China Status of CO2 Capture, Utilization and Storage (CCUS) 2021

——China CCUS Pathway

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Foreword

At the 75th session of the United Nations General Assembly on September 22, 2020, Chinese President Xi Jinping delivered an important speech and proposed that China aims to reach the carbon dioxide (CO_2) emissions peak before 2030 and strive to achieve carbon neutrality before 2060. President Xi's series of important statements have set clear goals and directions for China's response to climate change and green development and have injected strong political impetus into strengthening global climate action.

Carbon dioxide capture, utilization, and storage (CCUS) is a large-scale greenhouse gas emission reduction technology. In recent years, CCUS policies, research and development in China have been gradually improved under the joint promotion of the Ministry of Ecology and Environment, the Ministry of Science and Technology, and the National Development and Reform Commission. What’s more, the scale of pilot demonstration projects continues to grow, and the competitiveness is further enhanced. But overall, China's green and low-carbon technology system for carbon neutrality has not yet been established. There is still a big gap between the existing technology system for emission reduction and the actual need for carbon neutrality. Studies have shown that CCUS will become one of the indispensable key technologies for China to achieve the goal of carbon neutrality. Therefore, the strategic positioning of CCUS should be rethought and reassessed according to the new situation, and it should be accelerated and deployed in advance on this basis.

The release of *China Status of* CO_2 *Capture, Utilization and Storage (CCUS) (2021) – China CCUS Pathway* is timely, which plays an important role in studying the strategic positioning and development path of CCUS under the carbon-neutral goal in China. This report will support policymakers to carry out CCUS related work in strategy, planning and policy, and help the researchers determine future emissions anchors in different periods based on the current understanding of CCUS. It will further help the public to understand CCUS, such as the position and role of CCUS, which will strengthen China’s goal of achieving carbon neutrality together.

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Abbreviations

BECCS	Bioenergy with carbon capture and storage
CCS	Carbon dioxide capture and storage
CCU	Carbon dioxide capture and utilization
CCUS	Carbon dioxide capture, utilization and storage
CO_2-ECBM	Carbon dioxide enhanced coal bed methane recovery
CO_2-EOR	Carbon dioxide enhanced oil recovery
CO_2-EWR	Carbon dioxide enhanced water recovery
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DRI	Direct reduced iron
EU ETS	European union emissions trading system
GCCSI	Global carbon capture and storage institute
GDP	Gross domestic product
GJ	Gigajoule
GW	Gigawatt
IEA	International energy agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental panel on climate change
IRENA	International renewable energy agency
km	Kilometer
KWh	Kilowatt-hour
MJ/kg	Megajoule/Kilogram
NACSA	North American carbon storage atlas
TWh	Terawatt-hour
USGS	United states geological survey

Summary for Policymakers »»

To achieve carbon neutrality, developing Carbon dioxide Capture, Utilization and Storage (CCUS) technology is a strategic choice to reduce carbon dioxide emissions and ensure energy security. With the change of understanding and negotiation situation of climate change, the connotation and extension of CCUS technology are constantly enriched and expanded. It is urgent to systematically study and evaluate the development trend of CCUS technology, reposition the technology development vision, and consider the development pathway of CCUS comprehensively.

To achieve the goal of carbon neutrality, China needs to establish a zero-carbon energy system based on non-fossil energy, and decouples economic development from carbon emission. CCUS technology, as an important part of the carbon neutral technology portfolio in China, is the only technology choice for zero-carbon utilization of fossil energy and the main technical means to maintain the flexibility of the power system. Moreover, CCUS is a feasible technical solution for industries with great difficulties in emission reduction, such as iron and steel and cement industry. In addition, the negative emission technology (CCUS+ renewable energy) is also the base technology guarantee to offset the remained carbon emissions after reduction and achieve carbon neutrality.

In terms of the emission reductions required to achieve carbon neutrality and based on current technology projections, the carbon dioxide emission reductions to be achieved by CCUS are 0.6-1.4 billion tonnes and 1-1.8 billion tonnes in 2050 and 2060, respectively. Among them, Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS) need to contribute 0.3-0.6 billion tonnes and 0.2-0.3 billion tonnes respectively in 2060. From the perspective of source-sink matching in China, the emission reduction potential provided by CCUS can basically meet the demand of carbon neutrality target (0.6-2.1 billion tonnes of carbon dioxide).

China attaches great importance to the development of CCUS technology and steadily promotes its research, development and application. At present, China's CCUS technology is at industrial demonstration stage, but the scale of the existing demonstration projects is small. The costs of CCUS is an important factor affecting its large-scale application. With the development of technology, the costs of CCUS in China has a great potential of reduction. It is expected that by 2030, the technical costs of the whole-process CCUS (250 kilometers transportation) in China will be 310-770 yuan per tonne of CO_2, and by 2060, it will gradually drop to 140-410 yuan per tonne of CO_2.

To promote the development of CCUS technology in China and better support the realization of carbon dioxide emissions peaking and carbon neutralization, the following recommendations are proposed:

(1) Develop detailed pathway of CCUS for the carbon neutrality target. Taking full account of the industrial structure and emission path of key industries under the carbon neutrality target, a comprehensive and systematic assessment about the emission reduction demands and potential of CCUS in China from 2021 to 2060 need to be made.

(2) Improve CCUS policy support and standard system. China should promote the commercialization of CCUS, include CCUS in the catalog of industrial and technological development, improve and optimize the framework of laws and regulations, and formulate a scientific and reasonable standard system for construction, operation, supervision and termination.

(3) Plan and layout CCUS infrastructure construction. Increase the investment and construction scale of carbon dioxide capture, transportation and storage infrastructure, improve the management level of technical facilities, establish the cooperation and sharing mechanism of related infrastructure, and promote the coupling and integration of CCUS with different carbon emission fields and industries.

(4) Carry out large-scale CCUS demonstration and industrial cluster construction. China should improve the compatibility, integration, and optimization of technical units in whole-process CCUS, accelerate the technical breakthrough of large-scale whole-process CCUS demonstration, and promote the construction of CCUS industrial cluster.

Forty-nine researchers in the CCUS field complete this report, and we appreciate the scientific dedication of the authors and the 13 reviewers. Given the uncertainty of CCUS emission reduction demand and potential assessment in the academic community, it is urgent to carry out in-depth analysis under more clear boundary conditions such as technology, capital, and policy in the future to obtain a more reasonable potential assessment and development pathway.

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1.Overview »»

1.1 What is CCUS?

Carbon dioxide capture, utilization and storage (CCUS) refers to the process that CO_2 separated from industrial processes, energy utilization or atmosphere, is directly used or injected into storage location to achieve permanent CO_2 emission reduction (Figure 1). CCUS adds "Utilization" to the carbon dioxide capture and storage (CCS). This concept was formed with the development and the deepening of understanding of CCS technology, and the strong advocacy of China and the United States, which has been widely recognized in the world. According to the technical process, CCUS can be divided into capture, transportation, utilization and storage (Figure 2).

CO_2 capture refers to the process of separating CO_2 from the industrial process, energy utilization or atmosphere, which is mainly categorized as pre-combustion capture, post-combustion capture, oxy-fuel combustion capture and chemical looping capture.

CO_2 transportation refers to the process of transporting captured CO_2 to utilizing or storage sites. According to the different modes of transportation, it can be categorized as tanker transportation, ship transportation and pipeline transportation. Tanker transportation includes automobile transportation and railway transportation.

CO_2 utilization refers to the process of realizing the resource utilization of captured CO_2 through engineering and technical means. According to different engineering techniques, it can be categorized as CO_2 geological utilization, CO_2 chemical utilization and CO_2 biological utilization. Among them, CO_2 geological utilization is the process of injecting CO_2 into the ground to promote energy production and resource exploitation, such as enhancing the recovery of oil, natural gas, geothermal, deep saline (brine) water, uranium and oth-

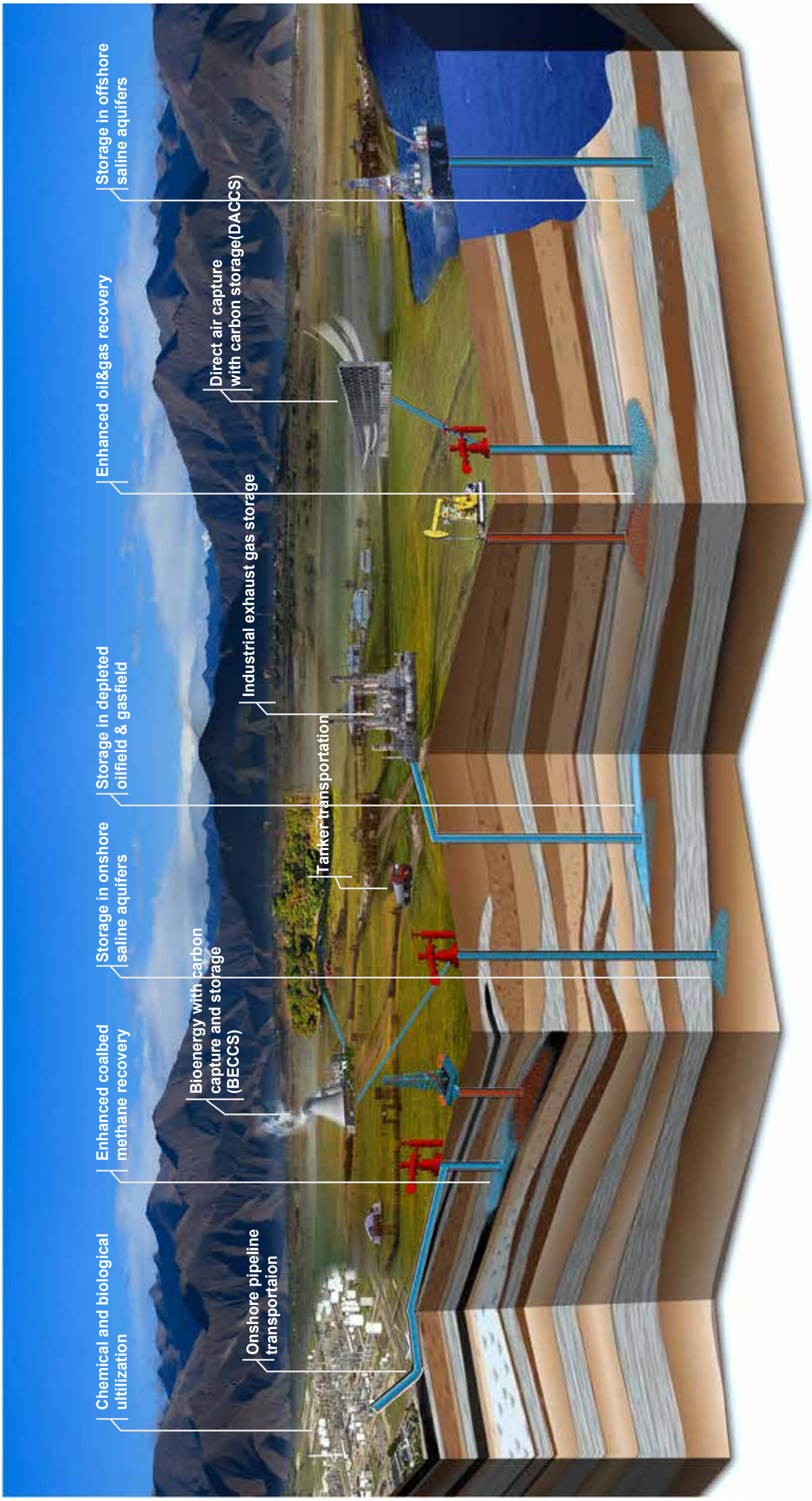

Figure 1 Types of CCUS technology

er types of resources.

CO_2 storage refers to the process of injecting captured CO_2 into deep storage location by means of engineering technology to achieve long-term isolation of CO_2 from the atmosphere. According to different storage locations, it can be classified as geological storage and ocean storage. The different geological sealing bodies can also be classified as saline formations storage, depleted oil and gas reservoirs storage, etc.

Bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) have been highly valued as negative emission technologies. BECCS refers to the process of capturing, utilizing or storing CO_2 generated during the combustion or conversion of biomass. DACCS is a process of capturing CO_2 directly from the atmosphere before utilization and storage.

