, utilization in the food industry	80,000 t/a	2010	In operation as of 2010
8	Shenhua Group coal-to-oil capture and demonstration storage	Coal-to-oil pre-combustion capture	Truck Tank (13 km)	Aquifer storage	0.1 Mt/a	2011	Closed in April 2015, with a cumulative storage of 302.365 million tons under monitoring

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Table A1 continued

No.	Project	Capture Mode	Transport Mode	Storage/ Utilization	Capacity (CO ₂)	Year of Operation	Status
9	Research and demonstration of 35 MW oxygen-rich combustion technology at Hua Zhong University of Science and Technology	Oxygen-rich combustion technology of coal power plant	–	–	100,000 t/a	2011	In operation
10	Guodian Group Tianjin Beitang thermal power plant	Post-combustion capture technology for coal-fired power plants	–	–	20,000 t/a	2012	In operation
11	Jingbian CCS Project	Shaanxi Yanchang Petroleum Yulin Coalification Co., Ltd. Coal-chemical pre-combustion capture	By tank truck	EOR	50,000 t/a	2012	In operation
12	Jinchang Company of Lanzhou Yulongda Gas Co., Ltd.	Hexibao Chemical Circular Economy Industrial Park chlor-alkali chemical emission capture	By tank truck	Utilization in food and industry	50,000 t/a	2013	In operation as of 10 May 2013
13	Sinopec Zhongyuan oil field EOR project	Henan Xinlianxin Fertilizer Plant Coal-chemical pre-combustion capture	By tank truck	EOR	100,000 t/a	2015	In operation
14	Xinjiang Oilfield—Karamay Gas Clean Plant of Dunhua Petroleum Company	Capture from oil refining process	By tank truck	EOR in CNPC Xinjiang Oil Company	100,000 t/a	2015	Put into operation on 30 November 2015.
15	Changqing Oilfield—Ningxia Deda Gas Development Technology Ltd.	Capture from coal to chemical processing	By tank truck	Mainly used in EOR for CNPC Changqing Oil Company; Food and beverage use	400,000 t/a	2015	Put into operation on 12 December, 2015, extended its CO ₂ capture capacity from 300,000 t/a to 400,000 t/a in 2019

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Table A1 continued

No.	Project	Capture Mode	Transport Mode	Storage/ Utilization	Capacity (CO ₂)	Year of Operation	Status
16	Xinjiang Yulongda Gas Co., Ltd.	Using Xinjiang Meihua Amino Acid Co., Ltd. synthetic ammonia device decarbonized exhaust gas as raw material to capture CO ₂	By tank truck	Utilization in food and industry	50,000 t/a	2016	In operation as of 16 April 2016
17	China Huaneng Group Tianjin green coal power IGCC project	Pre-combustion capture for IGCC	By tank truck	Planned EOR of Dagang Oilfield in Tianjin EOR and saltwater layer storage	60,000 t/a	2017	Carbon capture unit completed in February 2017; carbon storage project delayed
18	Chongqing Tonghui Gas Co., Ltd.	Capture from potash fertilizer processing Chongqing Anton Potash Co., Ltd. contains CO ₂ exhaust gas capture	By tank truck	Utilization in food and industry	100,000 t/a	2018	In operation as of 2 April 2018
19	Conch Group Baimashan cement plant CCUS project	Capture from cement production	By tank truck	Utilization in the food industry	50,000 t/a	2018	Put into operation on 31 October 2018
20	Haifeng Power Plant of China Resources Power	Testing capture after combustion of coal-fired power plant with multiple technologies including amine and membrane technologies	By tank truck	Utilization in food processing and other industry	20,000 t/a	2019	Operation in May 2019
21	Chongqing Tonghui Gas Co., Ltd.	Capture from coal to chemical processing	By tank truck	Utilization in the electronic industry	100,000 t/a	2019	In operation as of May 2019
22	Guizhou Kaiyang Tonghui Gas Co., Ltd.	Capture from coal to chemical processing	By tank truck	Utilization in food and industry	150,000 t/a	2019	In operation as of 29 October 2019
23	State Energy Group Shaanxi Guohua Electric Power Jinjie Power Plant	Pre-combustion capture	By tank truck	–	150,000 t/a	2021	In operation as of 21 January 2021

– = not applicable; CCS = carbon capture and storage; CCUS = carbon capture, utilization, and storage; CO₂ = carbon dioxide; EOR = enhanced oil recovery; IGCC = integrated generation of combined cycle; km = kilometer; Mt/a = million tons per year; MW = megawatt; t/a = ton per year.