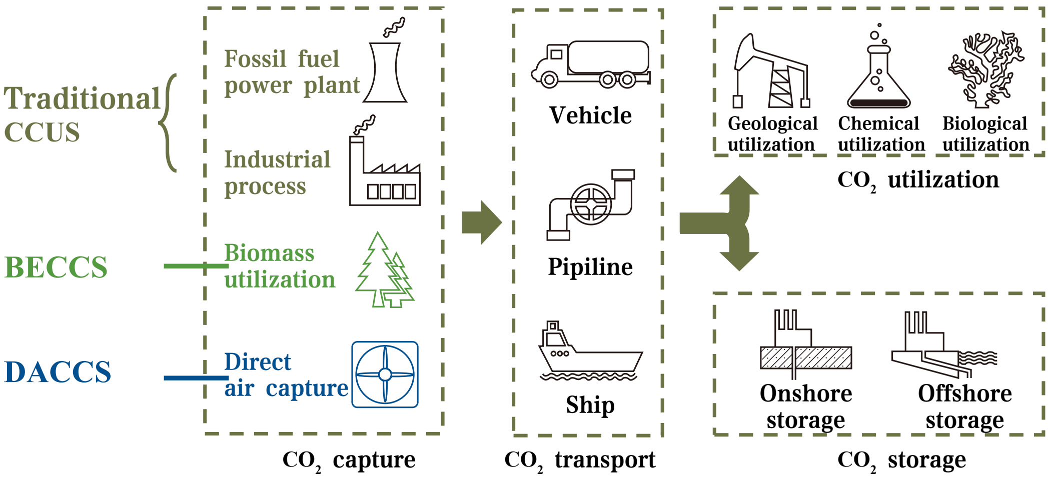

Figure 2 Schematic of CCUS process

1.2 The role of CCUS in carbon neutrality

In September 2020, President Xi Jinping announced that China aim to reach the CO_2 emission peak before 2030 and strive to achieve carbon neutrality by 2060 at the 75th session of the United Nations General Assembly, which contributes to the global climate governance and the implementation of the Paris Agreement. By May 2021, 131 countries, whose greenhouse gas emissions account for more than 65% and gross domestic product (GDP) accounts for more than 75% of the world have announced the goal of carbon neutrality. With the global and Chinese carbon-neutral vision becoming clear and mitigation actions being accelerated, the role of CCUS has become more prominent, and its status is changed significantly.

CCUS is currently the only technology choice to realize zero-carbon utilization of fossil energy. The scale of China's energy system is huge, and the energy demands are diverse. From the perspective of achieving carbon neutrality and ensuring energy security, China should actively build a clean, low-carbon, safe and efficient modern energy system that is dominated by a high proportion of renewable energy and supplemented by nuclear energy, fossil energy, etc. In 2019, coal accounted for 58% of China's energy consumption. According to the prediction of previous studies, fossil energy will still play an important role by 2050, accounting for 10~15% of China's energy consumption. CCUS will be the only technology option to achieve near-zero emission of this part of fossil energy.

CCUS is the main technical means to maintain the flexibility of the power system under the goal of carbon neutrality. The carbon-neutral goal requires the power system to achieve net-zero emission and significantly increase the proportion of non-fossil power, which will inevitably lead to a significant increase in the uncertainty of the power system on the supply and consumption ends, as well as affect the security and stability of the power system. Considering the multiple needs of the power system to achieve rapid emission reduction while ensuring flexibility and maintaining high reliability, the installation of CCUS in thermal power is an important competitive technical means, which can achieve near-zero carbon emission, provide stable, clean and low-carbon power, and balance the fluctuation of renewable energy power generation. It also plays an important role in avoiding seasonal or long-term power shortages.

CCUS is a feasible technology choice for low-carbon transformation of industries which are difficult to reduce emissions, such as steel and cement. The International Energy Agency (IEA) released the iron and steel technology roadmap (2020). It is estimated that by 2050, the iron and steel industry will still have 34% CO_2 emissions remained after adopting conventional emission reduction plans such as process improvement, efficiency improvement, energy and raw material substitution, etc. Even though the hydrogen direct reduced iron (DRI) technology has made a major breakthrough, the remained CO_2 emissions still exceed 8%. The cement industry will still have 48% CO_2 emissions remained after adopting other conventional emission reduction plans. CCUS is one of the few viable technology options for achieving net-zero emissions in industries such as steel and cement that are struggling to reduce emissions.

As a negative emission technology (CCUS+ renewable energy), CCUS is the essential technical support to achieve the goal of carbon neutrality. It is estimated that by 2060, China will still have hundreds of millions of tonnes of non-CO_2 greenhouse gases. BECCS and other negative emission technologies can neutralize this part of greenhouse gas emission, promote net-zero emission, and provide important support for achieving the goal of carbon neutrality.

2.Global CCUS development »»

2.1 The storage potential of CCUS in the world and major countries

The global onshore theoretical storage capacity of CO_2 is 6~42 trillion tonnes, and the offshore theoretical storage capacity is 2~13 trillion tonnes. Among all the storage types, deep saline formation occupies the dominant position. It is widely distributed and accounts for about 98% of the storage capacity, making it ideal for CO_2 storage. Oil and gas reservoirs are the most suitable early geological sites for CO_2 storage because of their complete structure and detailed geological exploration basis.

In China, the theoretical storage capacity is about 1.21~4.13 trillion tonnes. China's oil fields are mainly concentrated in the Songliao Basin, Bohai Bay Basin, Ordos Basin, and Junggar Basin. 5.1 billion tonnes of CO_2 can be sequestered through CO_2-enhanced oil recovery technology (CO_2-EOR). China's gas reservoirs, which are mainly distributed in the Ordos, Sichuan, Bohai Bay, and Tarim basins, can be used to sequester about 15.3 billion tonnes of CO_2 from depleted gas reservoirs, while about 9 billion tonnes of CO_2 can be stored through CO_2 enhanced oil recovery technology. The CO_2 storage capacity of the deep saline formations in China is about 2.24 trillion tonnes, and its distribution is basically the same as that of the petroliferous basins. Among them, Songliao Basin (694.5 billion tonnes), Tarim Basin (552.8 billion tonnes), and Bohai Bay Basin (490.6 billion tonnes) are the three largest land storage areas, accounting for 55.9% of the total storage. In addition, the Subei Basin (435.7 billion tonnes) and Ordos Basin (335.6 billion tonnes) also have large CO_2 storage potential in the deep saltwater.

In East Asia, excluding China, the theoretical storage capacity is about 490 to 550 billion tonnes. The theoretical storage capacity of CO_2 in Japan is 140 billion tonnes, mainly distributed in the large sedimentary basins around the

Japanese islands, including the Tokyo Bay Basin, Osaka Bay Basin, the northern region of Kyushu Region, and the Ise Bay Basin. The CO_2 theoretical storage capacity of the deep saline layer in South Korea is 940 million tonnes, including 900 million tonnes in the Peiping Basin and 40 million tonnes in the Pohang Basin. The oil and gas basins in South Korea are mainly oil reservoirs, among which the CO_2 sequestration potential of the Oolong basin is 3 billion tonnes, the Jeju basin is 23.5 billion tonnes, Kunsan basin is 300 million tonnes. Indonesia, Thailand, Philippines, and Vietnam have a combined mothballed potential of about 54 billion tonnes.

In North America, the potential for geological sequestration is about 2.3 to 21.53 trillion tonnes. The United States Geological Survey (USGS) evaluates tectonic-technology storage capacity for individual storage assessment units in 36 basins in the United States, with a national average of about 3 trillion tonnes. Based on available information, the Global Carbon Capture and Storage Institute (GCCSI) estimated that the storage potential of the United States is between 2 and 21 trillion tonnes.

According to the North American Carbon Sequestration Atlas (NACSA), the potential for CO_2 sequestration in oil and gas basins in the United States and Canada is 120 and 16 billion tonnes, respectively, and the potential for CO_2 sequestration in saline formations is 1.61~20.155 trillion tonnes and 28~296 billion tonnes, respectively. Mexico's saline formation’s theoretical storage capacity exceeds 100 billion tonnes.

In Europe, the theoretical storage capacity is about 500 billion tonnes. The oil-bearing basins in Europe are mainly concentrated in the North Sea, Western and Eastern Europe, while the saltwater basins are mainly distributed in Western and Eastern Europe. According to the EU Geocapacity Project assessment, the potential for CO_2 storage in Europe's oil and gas basins is 30 billion tonnes, and the potential for CO_2 storage in deep saline formation is 325 billion tonnes. Anthonsen KL et al. (2009) gave a conservative estimate of oil and gas reservoirs, aquifers, and coal seam storage potential in 25 European countries at 126 billion tonnes.


The construction site of CCS northern Lights project in Norway-By Wulong

In Australia, the potential for geological storage is about 220 to 410 billion tonnes. There are 65 sedimentary structures suitable for CO_2 storage in Australia, and the potential CO_2 storage basins are mainly distributed in the coastal and central regions.

Table 1 CCUS geological storage potential and carbon dioxide emissions in major countries and regions in the world

Country/Region	Theoretical storage potential (billion tonnes)	Emissions by 2019 (billion tonnes per year)	Estimated cumulative CO_2 emissions to 2060 (billion tonnes)
China	1210 ~ 4130	9.8	400
Asia (excluding China)	490 ~ 550	7.4	300
North America	2300 ~ 21530	6.0	250
Europe	500	4.1	170
Australia	220 ~ 410	0.4	16

Data sources: Bradshaw ***et al.***, 2004; Flett ***et al.***, 2008; Cook, 2009; Takahashi ***et al.***, 2009; Vangkilde-Pedersen ***et al.***, 2009; Ogawa ***et al.***, 2011; Kim ***et al.***, 2013; Wright ***et al.***, 2013; Lee ***et al.***, 2014; Wei, 2015; Kim ***et al.***, 2016; GCCSI, 2019a, 2019b, 2020. Emissions data for 2019 are from BP, 2021; Estimates of cumulative CO_2 emissions to 2060 are calculated by assuming that emissions from 2019 to 2060 stay at the same level in 2019.

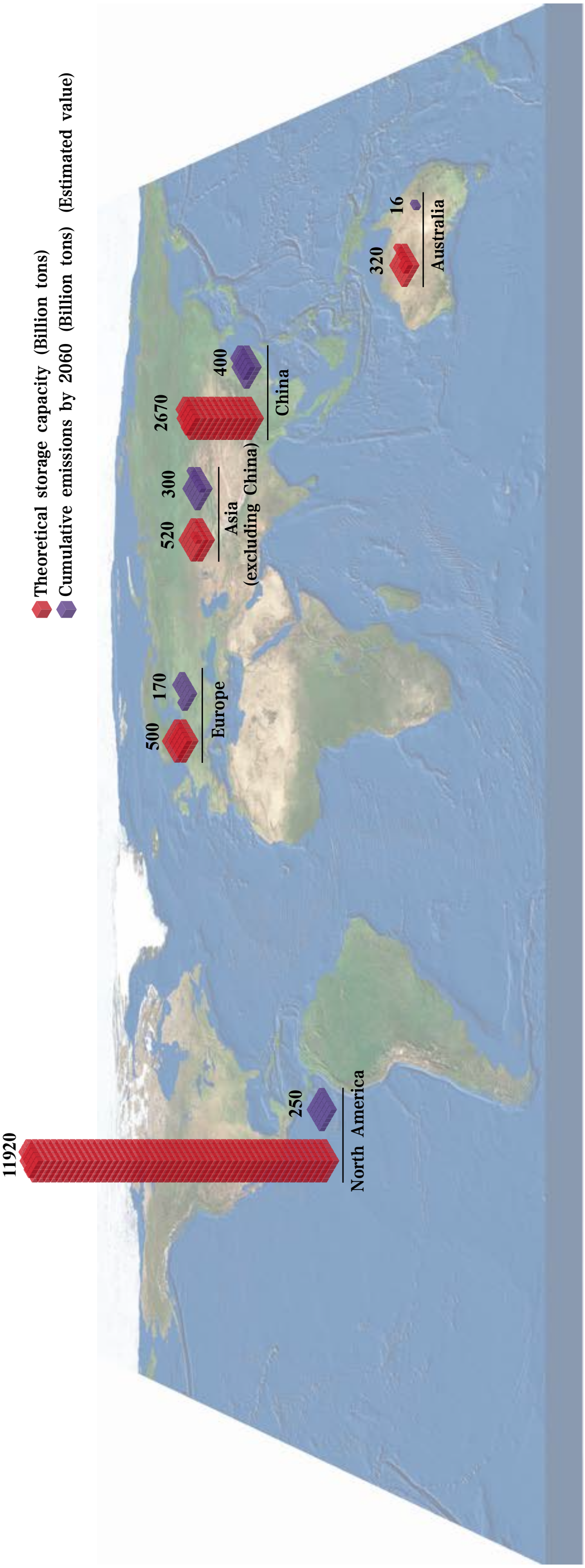

Figure 3 CCUS geological sequestration potential and carbon emissions in major countries and regions in the world

Note: The data in Figure 3 are from Table 1, and the values are the median of the interval.

2.2 CCUS contributions in emission reduction

The contribution of CCUS to emission reduction in different scenarios varies greatly. Under different scenarios, global emission reduced by CCUS in 2030 varies from 0.1 to 1.67 billion tonnes/year, with an average of 490 million tonnes/year. In 2050, it will be 2.79 to 7.6 billion tonnes/year, with an average of 4.66 billion tonnes/year.

In the *Special Report on 1.5 °C Global Warming*, the Intergovernmental Panel on Climate Change (IPCC) pointed out that the emission reduction of different CCUS pathways would be 100 to 400 million tonnes per year in 2030, and 3 to 6.8 billion tonnes per year in 2050. In its Fifth Assessment Report (2014), the IPCC pointed out that CCS is so important for global greenhouse gas reduction and that most models that do not take CCS into account will not be able to achieve the target of 450 ppm CO_2 equivalent by 2100. IPCC Special Report on 1.5°C Global Warming has assessed 90 scenarios, almost all of which require CCUS involvement to keep the temperature rise within 1.5°C. The 90% scenario calls for global storage to reach 3.6 billion tonnes per year by 2050. The global capture and storage of CO_2 are about 40 million tonnes in 2020. To achieve the 1.5°C scenario proposed by the IPCC, capture and storage of CO_2 in 2050 will need to increase by about 100 times. Of the four scenarios for achieving the 1.5°C, only one (a significant decline in terminal energy demand) did not use CCUS. In the other three scenarios, CCUS is expected to achieve accumulative emissions reductions of 348 billion tonnes from 2020 to 2100. BECCS deployments remain limited in 2030 (300 million tonnes, median scenario level). Under a path that limits global temperature rise to 1.5°C with no or only limited overshot, global net anthropogenic CO_2 emissions should be reduced by about 45% from 2010 levels by 2030 and achieve net-zero global CO_2 emissions around 2050, the scale of BECCS needs to be about 4.5 billion tonnes.

The IEA's Sustainable Development Scenario aims to achieve net-zero emissions globally by

2070. CCUS is the fourth most contributory technology, accounting for 15% of cumulative emissions reductions. The IEA Sustainable Development Scenario describes the important tools needed to achieve the key energy-related goals of the *United Nations Agenda for Sustainable Development* which include the early realization of carbon peak and rapid emission reduction after the peak in line with the Paris Agreement, and the popularization of modern energy by 2030. The role of CCUS in the IEA's sustainability scenario grow in importance over time and can be broadly divided into three phases. The first phase, until 2030, focus on carbon capture from existing power plants and industrial processes, such as coal power, chemicals, fertilizers, cement, and steel metallurgy. Between 2030 and 2050, the second phase will see a rapid increase in CCUS deployments, particularly in the cement, steel, and chemical industries, which will account for nearly a third of the increase in carbon capture. BECCS deployments will also increase rapidly, to 15%, particularly carbon capture in power generation and low-carbon biofuels. Between 2050 and 2070, the third phase, carbon capture will increase by 85% over the previous phase. 45% of the increase is from BECCS and 15% is from direct air capture (DAC). Natural gas-related CO_2 capture mainly comes from blue hydrogen (fossil energy hydrogen production + CCUS) production and natural gas power generation.

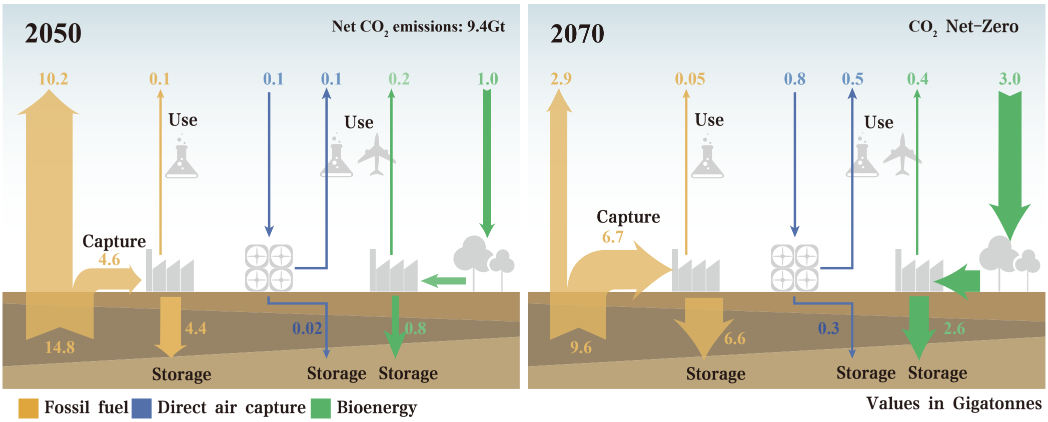

Figure 4 CCUS under IEA sustainable development scenario (IEA, 2020)

Under the IEA's Net-Zero Emissions by 2050 Scenario (NZE), the global CO_2 capture will be 1.67 billion tonnes/year in 2030 and 7.6 billion tonnes/year in 2050. In 2030, carbon capture from fossil fuels and industrial processes, biomass energy, and DAC will be 1325 million tonnes, 255 million tonnes, and 90 million tonnes, respectively. About 4% of coal plants (50 GW) and 1% of natural gas plants (30 GW) need to be equipped with CCUS. In 2050, carbon capture from fossil fuels and industrial processes, biomass energy and DAC will be 5.245 billion tonnes, 1.38 billion tonnes, and 985 million tonnes, respectively. Among them, about 95% of the captured CO_2 will be permanently geologically sequestered and 5% will be used to provide synthetic fuels. The proportion of coal-fired and natural gas plants equipped with CCUS will increase to about 50% (220 GW) and 7% (170 GW), respectively.

The International Renewable Energy Agency's (IRENA) deep decarbonization scenario aims to achieve net-zero emissions over the period of 2050-2060, with CCUS contributing about 6% of annual emissions reductions in 2050, which is 2.79 billion tonnes per year. In Zero Emissions from Renewable Energy report and Global Renewable Energy Outlook published in 2020, IRENA proposed four scenarios for future global CO_2 emissions: (1) Baseline Energy Scenario, that is, the policy scenario when the Paris Agreement was signed; (2) Planned Energy Scenario, that is, the Planned policy Scenario of each national government; (3) Transforming Energy Scenario, which is a more ambitious but still feasible path; (4) Deeper Decarbonization Perspective, which is a scenario where net-zero emissions are to be achieved between 2050 and 2060.

By 2050, from the planned energy scenario to the energy transition scenario, carbon removal would contribute about 10% of the emissions reductions (about 2.61 billion tonnes). From the energy transition scenario to the deep decarbonization scenario, there are two scenarios. (1) Zero emissions, where deep decarbonization of all power generation and industrial processes leads to (almost) zero carbon emissions. This scenario is mainly based on renewable and clean energy, so carbon removal is only 2% (about 200 million tonnes per year), mainly in the cement industry. (2) Net-zero emissions, where CCUS accounts for 34% (contribute 3.5 billion tonnes per year). Overall, from baseline energy scenarios (46.5 billion carbon emissions in 2050) to a deep decarbonization scenario of zero emissions, carbon removal technologies by 2050 will account for approximately 6% of total annual emissions reductions (2.79 billion tonnes per year).

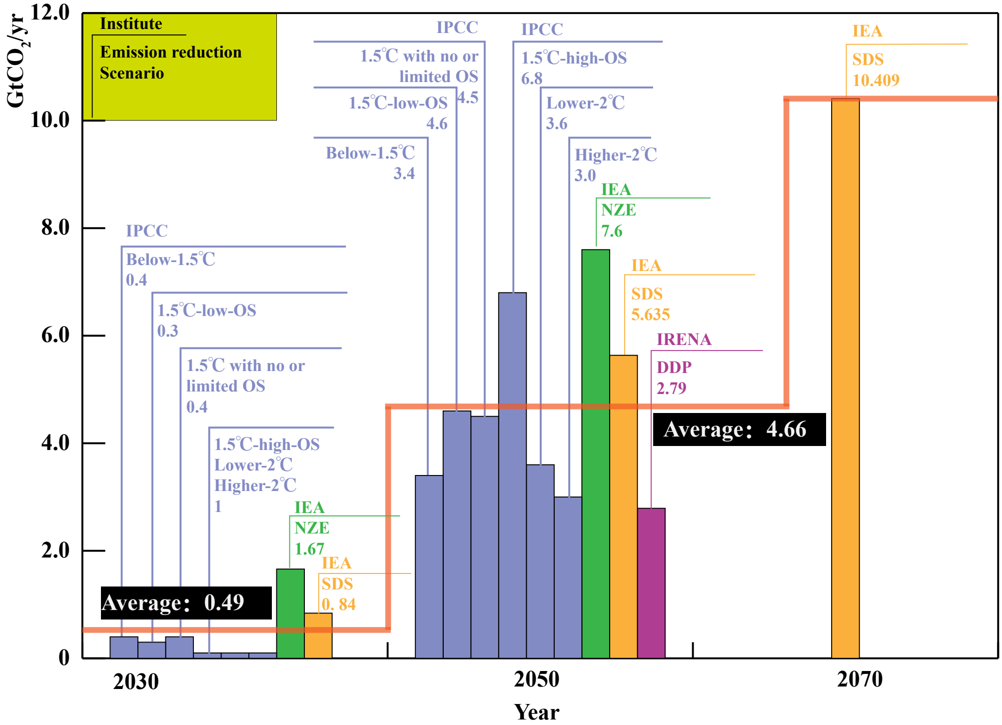

Figure 5 Contributions of CCUS assessed by major global institutions

Note: According to IPCC (2018), global warming should be controlled within 1.5°C. Global zero-emission time for different paths: below 1.5°C—2044; no overshoot 1.5°C—2050; no or limited overshoot 1.5°C—2050; high overshoot 1.5°C—2052; below 2°C—2070; higher than 2°C—2085. The International Energy Agency (IEA, 2020) proposes sustainable development scenarios. The important tools needed to achieve the key energy-related goals of the United Nations Agenda for Sustainable Development includes the early and rapid post-peak emissions reductions in line with the Paris Agreement, and universal access to modern energy by 2030 and zero global emissions by 2070; International Renewable Energy Agency (IRENA, 2020a; 2020b): Prospect of deep decarbonization, achieve net zero emissions between 2050 and 2060; and Consultation Report of the Chinese Academy of Sciences on Carbon Neutrality (2021).

2.3 The scenarios of CCUS in selected countries and regions

In the United States, there are 12 new CCUS commercial projects in 2020. The number of CCUS projects in operation has increased to 38, accounting for about half of the number of global projects in operation, and the CO_2 capture capacity has exceeded 30 million tonnes. The portfolio of CCUS in the United States is diverse, including cement manufacturing, coal-fired power generation, gas power generation, garbage power generation, chemical industry, etc. About half of the projects no longer rely on CO_2-EOR for revenue, which benefits from the subsidy policy launched by the United States government. CCUS projects in the United States can obtain financial support from the federal and local governments through the 45Q tax credit of the federal government and the California low carbon fuel standard of the California government. These measures greatly improve the feasibility of the CCUS projects and make their long-term operation possible. In addition, the United States Department of Energy invested 270 million dollars in supporting the CCUS projects in 2020, which also greatly encouraged the development of the CCUS projects. After the revision of the 45Q tax credit policy in 2018, the amount of subsidy per tonne of CO_2 has been greatly increased. 45Q adopts a progressive CO_2 subsidy price-setting method, as shown in Table 2. Among them, the subsidy price for geological storage of CO_2 increased from \$25.70/tonne CO_2 (2018) to \$50.00/tonne CO_2 (2026), and the subsidy price for non-geological storage (mainly CO_2-EOR and CO_2 utilization) increased from \$15.29/tonne of CO_2 (2018) to \$35.00/tonne of CO_2 (2026). On January 15, 2021, the United States issued the final regulation of 45Q, which made the credit eligibility allocation system more flexible and made it clear that private capital had the opportunity to qualify for the credit. This approach allows investment companies to ensure the long-term stability of CCUS project cash flow and dramatically reduces the financial risk of the project, thus encouraging companies to invest in new CCUS projects.

Table 2 CO_2 subsidy price of 45Q tax credit policy (USD/tonne CO_2)

Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Geological storage	25.70	28.74	31.77	34.81	37.85	40.89	43.92	46.96	50.00
EOR/CCU	15.29	17.76	20.22	22.68	25.15	27.61	30.07	32.54	35.00

Note: The data in this table comes from the U.S. Department of the Treasury.

On the premise of achieving the goal of 1.5°C, in 2030, 2040 and 2050, the emission reductions of CCUS in the United States will be 91~800 million tonnes, 0.6~1.73 billion tonnes and 0.9~2.45 billion tonnes, respectively. Compared with the 30 million tonnes of CCUS equipment capacity in operation in 2020, the United States needs to build many CCUS projects by 2050 to achieve its climate goals.