Source: This table is integrated and based on the reference Administrative Center for China's Agenda 21 (2019); and expert information.

ANNEX 2

Locations of Priority Carbon Dioxide Emission Sources and Storage Sinks in the People's Republic of China

Coal-chemical plants or natural gas purification plants have been widely established across the eastern, northeastern, and northern regions of the People's Republic of China (PRC). As sector rationalization takes hold, the location focus for new very large capacity units will be the eastern, northwestern, and western PRC, in particular, the Inner Mongolia Autonomous Region, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, and Shaanxi and Henan provinces.

These provinces share important oil and gas basins, and many coal-chemical industries or natural gas purification plants are located in these regions. Moreover, many opportunities for enhanced hydrocarbon recovery are available there in the near to medium term.

At the same time, large-scale coal-fired power plants are likely to be built in these regions to offset the shutting down of coal-fired power plants in the three key environmental areas of Beijing–Tianjin–Hebei, the Yangtze River Delta, and the Pearl River Delta. This will create opportunities for the demonstration of carbon capture, utilization, and storage (CCUS), and the development of CCUS project clusters. Figure A1 in the report (ADB 2015) provides a geographic overview and includes the large-scale carbon dioxide (CO₂) point sources; among them, the existing and future coal-chemical plants must be within 200 kilometers (km), and power plants must be within 80 km of favorable storage sites.

According to the source-sink matching, about 60% of large-scale point sources with high purity are within 80 km (coal-fired power plants) to 200 km (coal-chemical plants) of favorable storage sites. Five areas can be considered priority areas, as shown in Table A2.

Table A2: Matching of Priority Basins and Storage Sinks in the People's Republic of China

Priority Area	Storage Sink
Ordos Basin ^a	CNPC Changqing oil field, Yanchang Petroleum Group
Bohai Bay Basin ^b	Sinopec Shengli, Zhongyuan, CNPC Dagang, Jidong, Liaohe, CNOOC Bohai
Songliao Basin	CNPC Daqing, Jilin, Liaohe oil field
Jiangsu–Southern South Yellow Sea Basin	Sinopec East China Petroleum Bureau, Jiangsu oil field
Xinjiang area ^c	CNPC Xinjiang oil field (Jungar), CNPC Tarim oil field, CNPC Tuha oil fields, Sinopec Tahe oil field
Zhujiangkou (Pearl River Mouth) Basin	China Offshore Nanhai West of CNOOC

CNOOC = China National Offshore Oil Corporation, CNPC = China National Petroleum Corporation.

^a Shaanxi Yulin, 2 million–3 million tons per year of planned storage in onshore oil or gas reservoirs; Ningxia, 1 million tons per year enhanced oil recovery planned; Ordos Basin, saline aquifer storage planned.

^b Shengli and Zhongyuan oil field, enhanced oil recovery as primary storage option.

^c Xinjiang Oil Field in Karamy, 3 million tons per year of planned storage in onshore oil or gas reservoirs.

Source: Generated by the authors.

When both coal-chemical plants and power plants are close to the favorable storage sites, the cost of CO₂ captured from power plants should have no comparative advantage. CO₂ capture of coal-fired power plants may be at a loss. Still, from the perspective of local overall greenhouse gas emission reduction, the government's policy needs to support the CO₂ capture of power plants to achieve the factory price of CO₂ which can be equivalent to that of coal-chemical plants.

ANNEX 3

Potential Early Opportunity Carbon Capture, Utilization, and Storage Projects in the People's Republic of China

Key carbon capture, utilization, and storage (CCUS) demonstration activities include the following:

1. China National Petroleum Company (CNPC) Changqing CCUS Project in Ordos Basin and CNPC Xinjiang CCUS Project in Junger Basin. CNPC Changqing Oil Company is the largest oil company in the People's Republic of China (PRC), where its oil and gas equivalent production was 60 million tons (Mt) in 2020.
2. CNPC Xinjiang CCUS Project was incorporated by OGCI under the CCUS Kickstarter.
3. CNPC Jilin Oil Company's CCUS Project has been using cheap carbon dioxide (CO₂) source, which is separated from natural gas in its own gas field and obtained a profit from CO₂-enhanced oil recovery (EOR). The only CO₂ transport pipeline in the PRC was constructed in Jilin Oil Company.

Other CCUS demonstration activities in those priority basins in the PRC must be encouraged as well.