The European Union has 13 commercial CCUS projects in operation in 2020, including one in Ireland, one in the Netherlands, four in Norway and seven in the UK. In addition, about 11 projects are scheduled to run before 2030. Major commercial CCUS facilities in Europe are distributed around the North Sea, while CCUS projects in continental Europe are progressing relatively slowly due to various institutional costs and public acceptance. Unlike the United States, the CO_2 emission reduction benefits of the European CCUS project is mainly reflected by the EU ETS and EOR. Before 2020, the price of CO_2 in the European carbon trading market was low, and the market support for CCS projects is limited. In addition, the uncertainty of carbon prices in the carbon market also affects companies' judgments on CCUS investment. European NER300, Horizon 2020, Horizon Europe, and other funds have announced plans to provide public funding support for CCUS projects. But NER300 was criticized for failing to provide support for any CCUS project in the end. The European Union has been actively promoting a low-carbon economy and has adopted active policies and systems to promote low-carbon transition. In 2020, the European Green Deal and the European Climate Law turned the goal of zero net emissions by 2050 into a political goal and a legal obligation, which makes it possible for Europe to implement more emission reduction policies in the future. As CCUS is an important means of emission reduction, it is possible that Europe will adopt more active policies to support CCUS. The innovation fund, founded in June 2020, with a total value of 10 billion euros, is widely considered the main public fund source for future CCUS projects. It is worth noting that European Union policy support for CCUS is prudent and conservative compared to other low-carbon energy projects.

On the premise of achieving the 1.5°C target, the EU's CCUS emission reductions will be between 20 million tonnes and 604 million tonnes in 2030, between 140 million tonnes and 1.57 billion tonnes in 2040, between 430 million tonnes and 2.23 billion tonnes in 2050. In the 1.5 LIFE (Sustainable Living Scenario) and 1.5 TECH (Technical Scenario) scenarios announced by the European Union in 2018, CCUS emission reductions in 2050 will be between 370 and 600 million tonnes. It is worth noting that compared with the emission reductions of other comprehensive evaluation models, the EU's official model POLES used in policymaking and the EU's official 1.5°C scenario, CCUS emission reductions from 2030 to 2050 are significantly lower.

In Japan, there are no oil and gas producing areas that can be used for EOR due to the geological conditions. But Japan invested in overseas CCUS intensively, such as the Petra Nova project in the United States and the EOR project in Southeast Asia. Tomakomai CCS project is the only whole process project in Japan, which started construction in 2012 and operated in 2016. The Integrated coal gasification combined cycle power generation (IGCC) project in Hiroshima has already started CO_2 capture and is preparing to carry out an empirical pilot of CO_2 utilization in the future. In 2020, the Japanese government announced the goal of net zero emissions by 2050. In the same year, the Parliament passed a growth strategy and formulated an implementation plan. Among them, CCUS is one of the 14 key areas that the Ministry of Economy, Trade, and Industry has formulated a road map for its popularization in the fields of cement, fuel, chemical industry, and electric power. It should be noted that in recent years, the focus of the Japanese government's work is the utilization of CO_2, so the investment in geological storage has been reduced compared with the past.

On the premise of achieving the 1.5°C target, Japan's CCUS emission reductions will be between 20 million tonnes and 210 million tonnes in 2030, 23 million tonnes and 430 million tonnes in 2040, 110 million tonnes and 890 million tonnes in 2050, respectively.

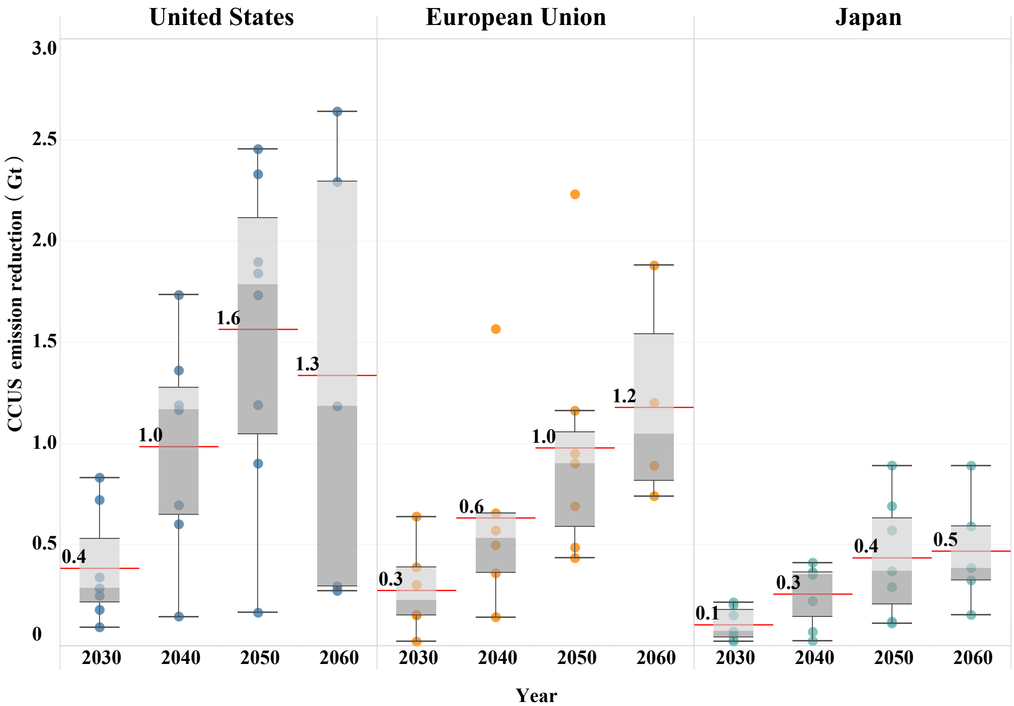

Figure 6 CCUS emission reduction contribution of developed countries

Note: The dots in the figure represent specific models or strategic research data; the red line represents the median value in a certain time (numbered in the figure); Data sources: SSP database; CD-LINKS database; European Commission, 2018; van Vuuren, *et al.*, 2018; Williams *et al.*, 2021.

3.Development needs and potential of CCUS in China »»

3.1 Current status of CCUS in China

In China, about 40 CCUS demonstration and pilot projects have been put into operation and under construction with a capture capacity of 3 million tonnes/year. These projects mainly focus on the small-scale EOR demonstration in the petroleum, coal chemical and thermal power industries, lacking large-scale and full-chain industrialization demonstration with various technology combinations. Since 2019, the main progress is as follows:

CO_2 capture: China Energy Investment Corporation (China Energy) Guohua Jinjie Power Plant builds 150,000 tonnes/year post-combustion CO_2 capture project. China National Offshore Oil Corporation (CNOOC) Lishui *36-1* gas field develops a CO_2 separation, liquefaction, and dry ice production project, with a 250,000 tonnes/year capture scale.

Geological utilization and storage: Guohua Jinjie Power Plant plans to store the captured CO_2 in saline aquifers, and the scale of some CO_2-EOR projects is expanded.

Chemical and biological utilization: 200,000 tonnes/year microalgae fixed coal chemical flue gas CO_2 biological utilization project; 10,000-tonnes/year CO_2 concrete mineralization utilization project; 3,000 tonnes/year carbonization steel slag utilization project.

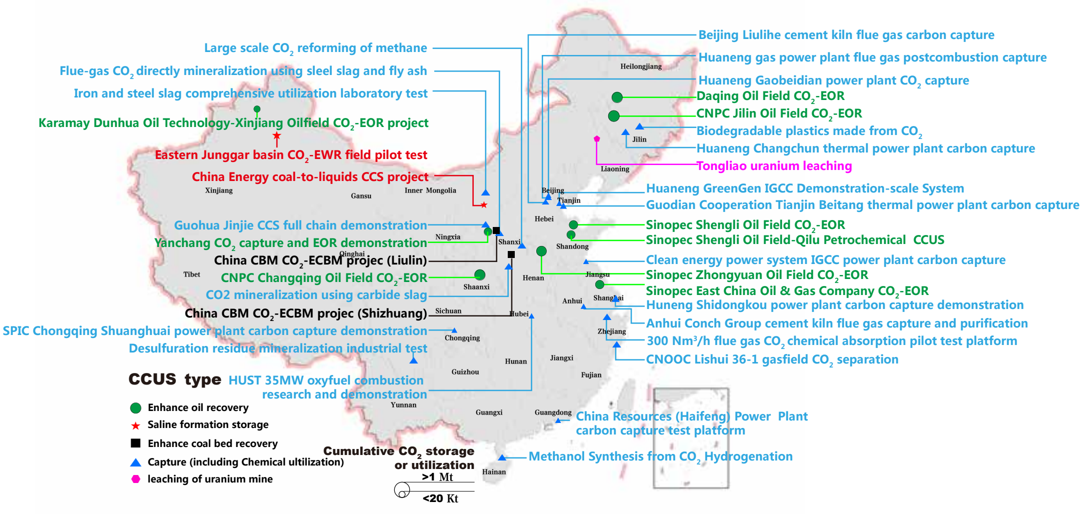

Figure 7　Distribution of CCUS projects in China

The engineering capacity in China is ready to capture and store CO_2 on a large scale and is actively preparing for a full-process CCUS industrial cluster. China Energy Investment Corporation (China Energy) Ordos CCUS Demonstration Project has successfully carried out a full-process demonstration of CCUS with an annual scale of 100,000 tonnes. China National Petroleum Corporation (CNPC) Jilin Oilfield EOR project is the only Chinese project among the 21 large-scale CCUS projects currently in operation globally and is presently the largest EOR project in Asia, with a total of over 2 million tonnes of CO_2 injected. Besides that, construction of the 150,000 tonnes/year post-combustion CO_2 capture and storage demonstration project of China Energy Investment Corporation (China Energy) Guohua Jinjie Power Plant started in 2019. It will become China's largest coal-fired power plant CCUS demonstration project. In July 2021, China Petrochemical Corporation (Sinopec Group) officially launched China's first million-tonne CCUS project (Qilu Petrochemical Corporation-Shengli Oilfield CCUS project).

China's CCUS projects are distributed in 19 provinces, and the industries of capture sources and the types of storage and utilization are diversifying. The total CO_2 capture scale of China's 13 capture demonstration projects (including power plants and cement plants) reached 856,500 tonnes/year. The total CO_2 geological utilization and storage scale of China's 11 CO_2 geological utilization and storage projects is 1.821 million tonnes/year, among which the scale of CO_2-EOR is about 1.54 million tonnes/year. China's CO_2 capture covers pre-combustion, post-combustion and oxy-fuel combustion capture in coal-fired power plants, post-combustion capture in gas-fired power plants, CO_2 capture in coal chemical industries, and post-combustion capture in cement kiln. CO_2 storage and utilization involve various types such as saline aquifer storage, enhanced oil recovery (EOR), enhanced coal bed methane recovery (ECBM), enhanced uranium leaching, CO_2 mineralization utilization, synthetize degradable polymer reforming of methane to syngas, and microalgae immobilization.

Anhui Conch Cement Co., Ltd. Baimashan Cement Plant CO_2 Capture Project-By Yang Jiwei

Significant progress has been made in all technical aspects of CCUS in China, some technologies have the potential for commercial application.

Capture technology: The maturity of CO_2 capture technology varies greatly. At present, the pre-combustion physical absorption method is already at the commercial application stage. The post-combustion chemical adsorption method is still at the pilot stage, and most other capture technologies are at the industrial demonstration stage. The post-combustion capture technology is currently the most mature capture technology, which can be used in the decarbonization transformation of most thermal power plants. For example, the 150,000-tonnes carbon capture and storage demonstration project carried out by Guohua Jinjie Power Plant is under construction. It is the largest post-combustion carbon capture and storage demonstration project in China. The pre-combustion capture system is relatively complicated, and the integrated gasification combined cycle (IGCC) technology is a typical pre-combustion carbon capture system. China's IGCC projects include Huaneng Tianjin IGCC project and Lianyungang Clean energy power system research facility. Oxygen-fuel combustion technology is one of the most potential large-scale carbon capture technologies for coal-fired power plants, producing higher CO_2 concentration (about 90~95%) and is easier to capture. The oxygen-fuel combustion technology has developed rapidly and can be used in new coal-fired power plants and retrofitted coal-fired power plants. At present, the first-generation carbon capture technology (post-combustion capture technology, pre-combustion capture technology, oxy-fuel combustion technology) has gradually matured. The main bottleneck is high cost and energy consumption, and lack of extensive large-scale project experience. Meanwhile, the second-generation technology (such as new membrane separation technology, new absorption technology, pressurized oxygen-fuel combustion technology, etc.) is still in the laboratory research or small-scale test stage. When the second-generation technology is mature, the energy consumption and cost will be reduced by more than 30% compared with the first-generation technology. And it is expected to be widely applied around 2035.

Transportation technology: Among the existing CO_2 transportation technologies, tanker and ship transportation technologies have reached the commercial application stage, while pipeline transportation is still in the pilot stage. CO_2 land vehicle transportation and inland ship transportation technology has matured, and it is mainly applied to CO_2 transportation with a scale of less than 100,000 tonnes/year. The scale of China's existing CCUS demonstration projects is relatively small, and most of them are transported by tankers. Jilin Oilfield and Qilu Petrochemical Corporation use land pipeline transportation. Part of the CO_2 from East China Oil and Gas Field and Lishui Gas Field is transported by ship. The cost of submarine pipeline transportation is 40% to 70% higher than that of land pipelines. At present, the technology of submarine pipeline transportation of CO_2 lacks experience, and it is still at the research stage in China.

Utilization and storage technology: Among CO_2 geological utilization and storage technologies, CO_2-enhanced uranium leaching has reached the commercial application stage, EOR has been in the industrial demonstration stage, EWR pilot test study has been completed, ECBM has also completed the pilot-scale research and the mineralization utilization has also been in the industrial test stage. CO_2 enhanced natural gas and shale gas recovery are still in the primary research stage. China's CO_2-EOR projects are mainly concentrated in oil fields and offshore areas in eastern, northern, northwestern and western China. The 100,000 tonnes/year CO_2 storage in Ordos saline aquifers implemented by China Energy Investment Corporation has completed the injection target of 300,000 tonnes in 2015 and stopped further injection. The 150,000 tonnes/year post-combustion CO_2 capture and storage demonstration project implemented by China Energy Investment Corporation Guohua Jinjie Power Plant plans to store the captured CO_2 in saline aquifers, which is currently under construction. In July 2021, China Petrochemical Corporation (Sinopec Group) officially launched China's first million-tonne CCUS project (Qilu Petrochemical Corporation-Shengli Oilfield CCUS project), which is expected to become the largest demonstration base for the whole industry chain of CCUS in China. The Institute of Process Engineering (IPE), Chinese Academy of Sciences (CAS), launched a 50,000 tonnes/year steel slag mineralization industrial verification project in Dazhou, Sichuan. Zhejiang University has carried out a 10,000-tonnes industrial test project of CO_2 deep mineralization for building materials in Henan. Along with China Petrochemical Corporation (Sinopec Group) and other companies, Sichuan University has made good progress in developing the technology for direct mineralization of phosphogypsum co-production of sulfur-based compound fertilizer from low concentration CO_2 exhaust gas. In China, significant progress has been made in CO_2 chemical utilization technology, and many new technologies such as electrocatalysis and photocatalysis have emerged. However, some technical bottlenecks still exist in the post-combustion CO_2 capture system and chemical conversion and utilization device. Biological utilization mainly focused on microalgae fixation and gas fertilizer utilization.

Pressure swing adsorption (PSA) at Karamay refinery in Xinjiang-By Peng Bo

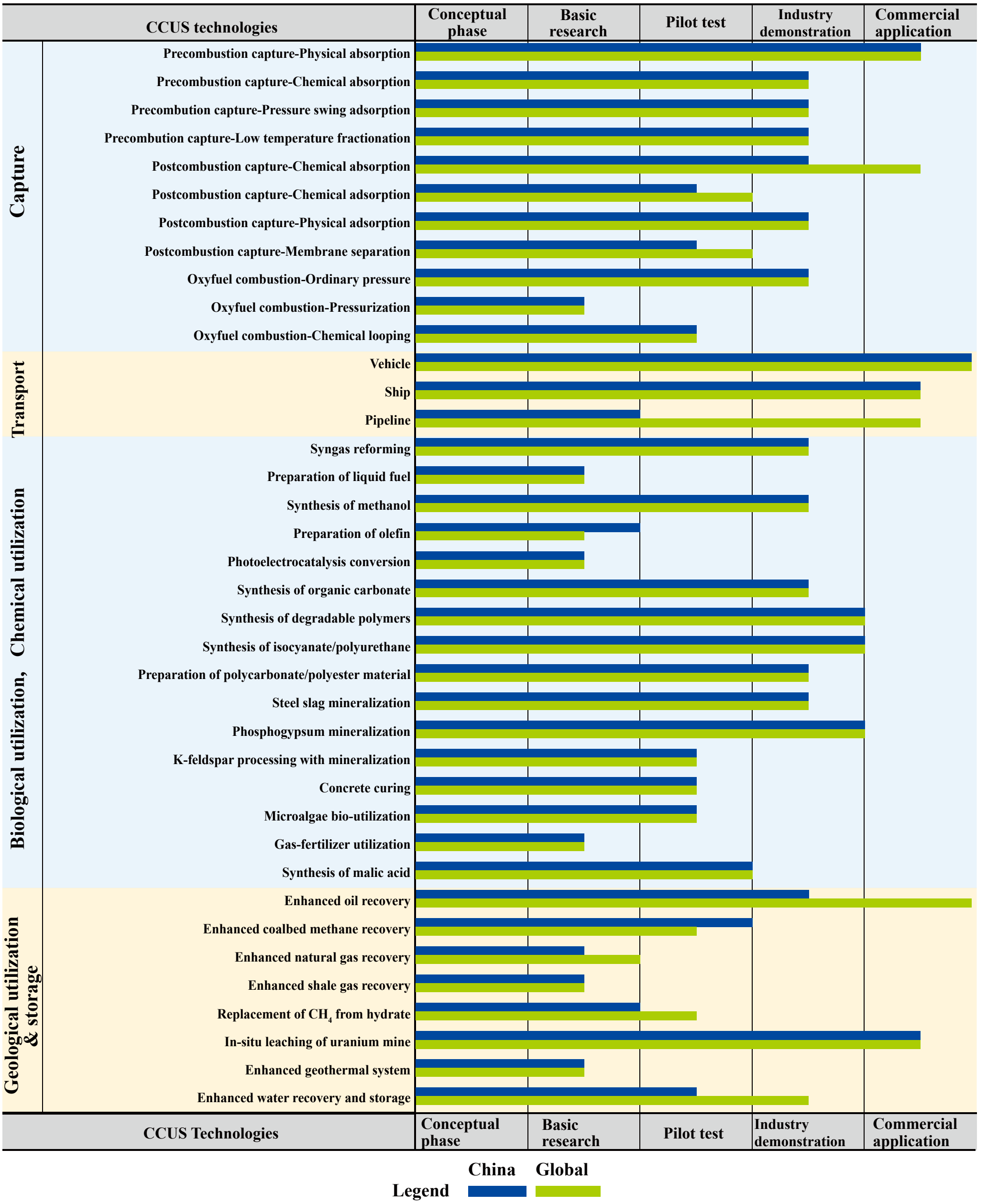

Figure 8 Types and development stages of CCUS technologies in China

Note: The Administrative Center for China's Agenda 21, 2021

3.2 Emission reduction demand of CCUS under the carbon neutrality target

According to the research of various domestic and foreign research institutions, to achieve the carbon neutralization target, China's CCUS emission reduction is 20 to 408 million tonnes in 2030, 600 million to 1.45 billion tonnes in 2050, and 1 to 1.82 billion tonnes in 2060. The scenarios mainly consider China's achievement of the 1.5°C and 2°C temperature control targets, sustainable Development Goals, carbon peaking and carbon neutral targets, CO_2 emission pathways by industry, development of CCUS technology, and scenarios in which CCUS can be used or may be used.

Table 3 Potential of CCUS CO_2 emission reduction in various industries from 2025 to 2060 (million tonnes/year)

Year	2025	2030	2035	2040	2050	2060
Coal power	6	20	50~100	200~500	200~500	200~500
Gas power	1	5	20~100	20~100	20~100	20~100
Steel	1	2~5	10~20	20~30	50~70	90~110
Cement	0.1~17	10~152	20~80	30~150	80~180	190~210
BECCS	0.5	1	18	80~100	200~500	300~600
DACCS	0	0	1	15	50~100	200~300
Petrochemical and chemical industry	5	50	30	0	0	0
All industries	9~30	20~408	119~850	370~1300	600~ 1450	1000~1820

Note for data sources: IEA, 2011, 2000; Wang ***et al***., 2014; Asian Development Bank, 2015; Xu ***et al***., 2016; The Administrative Center for China's Agenda 21, 2019; DNV, 2020; Goldman Sachs, 2020; Boston Consulting Corporation, 2020; Energy Transitions Commission, 2020; He Jiankun, 2020; Energy Foundation, 2020; WRI, 2021; Mckinsey, 2021; Global Energy Interconnection Development and Cooperation Organization, 2021a, 2021b; The Administrative Center for China's Agenda 21, 2021; Chinese Academy of Engineering, 2021; Tsinghua University, Beijing Institute of Technology, Development Research Center of the State Council, National Center for Climate Change Strategy and International Cooperation, Energy Research Institute, NDRC, P.R. China and other units based on China's carbon-neutral scenario joint forecast data. DACCS is in the primary research stage, and its technological maturity and economy need to be improved. The emission reduction potential is difficult to release in the short term. It is expected that industrialization demonstration and promotion will be carried out around 2035.

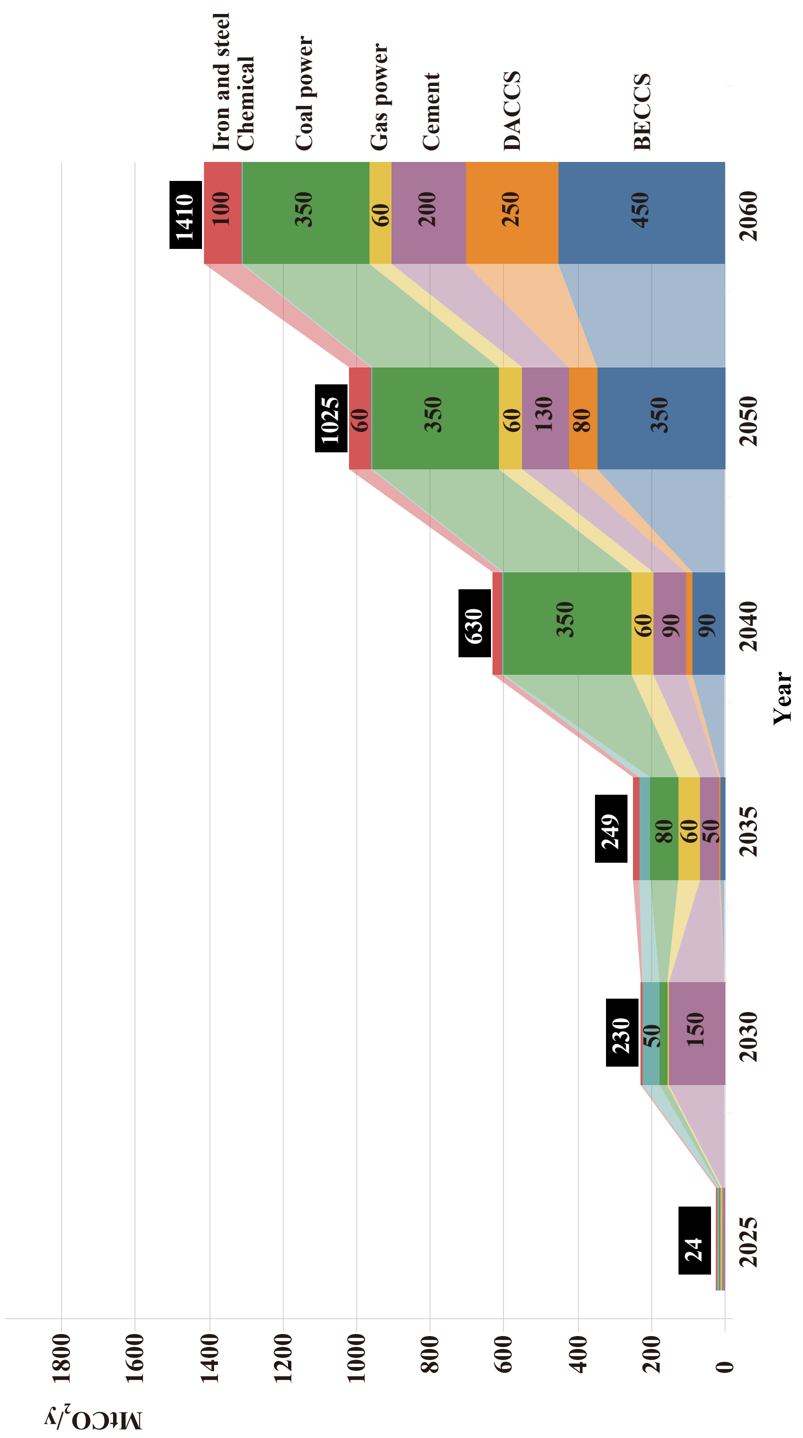

Figure 9 China's CCUS emission reduction demand

Note: Data came from Table 3, and values were taken as the median of the interval.

The thermal power industry is the main area of CCUS demonstration in China currently. It is expected that emission reduction by CCUS in coal power will reach 6 million tonnes/year by 2025, peak at 200 to 500 million tonnes/year in 2040, and then remain unchanged. The deployment of CCUS in gas power plants will be gradually carried out and will remain intact after reaching a peak in 2035, with 20 to 100 million tonnes per year. Coal-fired power plants equipped with CCUS can capture 90% of carbon emissions, turning them into relatively low-carbon power generation technology. About 900 million kilowatts of China's current installed capacity will still be in operation by 2050. The deployment of CCUS technology helps to make full use of existing coal-fired power generation units, appropriately retain coal-fired power production capacity, and avoid the premature retirement of some coal-fired power assets that may lead to resource waste. Technical suitability standards and costs are the main factors affecting the installation of CCUS in active coal-fired power. Technical suitability standard determines whether a power plant can be a candidate for transformation. At the present stage, technical suitability criteria that need to be considered in retrofitting coal-fired power plants includes the implementation year of CCUS, unit capacity, remaining service life, unit load rate, capture rate, and valley value/peak value, etc.