Table A3.1: Early Opportunity Carbon Capture, Utilization, and Storage Demonstration Projects in the People's Republic of China's Ordos Basin

Priority Area	Storage Sink	CO ₂ Transportation Distance (km)
Shenhua Coal-to-Oil 100,000 t/y CO ₂ capture facility of CHN Energy (closed)	Ordos Basin aquifer storage	<20
Shaanxi Guohua Coal Power Plant of CHN Energy post-combustion 150,000 t/y CO ₂ capture facility in Shenmu, Shaanxi (under construction from 1 November 2019 to 21 January 2021)	Jingbian oil field	300–400
Yulin Coal Chemical Industry Group of Shaanxi Yanchang Petroleum (Group) 50,000 t/y CO ₂ capture facility (planned to capture CO ₂ 250000 t/y)	Jingbian oil field	140
	Ansai oil field	220
	Wuqi oil field	230
Yulin Shenghui Hengtong Gas Technology Co., Ltd. 500,000 t/y coal to chemical process CO ₂ capture facility (under construction)		
Shaanxi Yulong Gas Co., Ltd. (Shaanxi Baoji Fengxiang Industrial Zone) 100,000 t/y coal to chemical process CO ₂ capture facility	Jingbian oil field	400–500
	Ansai oil field	300–400
Shaanxi Xingping Fertilizer Group of Shaanxi Yanchang Petroleum (Group) 80,000 t/y coal to chemical CO ₂ capture facility		
Xi'an Kewei Chemical Co., Ltd. 30,000 t/y coal to chemical process CO ₂ capture facility, affiliated to Shaanxi Weihe Coal Chemical industry group company of Shaanxi Coal Chemical Industry Group Co. Ltd.		

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Table A3.1 *continued*

Priority Area	Storage Sink	CO ₂ Transportation Distance (km)
Ningxia Deda Gas Development Technology Ltd. 400,000 t/y coal to chemical processing CO ₂ capture facility at Ningxia Ningdong Coal Chemical Industrial Zone	Jiyuan oil field	120–200
Dunhua Petroleum company 100,000 t/y coal to chemical processing CO ₂ capture facility at Ningxia Ningdong Coal Chemical Industrial Zone (under construction)		
CNPC Changqing Natural Gas Purification Plant 100,000 t/y CO ₂ capture facility at Shaanxi Jingbian (applying for approval)	Jiyuan oil field	100–120

CO₂ = carbon dioxide, km = kilometer, t/y = ton per year.

Source: Generated by the authors.

Table A3.2: Early Opportunity Carbon Capture, Utilization, and Storage Demonstration Projects in the People's Republic of China's Junggar Basin

Priority Area	Storage Sink	CO ₂ Transportation Distance (km)
Karamay Gas Clean Plant of Dunhua Petroleum Company 100,000 t/y CO ₂ capture facility from the oil refining process	Xinjiang oil field	195
200,000 t/y CO ₂ capture facility from coal to chemical process at Xinjiang Shenleng Gas Ltd. of Henan Xinlianxin Fertilizer Company in Changji, Xinjiang (under construction)	Xinjiang oil field	400

CO₂ = carbon dioxide, km = kilometer, t/y = ton per year.

Source: Generated by the authors.

ANNEX 4

International Policy Summary

International Carbon Capture, Utilization, and Storage Policy Experiences

In the last 2 decades, 19 large-scale integrated carbon capture, utilization, and storage (CCUS) projects were built and became operational globally. These projects are primarily driven by the following six measures:

- (i) **Enhanced oil recovery.** More than half of operating large-scale CCUS projects (13 out of 18) in the world utilizes captured carbon dioxide (CO₂) for enhancing oil production (GCCSI 2020). The price that oil companies paid for CO₂ was approximately \$30/tCO₂ when the oil price was \$70 per barrel (UNEP 2020; World Bank 2020). The price is able to support CO₂ capture from high concentration sources such as steam reforming, natural gas purification, coal gasification, and fertilizer plants.
- (ii) **Tax credit.** Tax credits have the benefit of being well established in the context of climate change mitigation, having been used to drive significant investment in renewables over the past 20 years. The Form 45Q Tax credit applied in the United States (US) is the first national-level incentive for CCUS deployment, enabling a large number of CCUS projects in the US (GCCSI 2020). The 45Q tax credit worth \$18/tCO₂ for CO₂ used for enhanced oil recovery (EOR) and \$29/tCO₂ for CO₂ stored through dedicated geological storage since 2011. The level has increased to \$35/tCO₂ for EOR and \$50/tCO₂ for dedicated geological storage in 2019. With Form 45Q policy support, more than 30 large-scale CCUS projects were initiated in the US. The credits can be used to reduce a company's tax liability or if they have no tax liability, transferred to the company that disposes of the CO₂ or traded on the tax equity market.
- (iii) **Carbon pricing with emission trading system.** CCUS is included in the European Union (EU) ETS, but there is no operational large-scale CCUS project in the EU. If the surge of carbon allowance future price above €80/tCO₂ in EU ETS from Nov 2021 is persistent (ICE 2021), the price signal could be adequate drive for some large-scale CCUS projects. In terms of incentivizing CCUS developing countries, CCUS was conditionally accepted in the Clean Development Mechanism (CDM) in COP16 in 2010 (GCCSI 2013; Santos and Dixon 2012), but no CCUS project has been verified by CDM as a more accurate methodology to be developed. Operating CCUS projects may generate certified emission reduction (CER) credits. However, these incentives in ETS are not significant enough to drive the deployment of CCUS in developing countries given the level of the low price of CER credit (Barchart 2021). An alternative to "carrot" is to introduce a "stick," such as a carbon tax. The carbon tax introduced in Norway in 1991 has been successful in enabling the Sleipner and Snøhvit CCUS projects. At approximately \$17/tCO₂, the cost of injecting and storing CO₂ for the Sleipner project was much less than the \$50/tCO₂ tax penalty at the time for CO₂ vented to the atmosphere (GCCSI 2019). California in the US is introducing the Low-Carbon Fuel Standard to incentivize air capture with a carbon price level at \$180/ton of CO₂ (Low Carbon Fuel Coalition 2019).
- (iv) **Regulation of emissions.** Emission performance standard (EPS) has been introduced in the United Kingdom (UK) for the power sector, which requires all new fossil power plants to have an emission level lower than 450gram/kilowatt-hour (kWh) as a nationwide policy. Australia also adopts EPS at the project level, which requires 80% of CO₂ in the gas processing plant of the Gorgon project to be injected for geological storage. The policy leads to 4 million tons of CO₂ stored each year, as the largest CCUS project by far in the world. In Canada, the launch of EPS in the power sector is also one of key drivers for deploying CCUS in Canada, leading the investment of the first large-scale CCUS demonstration in the power sector in the world.

- (v) **Capital grant.** Financing for technologies being proven but not yet commercially deployed are particularly difficult. CCUS demonstration projects usually find it difficult to secure commercial investment. Therefore a capital grant from the government is important to bridge the funding deficit. Capital grant from the government contributes to 70% of Illinois industrial CCS project capital need and 25% of Saskpower Boundary Dam CCUS project capital need. Capital grant will complement with other incentives (such as tax credit and carbon pricing) in supporting CCUS development. Capital grant support is also adopted for scaling up CO₂ transportation infrastructure to lower the cost for CCUS in the future, such as €2.1 billion grant support for the Northern Light project in Norway announced in 2020, and CAN\$ 558 million for the Alberta Carbon Trunk Line.
- (vi) **State ownership of CCS facilities.** Some governments set up state-owned enterprises (SOEs) in developing CCS facilities. SOEs have benefits in taking a higher level of risk and usually can borrow at a lower interest rate. The Government of Norway set up Gassnova to invest in and operate commercial-scale CCUS projects in Norway. Saudi Arabia and the Government of the United Arab Emirates adopted the state ownership strategy of CCS facilities to supply CO₂ for EOR. Alternatively, the Government of Japan supports the establishment of the Japan CCS Company, in which more than 40 companies invest to maximize knowledge sharing. The Japan CCS Company has invested in and operated the Tomakomai pilot capture and injection project.
- (vii) **EU Border Tax.** This is an important signal to emphasize that more investment must be transferred to CCUS in the future. Policy support is crucial for early-stage development and demonstration of CCUS projects, as five out of six measures above are based on public policy support. Based on an approach suggested by the International Energy Agency (IEA) in 2016, CCUS policies could be classified into three categories, depending on national or provincial circumstances:
 - (a) climate-based regulation which may require or encourage CCUS;
 - (b) CCUS targeted policy incentives; and
 - (c) regulation of CCS operations, notably to facilitate safe and effective storage of CO₂.

Based on initial indications, the carbon border tax will be limited to cement, iron and steel, aluminum, fertilizer, and electricity sectors.¹ A simplified carbon border adjustment mechanism (CBAM) system, where importers will have to report emissions embedded in their goods without paying a financial adjustment will apply as from 2023 for selected products with the objective of facilitating a smooth rollout and to facilitate dialogue with third countries.