In steel industry, CCUS emission reduction demand is 2~5 million tonnes/year in 2030 and 90~110 million tonnes/year in 2060. China's iron and steel production process is dominated by the blast furnace-converter method with high emissions, and the output of electric furnace steel accounts for only about 10%. About 89% of energy input in blast furnace-converter steelmaking comes from coal, leading to high carbon emissions per tonne of steel in China. CCUS technology can be applied to many aspects of the steel industry, mainly in hydrogen production in hydrogen reduction ironmaking technology and steelmaking process. In addition, the CO_2-EOR project is also a vital driving force for the development of carbon capture technology in China's steel industry.

The CO_2 in China's steel plants is mainly of medium concentration, which can be captured by pre-combustion and post-combustion capture technology. Coking and blast furnace ironmaking processes have the most significant CO_2 emissions in the entire steelmaking process, and these two processes have the largest carbon capture potential. The mainstream carbon capture technology in China's steel industry is post-combustion CO_2 capture from coking and blast furnace.

In addition to utilization and storage, CO_2 captured in the iron and steel industry can also be directly used in the steelmaking process. These technologies have been tested successfully by Shougang Group and promoted to Tianjin Pipe International Economic & Trading Corporation and Xining Special Steel Co., Ltd. Full application of these technologies can reduce the total emissions by 5%~10%. There are four main development directions for CO_2 utilization in the steel industry: (1) It can be used for mixing. CO_2 can replace nitrogen (N2) or argon (Ar) for the top/bottom blowing of the converter or for the mixing of molten steel in the ladle; (2) It acts as a reactant and reduces the volatilization and oxidation loss caused by direct collision of oxygen and molten iron in CO_2-O_2 mixed spray steelmaking; (3) It can partially replace N2 as a protective gas in steelmaking, thereby minimizing the loss of steel, as well as the nitrogen content and porosity in the finished steel; (4)It also can be used to synthesize fuel. The dry reforming reaction of CO_2 and methane can produce synthesis gas (CO and hydrogen), which can then be used in DRI steelmaking or the production of other chemicals.

In the cement industry, the CCUS CO_2 emission reduction demand in 2030 will be 10~152 million tonnes/year, and the emission reduction demand in 2060 will be 190~210 million tonnes/year. The CO_2 emissions from the decomposition of limestone in the cement industry account for about 60% of the total emissions in the cement industry. CCUS is a necessary technical means for cement decarbonization.

The petrochemical and chemical industries are the main areas of CO_2 utilization, through chemical reactions to convert CO_2 into other substances and then for resource reuse. China's petrochemical and chemical industry has many high CO_2 concentration sources (above 70%) (including natural gas processing plants, coal plants, ammonia/fertilizer production plants, ethylene plants, methanol, ethanol and dimethyl ether production plants, etc.). Compared with low-concentration emission sources, the CO_2 capture of high concentration CO_2 emission sources have lower energy consumption, lower investment costs, and lower operation and maintenance costs, which have significant advantages. Therefore, high-concentration emission sources in the petrochemical and coal chemical industries can provide low-cost opportunities for early CCUS demonstrations. Early CCUS demonstration projects in China preferred combining high-concentration emission sources and EOR to generate revenue through CO_2-EOR. When the oil price is high, CO_2-EOR revenue can fully offset the cost of CCUS and create additional economic profits for the stakeholders of CCUS, that is, achieve CO_2 emission reduction at a negative cost. The demand for CCUS emission reduction in the petrochemical and chemical industries will be about 50 million tonnes in 2030 and will gradually decrease to zero by 2040.


Wellhead injection of carbon dioxide tanker in Xinjiang Oilfield-the initial stage of the project-By Peng Bo

3.3 Emission reduction potential of CCUS based on source-sink matching

In the category of CO_2 geological utilization and storage technologies, CO_2-EWR technology can achieve large-scale deep CO_2 emission reduction, with a theoretical storage potential of 2.417 trillion tonnes. Under current technological conditions, CO_2-EOR and CO_2-EWR can achieve large-scale CO_2 emission reduction under specific economic incentives. Therefore, this report provides source-sink matching condition of CO_2-EOR and CO_2-EWR with major industries in China.

China has enormous potential for CO_2-EOR storage. From the perspective of basin-scale, Bohai Bay Basin and Songliao Basin have great potential for CO_2-EOR geological storage. They are regarded as the priority areas for the implementation of the CCUS project. Combined with the geological characteristics of China's major basins and the distribution of CO_2 emission sources, the key CO_2-EOR areas in China are the Songliao Basin in northeast China, the Bohai Bay Basin in north China, the Ordos Basin in central China, and the Junggar Basin and Tarim Basin in northwest China.

The basins suitable for CO_2-EWR are widely distributed in China with great storage potential. The Junggar Basin, Tarim Basin, Qaidam Basin, Songliao Basin and Ordos Basin are the most suitable regions for CO_2-EWR storage. In 2010, Shenhua Group carried out a CCS demonstration project in Ordos Basin, the first and largest full-process CCS saline reservoir storage project in Asia. The deep aquifer in Songliao Basin has good reservoir and caprock properties, which implies a potential site for large-scale CO_2 storage in China.

Sedimentary basins in the east and north, such as Bohai Bay Basin, Ordos Basin and Songliao Basin, match well with the distribution of carbon sources. The geological conditions of storage in northwest China are relatively good, and the Tarim and Junggar basins have great geological storage potential. Still, there are fewer carbon emission sources in this region. In the southern and coastal areas where carbon sources are concentrated, the sedimentary basins that can be sequestrated are small in space and scattered in distribution, with relatively poor geological conditions. The potential of onshore storage is minimal. Offshore geological storage in offshore sedimentary basins is an important alternative.

CCUS source-sink matching mainly considers the geographical location relationship and environmental suitability of emission sources and storage sites. 250 km is the longest distance of the pipeline that does not require a CO_2 relay compressor station, and the pipeline cost is relatively low. Therefore, it is often used as the distance limit in the analysis of source-sink matching in China, and more than 250 km is generally not considered. The Chinese government attaches great importance to the environmental impact and risks of CCUS. The Ministry of Environmental Protection released the *Technical Guidelines for Environmental Risk Assessment of CO_2 Capture, Utilization and Storage (Trial)* on June 20, 2016. Considering the regulatory requirements of the Chinese government for the environmental impacts and risks of CCUS projects, the environmental risks and impacts of CO_2 geological storage on water resources (groundwater and surface water), surface vegetation and human health are mainly considered.

Thermal power: The Junggar Basin, Turpan-Hami Basin, Ordos Basin, Songliao Basin and Bohai Bay Basin are considered as key areas for the deployment of CCUS technology (including CO_2-EOR) in the thermal power industry, which are suitable for the early integration demonstration projects to promote the large-scale and commercial development of CCUS technology.

In 2020, China's coal-fired power plants in service will be distributed in 798 grids with a width of 50 km, covering central and eastern China, most of South China, and parts of northeast and northwest China. There are 51 grids with annual CO_2 emissions of more than 20 million tonnes, mainly distributed in central China and the eastern coastal areas, where suitability of storage sites is particularly medium or low. In particular, there are almost no sites suitable for storage on land along the eastern coast. There are 99 grids with annual CO_2 emissions of 10-20 million tonnes, which have medium and high suitability for storage in Turpan-Hami

Basin, Ordos Basin, Junggar Basin, Songliao Basin and Qaidam Basin. However, Southern inland provinces, such as Guizhou, Jiangxi, Anhui and other regions with significant local thermal power emissions do not have matching storage sites. Hunan and Hubei provinces only have scattered sites with medium and low suitability in Dongting and Jianghan Basin.

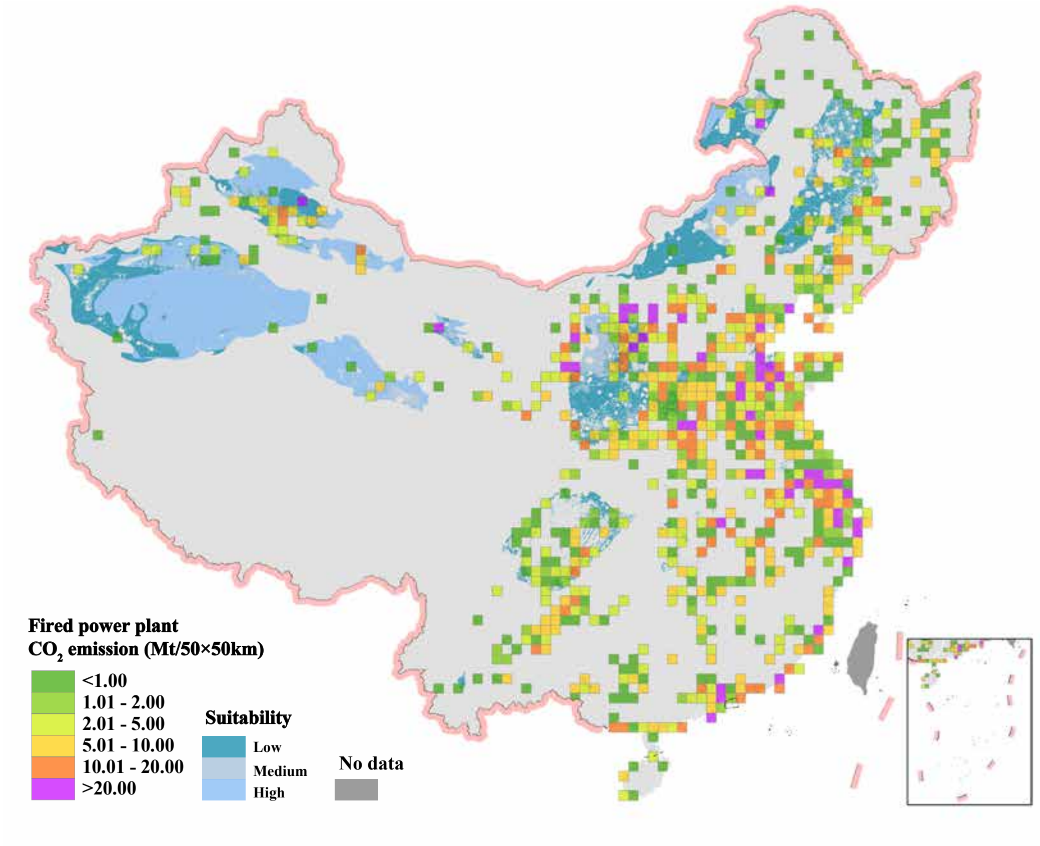

Figure 10 Distribution of emissions of thermal power enterprises in 2020 and suitable sites of geological storage of in China

Note: The 50 km grid emission data of China thermal power enterprises in 2020 comes from China high resolution emission gridded database (CHRED). Data on storage suitability came from Cai *et al*., 2017.

Iron and steel: Iron and steel companies are mainly located in provinces with rich iron ore and coal resources, such as Hebei, Liaoning, Shanxi, Inner Mongolia, etc., and the coastal areas with port resources.

In 2020, China's iron and steel enterprises were distributed in 253 grids with a width of 50 km. There are 26 grids with annual CO_2 emissions more than 20 million tonnes, mainly distributed in Hebei, Liaoning and Shanxi provinces. 28 grids with CO_2 yearly emissions ranging from 10 to 20 million tonnes, mainly distributed in Hebei, Shanxi, Liaoning, Shandong, etc. In addition, there are 1 to 2 such grids in each province or regions of Fujian, Hunan, Hubei, Guangdong, Jiangxi, Jiangsu, Xinjiang. There are scattered sites with medium and low suitability in Bohai Bay Basin, Shandong Province, among these high emission areas. Iron and steel plants in Shanxi should increase the transportation distance to find suitable sites in the Ordos, Linfen and other basins. Under the condition of 250 km matching distance, more than 79% of steel plants can find suitable geological utilization and storage sites.

Steel plant can carry out CO_2-EOR and CO_2-EWR joint projects or separate CO_2-EOR projects, and the levelized cost is low, and even some projects can be profitable. Due to the minimal CO_2 storage capacity of oil fields and the competition with CCUS in chemical, thermal power, cement and other industries, it is difficult for the steel industry to obtain enough oil fields to carry out CO_2-EOR to achieve deep carbon reduction. Therefore, the CO_2-EWR project must be carried out.