Once the definitive system becomes fully operational in 2026, EU importers will have to declare annually the quantity of goods and the amount of embedded emissions in the total goods they imported into the EU in the preceding year, and surrender the CBAM certificates.

The nature of support will evolve when CCUS deployment progresses. At the earlier stage, CCUS targeted incentives are likely playing a central role to enable demonstration projects and to help some innovative CCUS technologies phase through the “valley of death.” When CCUS technologies are widely demonstrated, climate-based regulations such as carbon pricing and EPS at each sector are likely key drivers for CCUS development.

At the national level, climate-based regulation is not CCS-specific, such as a country carbon emission or carbon-intensity goal, carbon ETS, EPS, but they are driving the development of CCUS projects. For example, the carbon tax in Norway has been driving the Sleipner project’s investment since the year before 1998; the EPS in Canada contributes to the investment decision on the Boundary Dam Unit 3 Carbon Capture Project. In the long term, carbon price may be required as the sole mechanism to drive deep emission reduction when the carbon price is higher than the cost of applying CCUS technologies. CCS was also recognized by the United Nations Framework

¹ European Commission. *Carbon Border Adjustment Mechanism*.

Convention on Climate Change as an acceptable CDM project type in 2011, laying the foundation to enable CCUS to be supported through Paris Agreement Article 6.2.

CCS's targeted measures include capital grant and subsidies, tax credit, capital grant support, feed-in tariff, contract for differences, CCS certificate schemes, loan guarantee, public-private partnership, and liability transfer. These approaches could be adopted as a portfolio of incentives to support CCUS at different stages, early development, engineering design, final investment decision, and operation. Usually, grant support is needed for early development and engineering design, unless a business case for CCS is enabled in a country or a region. The majority of operational CCUS projects received capital grant funding.

In terms of financing CCUS demonstration projects in the power, steel, and cement sectors, grant support is essential because their carbon capture cost is usually much higher than high concentration sources. The stability of policy incentive commitment in CCUS is also critical for enabling CCUS projects because there is a long lead time in developing large-scale CCUS projects. For example, the cancellation of the £1 billion CCS program in the UK in 2015 cost about 4 years of public finance in supporting project development and engineering design. Though the Government of the UK announced £0.8 billion CCS grant support in 2019, the damage of industry confidence and loss of early-stage financial support could not be recovered.

On the other hand, because of CCS's energy penalty, measures to address CCS operational costs are necessary. A stable policy to support the operating cost for CCS could help reduce risk in commercial finance and may reduce the upfront grant requirement to enable a CCUS project. The US Form 45Q policy is an excellent example to fully cover the operational cost for CCS projects by providing significant tax credit support.

The regulatory framework and permitting requirements for CCS are important for CCS deployment, but are usually incomplete or missing. Most CO₂ capture and transportation-related regulations are in place similar to existing sectoral regulations, but CO₂ storage needs to involve specific regulations in many jurisdictions. The key element in CO₂ storage regulation is the long-term liability in CO₂ storage and monitoring. The regulatory framework for CO₂ storage includes legal basis, property right for pore space, CO₂ storage site selection and permission, and long-term liability for CO₂ storage. Evidence from existing countries and regions with CO₂ storage regulation suggests the importance of sharing CO₂ storage liabilities by the government; otherwise, it will increase the cost of capital and require significantly higher policy incentive to enable CCUS demonstration projects.

Review of International Carbon Capture and Storage Policy

Policies play a key role in promoting CCS development. Various subsidy policies for CCS have different effects on the CCS investment decisions. To improve the development of CCS, some systematic mechanisms were created to encourage or drive CO₂ emitters deploying CCS. Public policy is crucial to enable CCS projects. Table A4.1 shows that almost every current running project is owned by the government or supported by the government in a certain context. The current carbon pricing schemes in most economies could not support the commercial deployment for CCUS. As illustrated in Table A4.2, the carbon price level in 2019/2020 could hardly reach abatement costs for deploying CCUS shown in Table A4.3.