The higher the net CO_2 capture rate of the steel plant, the lower the levelized cost of large-scale projects. Under the same net capture rate, the larger the matching distance, the more matched projects, and the more cumulative CO_2 emission reduction. Under the same capture rate and matching distance scenario, the levelized cost of the CO_2-EWR project is much higher than that of the CO_2-EOR project. There are many steel plants in Bohai Bay Basin, Junggar Basin, Jianghan Basin, Ordos Basin, with high suitability of storage sites. In contrast, the higher costs of steel plants in southern, coastal and other regions is due to the longer transportation distance and the lower estimated CO_2 emissions.

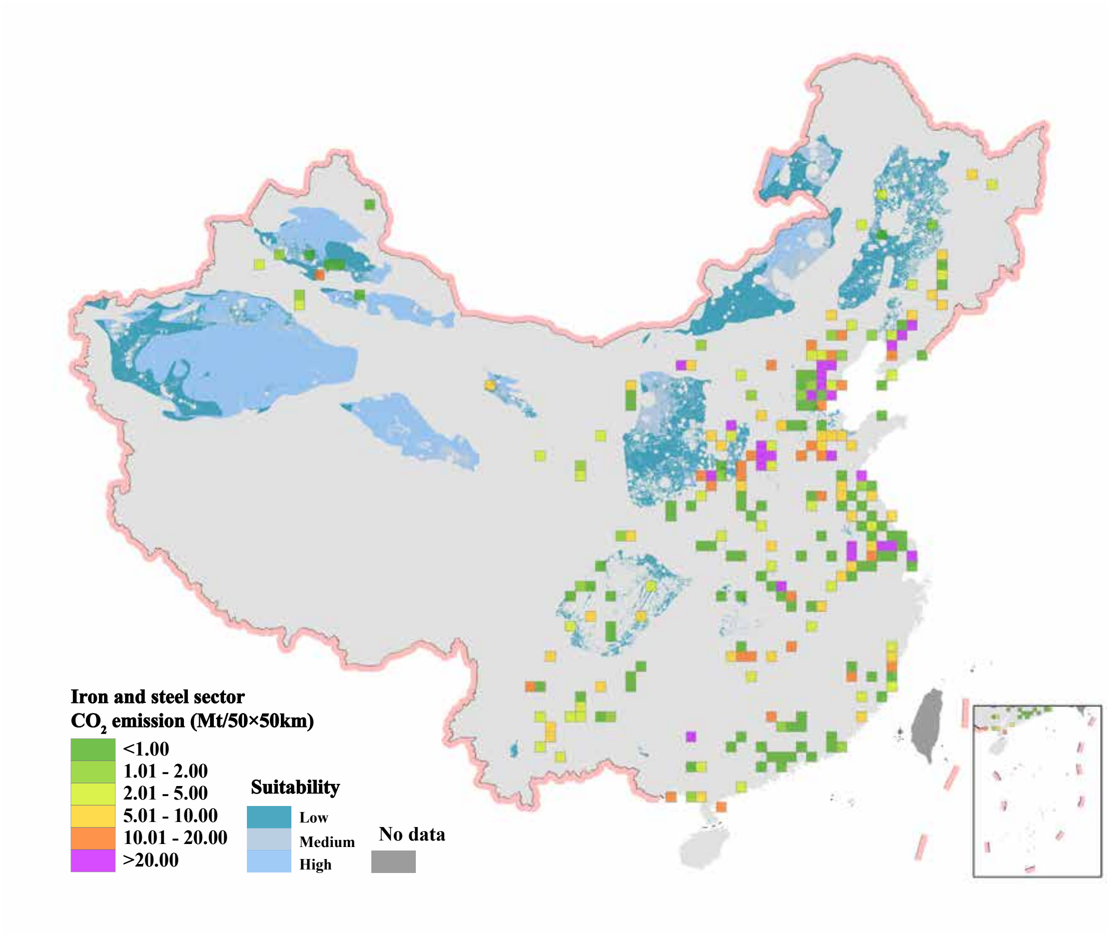

Figure 11 Distribution of emissions of iron and steel enterprises in 2020 and suitable sites of geological storage

Note: The 50 km grid emission data of China thermal power enterprises in 2020 comes from China high resolution emission gridded database (CHRED). Data on storage suitability came from Cai *et al.*, 2017.

Table 4 Potential of CCUS CO_2 utilization and storage in China from 2025 to 2060 (million tonnes/year)

Year	2025	2030	2035	2040	2050	2060
Chemical utilization& bioutilization	0.4~0.9	0.9~1.4	1.4~2.6	2.9~3.7	4.2~5.6	6.2~8.7
Geological utilization and storage	0.1~0.3	0.5~1.4	1.3~4.0	3.3~8.0	5.4~14.3	6.0~20.5
Total	0.5~1.2	1.4~2.8	2.7~6.6	6.2~11.7	9.6~19.9	12.2~29.2

Note: Wei *et al*., 2015; Hou Zhaolong *et al*., 2015; Tang Qingsi *et al*., 2016; Wang Chenye *et al*., 2016; Li Huiquan *et al*., 2017; Li *et al*., 2018; Gao *et al*., 2018; Jang *et al*., 2019; Zhou *et al*., 2019; Ye *et al*., 2019; Chen Mengmeng *et al*., 2019; Fang Yanfeng *et al*., 2020; Qin Jishun *et al*., 2020; Chinese Academy of Engineering, 2021. The upper limit of CO_2 chemical utilization potential is calculated based on the market share of chemical products. In contrast, the upper limit of geological utilization potential and storage potential is calculated based on the matching result of internal source and sink of 250 km. These two cannot be added.

CO_2-EOR project in Jiyuan Oilfield, Dingbian, Yulin, Changqing Oilfield Company-By Xu Dakang

3.4 Cost assessment of CCUS in China

The overall scale of CCUS demonstration projects in China is small, and the cost is high. The costs of CCUS mainly includes economic costs and environmental costs. Economic costs include fixed and operation costs, while environmental costs include environmental risk and energy consumption emission.

The primary component of economic costs is operation costs, which is the input costs required by each link of CCUS technology in the whole process of actual operation. The operation costs mainly include four segments: capture, transportation, storage and utilization. It is estimated that the capture costs will be 90~390 yuan/tonne in 2030 and 20~130 yuan/tonne in 2060. Pipeline transportation is the main transportation mode for future large-scale demonstration projects. It is estimated that the cost of pipeline transportation in 2030 and 2060 will be 0.7 and 0.4 yuan /(tonne·km), respectively. The storage costs in 2030 is 40~50 yuan/tonne, and in 2060, it is 20~25 yuan/tonne.

Table 5　Economic Costs of each segment of CCUS from 2025 to 2060

Year		2025	2030	2035	2040	2050	2060
Capture cost (Yuan/tonne)	Pre-combustion	100~180	90~130	70~80	50~70	30~50	20~40
	Post-combustion	230~310	190~280	160~220	100~180	80~150	70~120
	Oxyfuel combustion	300~480	160~390	130~320	110~230	90~150	80~130
Transportation cost (Yuan / (tonne·km))	Tanker	0.9~1.4	0.8~1.3	0.7~1.2	0.6~1.1	0.5~1.1	0.5~1
	Pipeline	0.8	0.7	0.6	0.5	0.45	0.4
Storage cost (yuan/tonne)		50~60	40~50	35~40	30~35	25~30	20~25

Note: Costs include fixed and operating costs. Data source: Wang Feng ***et al***., 2016; Liu Jiajia ***et al***., 2018; Ministry of Science and Technology, 2019; Fan ***et al***., 2019; Cai Bofeng ***et al***., 2020; Wei Ning ***et al***., 2020; Wang Tao ***et al***., 2020; Yang ***et al***.,2021.

The capture and compression costs are the main sources of CCUS operating costs in the petrochemical and chemical industries. Higher CO_2 production concentration usually means CO_2 capturing rate is high and compression costs will reduce, so increasing CO_2 production concentration is an effective way to reduce the total cost of CCUS operation.

After adopting CCS and CCU processes, the coal gasification costs increase by 10% and 38% respectively. And when the carbon tax is higher than \$15/tonne of CO_2, the production costs of CCS and CCU is more advantageous than that of traditional coal gasification processes. In the comprehensive CCUS project of Yanchang Petroleum Group, CO_2 is derived from the pre-combustion process of coal-to-gas (the production of syngas from coal-to-gas). As a result, compared to other CO_2 capture and transport projects, the capture and operation costs of the Yanchang Petroleum Group comprehensive CCUS project decreased by approximately 26.4% to only \$26.5/tonne, with capture costs of \$17.52/tonne and transport costs of \$9.03/tonne.

Another component of the economic cost is the fixed costs, which is the upfront investment of CCUS technology, such as equipment installation, land footprint investment, etc. It costs about \$27 million for a steel plant to install a CO_2 capture and storage facility with an annual capacity of 100,000 tonnes. Starting a CCUS project at Baosteel's Zhanjiang plant with an annual capture capacity of 500,000 tonnes (stored in the Beibu Gulf Basin, within 100 km of the plant) will require an investment of \$52 million. The economic assessment of Baosteel's Zhanjiang plant shows that combining with fixed and operating costs, the total cost of emission reduction is \$65/tonne of CO_2, which is similar to the costs in Japan (\$54/tonne of CO_2) and Australia (\$60~193/tonne of CO_2).

The extra costs caused by installing a carbon capture device is 0.26~0.4 yuan /kWh for thermal power. The cost per kilowatt-hour of electricity for power plants with large installed capacity, the increased cost of power generation after the installation of capture devices, and the cost of net CO_2 emission reduction and capture will be lower. In terms of cooling appliances, wet-cooled power plants have lower net CO_2 emission reduction costs and capture costs compared with air-cooled power plants, but higher water consumption. The total water consumption of the cooling system increases approximately 49.6% after installing a capture device in power plants, which causes more serious water resource pressure to local areas, especially areas with water shortages.

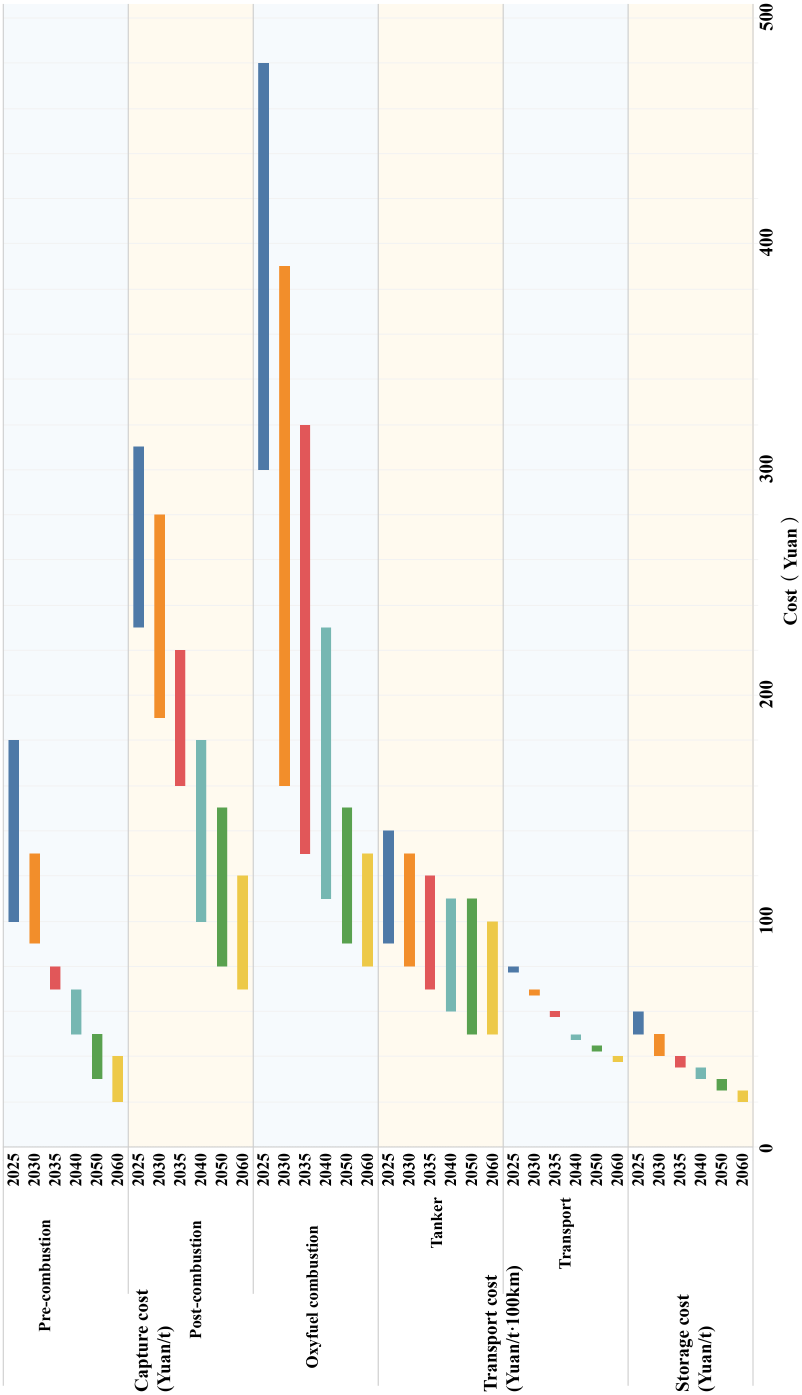

Figure 12 CCUS economic costs in China from 2025 to 2060 (The color of the bar in the figure represents different periods)

The environmental costs are mainly due to the environmental impacts and risks of CCUS. First, the technology of CCUS may bring environmental risks. CO_2 may leak during the process of capture, transportation, utilization and storage, which will have a certain impact on the nearby ecological environment and personal safety. Second, environmental pollution is caused by the additional energy consumption of CCUS technology. Most CCUS technologies have the characteristics of additional energy consumption, and the increase in energy consumption will inevitably bring the emission pollutants. Considering the storage scale, environmental risk and supervision, it is generally required that the safety period of CO_2 geological storage should be no less than 200 years abroad.