Table A4.1: Summary of Carbon Capture and Storage Project Case Studies

Project	Scale	Sector	Country	Ownership	Investment	Revenue	Risk Management
Weyburn	1.8 Mtpa	Synfuel plant and EOR	Canada	The Government of Canada, the Government of Saskatchewan, Cenovus Energy and the Petroleum Technology Research Centre in Regina, Saskatchewan	Government grants; Private equity	EOR	This is the world's first CO ₂ measuring, monitoring, and verification initiative led by the Government of Canada and the Government of Saskatchewan. The governments hold the main risks.
Petra Nova	1.4 Mtpa	Power plant CCS and EOR	United States	A 50/50 joint venture between NRG Energy and JX Nippon Oil & Gas Exploration	Joint venture equity; DOE grant; Debt	EOR; 45Q credit	Joint venture company holds all risks. The carbon capture facilities were shutdown in May 2020.
Al Reyadah Carbon Capture, Use, and Storage (CCUS) Project	Up to 0.8 Mtpa	Steel sector CCS and EOR	United Arab Emirates	Joint venture between Abu Dhabi National Oil Company and Masdar	Joint venture equity	EOR	State-owned. Steel plants provide CO ₂ to oil company.
Sleipner	1 Mtpa	Natural gas purification plant	Norway	Equinor	Joint venture equity	CO ₂ tax avoidance	Joint venture company holds all risks.
Quest	More than 1 Mtpa	CCS in hydrogen	Canada	Shell Canada	Government grants; Private equity	CO ₂ price avoidance offset credits	Government backed, reduced investment risk. Joint venture holds technical risk.
Illinois Basin	1 Mtpa	Bioenergy with CCS	United States	Archer Daniels Midland Company; DOE NETL, Schlumberger, University of Illinois through the Illinois State Geological Survey, Richland Community College	Government grants; partner equity	Potential 45Q credit	Government bears most of the risks.

CCS = carbon capture and storage, CO₂ = carbon dioxide, Mtpa = million tons per year, EOR = enhanced oil recovery.

Source: Generated by the authors.

Table A4.2: Reference Carbon Price Level in Different Regions in 2020

Country/Area	Range of Carbon Price (CNY/ton CO ₂)	Mechanism
European Union	195–323	Emission trading system
Norway	449	Carbon tax for petroleum sector
United Kingdom	159	Carbon price floor (tax) for the power sector
Canada	200 (2021) 250 (2022)	Carbon tax
Beijing, PRC	53–98	Emission trading system

CO₂ = carbon dioxide, PRC = the People's Republic of China.

Source: The World Bank Carbon Pricing Dashboard and The World Bank State and Trends of Carbon Pricing 2020.

Table A4.3: Estimated Abatement Cost of First-of-a-Kind Carbon Capture, Utilization, and Storage Projects (CNY/ton CO₂)

	Country	PC Supercritical	IGCC	NGCC	Iron and Steel	Cement	Natural Gas Purification	Fertilizer	Biomass to Ethanol
ANZ	Australia	730	948	1,124	836	1,363	189	232	189
Asia	PRC	421	569	695	520	906	170	195	170
	Republic of Korea	653	843	836	646	1,117	189	222	189
	Indonesia	520	744	674	534	878	160	189	160
Europe	Germany	850	1,039	969	794	1,320	192	232	192
	Poland	492	611	646	506	913	181	205	181
ME and Africa	Saudi Arabia	–	–	562	471	730	138	164	–
	United Arab Emirates	–	–	681	632	983	154	188	–
	Algeria	–	–	611	534	815	143	171	–
	Morocco	569	794	667	562	878	151	181	–
	Mozambique	674	941	730	604	983	165	197	165
Americas	United States	520	681	625	541	871	151	178	151
	Canada	808	1,004	709	646	1,025	157	190	157
	Mexico	569	801	618	499	794	150	176	150

– = not applicable, ANZ = Australia and New Zealand, CO₂ = carbon dioxide, IGCC = integrated gasification combined cycle, ME = Middle East, NGCC = natural gas combined cycle, PC = pulverized coal, PRC = People's Republic of China.

Source: GCCSI (2017).

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Road Map Update for Carbon Capture, Utilization, and Storage Demonstration and Deployment in the People’s Republic of China

This publication updates the 2015 carbon capture, utilization, and storage (CCUS) road map for the People’s Republic of China (PRC) developed by the Asian Development Bank (ADB) in consultation with the government of the PRC and other stakeholders. Reflecting changes in CCUS and low-carbon development targets in the PRC since 2015, it highlights the role of CCUS in decarbonizing hydrogen production from fossil fuels; CCUS-readiness of the cement and iron and steel industries; recommendations on CCUS deployment under the 14th Five-Year Plan; and implications for CCUS of the PRC’s ambition to achieve carbon neutrality by 2060.

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