The energy consumption is mainly concentrated in the capture stage, wherein the impact of energy consumption on the cost and environment is very significant. For example, alcohol amine absorbent is the most widely used absorbent to capture CO_2 from coal flue gas. However, the chemical absorption method based on alcohol amine absorbent still has obvious limitations in large-scale commercial applications. One of the main reasons is that the operation energy consumption is too high, reaching 4.0~6.0 MJ/kg CO_2.


CO_2-EOR project in Jilin Oilfield, CNPC-By Cai Bofeng

4.Policy Suggestions »»

(1) Develop detailed pathway of CCUS for the carbon neutrality target. Taking full account of the industrial structure and emission path of key industries under the carbon neutrality target, a comprehensive and systematic assessment about the emission reduction demands and potential of CCUS in China from 2021 to 2060 need to be made.

(2) Improve CCUS policy support and standard system. China should promote the commercialization of CCUS, include CCUS in the catalog of industrial and technological development, improve and optimize the framework of laws and regulations, and formulate a scientific and reasonable standard system for construction, operation, supervision and termination.

(3) Plan and layout CCUS infrastructure construction. Increase the investment and construction scale of carbon dioxide capture, transportation and storage infrastructure, improve the management level of technical facilities, establish the cooperation and sharing mechanism of related infrastructure, and promote the coupling and integration of CCUS with different carbon emission fields and industries.

(4) Carry out large-scale CCUS demonstration and industrial cluster construction. China should improve the compatibility, integration, and optimization of CCUS, accelerate the technical breakthrough of large-scale whole-process CCUS demonstration, and promote the construction of CCUS industrial cluster.

CCUS projects in China »»

Project name	Provinces, regions and cities	Capture									Transportation	
		Industry type of emission source	Management subject	Capture source	Capture technology	Capture scale (Kilotonnes/ year)	Energy consumption (GJ)	Water consumption (tonnes / tonne)	CO_2 purity (%)	CO_2 total production (Kilotonnes)	Transportation type	Transportation distance (km)
China Energy Investment Corporation Saline Aquifers Storage Project in Ordos	Ordos, Inner Mongolia	Coal to oil	Ordos Coal to Oil Branch of China Energy Investment Group Co. Ltd		Pre-combustion (physical adsorption)	100	1.23	–	99.5	302.6	Vehicle	~13
Yanchang Petroleum Shaanxi Coal Chemical Industry CO_2 capture and demonstration	Xi' an, Shaanxi Province	Coal-to-gas	Shaanxi Yanchang Petroleum Yulin Coal Chemical Company Gasification Plant		Pre-combustion (physical absorption)	300	NA	NA	99.8	50	Vehicle	200
China National Nuclear Corporation Limited leaching of uranium in Tongliao	Tongliao, Inner Mongolia	–	–	–	–	–	–	–	–	–	Vehicle	–
Research and demonstration of CO_2-EOR in Jilin oilfield of PetroChina	Songyuan, Jilin	Natural gas processing	Jilin oil field Changling natural gas processing plant		Pre-combustion (separation of associated gas)	600	NA	NA	99.9	1600	Pipeline	20
Huaneng Gaobeidian Power Plant	Beijing	Coal-fired power plants	Huaneng Gaobeidian Power Plant		Post-combustion (chemical absorption)	3	0.972	NA	> 99.9	NA	–	–
Huaneng Green Coal Power IGCC CO_2 Capture, utilization and storage	Tianjin	Coal-fired power plants	Tianjin Binhai New Area 400 MW IGCC demonstration unit		Pre-combustion (chemical absorption)	100	NA	NA	NA	NA	Vehicle	–
Guodian Group Tianjin Beitang Thermal Power Plant	Tianjin	Coal-fired power plants	Tianjin Beitang Power Plant		Post-combustion (chemical absorption)	20	NA	NA	NA	NA	Vehicle	–
Clean Energy Power System Research Facility in Lianyungang	Lianyungang, Jiangsu	Coal-fired power plants	Lianyungang Clean Energy Innovation Industrial Park	400 MW IGCC units	Pre-combustion	30	NA	NA	NA	NA	Pipeline	–
Huaneng Shidongkou Power Plant	Shanghai Shidongkou	Coal-fired power plants	Huaneng Shanghai Shidongkou No. 2 Power Plant	600 MW supercritical unit	Post-combustion (chemical absorption)	120	0.738	NA	NA	NA	–	–
Sinopec Shengli Oilfield, CO_2-EOR Project	Dongying, shandong province	Coal-fired power plants	Shengli power plant		Post-combustion (chemical absorption)	40	NA	NA	99.997	NA	Vehicle	–
Sinopec Zhongyuan Oilfield CO_2-EOR Project	Puyang , Henan Province	Fertilizer plant		Synthesis ammonia tail gas from fertilizer plant	Pre-combustion(chemical absorption)	100	NA	NA	NA	5000	Vehicle	NA

Utilization and Storage								Cost per tonne of CO_2 (yuan/ tonne)	First year of operation	Status in 2021,
Disposal enterprise	Disposal site	Disposal technology	CO_2 Annual utilization/ injection (Kilo-tonnes)	CO_2 total utilization (Kilo-tonnes)	Product	Capacity (Kilotonnes/ year)	Total resource production (Kilotonnes)			
Coal to Oil Branch of China Energy Investment Group Co. Ltd	Ordos basin	Saline aqui-fer storage	100	302.6	_	_	_	249	2011	Suspended in 2016, under monitoring
Yanchang Petroleum	Jingbian Oilfield, Yulin, Shaanxi	EOR	50	130	Crude oil	NA	NA	120	2013	In operation
Tongliao uranium industry	Qianjiadian uranium deposit	Leaching of uranium	NA	NA	NA	NA	NA	NA	NA	NA
Jilin oilfield	Daqing Zijing Oilfield	EOR	250	1400	Crude oil	75	NA	166	2008	In operation
Gaobeidian power plant	NA	NA	_	_	_	_	_	_	2008	Suspended
_	_	Emptying	_	_	_	_	_	_	2015 The capture device was completed, and the utilization and storage project was delayed	Suspended after experimental verifi-cation completed
_	Market sales	Food appli-cations	_	_	_	_	_	_	2012	In operation
_	_	Emptying	_	_	_	_	_	_	2011	In operation
Shidongkou power plant	Market sales	Industrial utilization and food application	_	_	_	_	_	_	2009	Intermittent operation
Shengli oilfield	Block G89, Shengli Oilfield, Dongying City	EOR	40		Crude oil	NA	NA	450	2010	In operation
Zhongyuan Oilfield	Zhongyuan Oilfield	EOR	100	740	Crude oil	NA	NA	350	2015	In operation

Project name	Provinces, regions and cities	Capture									Transportation	
		Industry type of emission source	Management subject	Capture source	Capture technology	Capture scale (Kilotonnes/year)	Energy consumption (GJ)	Water consumption (tonnes / tonne)	CO_2 purity (%)	CO_2 total production (Kilotonnes)	Transportation type	Transportation distance (km)
China Power Investment Corporation Chongqing Shuanghuai Power Plant Carbon Capture Demonstration Project	Chongqing	Coal-fired power plants	Chongqing Hechuan Shuanghuai Power Plant	Two 300 MW units	Post-combustion (chemical absorption)	10	NA	NA	> 99.9	NA	_	_
China United Coalbed Methane Corporation CO_2-ECBM Project(Shizhuang)	Qinshui, Shanxi	Outsourcing gas	–	–	–	–	–	–	–	–	Vehicle	NA
oxyfuel combustion demonstration of Huazhong University of Science and Technology	Wuhan, Hubei	Coal-fired power plants	Hubei Jiuda (Yingcheng) Company	Thermal power plant workshop 2	Oxyfuel combustion	100	15.48	40	95	NA	Vehicle	_
China United Coalbed Methane Corporation CO_2-ECBM Project(Liulin)	Liulin, Shanxi	–	–	–	–	–	–	–	–	–	Vehicle	NA
Kelamay Dunhua Petroleum - Xinjiang Oilfield CO_2-EOR Project	Karamay, Xinjiang	Methanol factory	Xinjiang Dunhua Petroleum Technology Co. Ltd	Methanol Plant of PetroChina Karamay Petrochemical Company	Pre-combustion(chemical absorption)	100	2.5	45	99.96	NA	Vehicle	26
Changqing Oilfield CO_2-EOR project	Xi' an, Shaanxi	Methanol factory	Ningxia Deda Gas Development Technology Co. Ltd	Shenning Coal Chemical Methanol Plant	Pre-combustion	50	NA	NA	NA	NA	Vehicle	NA
Daqing Oilfield CO_2-EOR Demonstration Project	Daqing, Heilongjiang	Natural gas processing	Xushen 9th natural gas purification plant, Daqing natural gas branch	Xushen gas field	Pre-combustion(Separation of associated gas)	NA	NA	NA	NA	NA	Vehicle (purchased gas) + pipeline (Xushen 9th Natural Gas Purification Plant)	NA
CO_2 capture and purification demonstration project of Wuhu Baimashan Cement Plant of Conch Group	Wuhu, Anhui	Cement plant	Wuhu Baimashan Cement Factory		Pre-combustion(chemical absorption)	50	NA	NA	99.99	_	Vehicle	_
China Resources Power Holdings Co., Ltd. (CR Power) Haifeng Carbon Capture Test Platform	Haifeng County, Guangdong Province	Coal-fired power plants	Sino-British (Canton) CCUS Center	No. 1 unit of (CR Power) Haifeng Power Plant	Post-combustion	20	3.24	20t/h	99.99	NA	-	_
Sinopec East China Oil & Gas Field CCUS Whole Process Demonstration Project	Dongtai, Jiangsu	Chemical plant	Jiangsu Huayang Liquid Carbon Co. Ltd. Taixing Carbon Dioxide Factory	Sinopec nanjing chemical company	Pre-combustion	100	124yuan/tonne	8.6 yuan/tonne	99	100	Vehicle/ship	100

Utilization and Storage										
Disposal enterprise	**Disposal site**	**Disposal technology**	**CO_2 Annual utilization/ injection (Kilo-tonnes)**	**CO_2 total utilization (Kilo-tonnes)**	**Product**	**Capacity (Kilotonnes/ year)**	**Total resource production (Kilotonnes)**	**Cost per tonne of CO_2 (yuan/ tonne)**	**First year of operation**	**Status in 2021,**
–	Used in their power plant	Used for welding protection, hydrogen cooling re-placement of power plant , etc	–	–	–	–	–	NA	2010	In operation
China United Coalbed Methane Corporation	Shizhuang block, Qinshui basin	ECBM	1	NA	Coalbed methane (CBM)	NA	NA	NA	2004	In operation
_	Market sales	Industrial application	–	–	–	–	_	780~900	2014	In operation
China United Coalbed Methane Corporation	Liulin Block, Ordos Basin	ECBM	1	NA	Coalbed methane (CBM)	NA	NA	NA	2012	In operation
Xinjiang Oilfield	Xinjiang Oilfield, Junggar basin	EOR	50~100	1239	Crude oil	14~39	495.1	800	2015	In operation
Changqing Oilfield	Jiyuan Oil Area, Changqing Oil-field, Dingbian County, Shaanxi Province	EOR	50	376	Crude oil	NA	NA	NA	2017	In operation
Daqing Oilfield	Block 101, Changyuan Peripheral, Block 14, Hailaer Oilfield	EOR	200	NA	Crude oil	NA	NA	NA	2003	In operation
_	Market sales	_	_	_	_	_	_	NA	2018	In operation
CR Power (Haifeng) Power Plant	NA	_	_	_	_	_	_	500	2019	In operation
Sinopec East China Branch	Zhenwu, Huazhuang, Shuaiduo, Caoshe and Hai' an blocks of East China oil and gas fields	EOR	100	400	Crude oil		130		2005	In operation

Project name	Provinces, regions and cities	Capture									Transportation	
		Industry type of emission source	Management subject	Capture source	Capture technology	Capture scale (Kilotonnes/year)	Energy consumption (GJ)	Water consumption (tonnes / tonne)	CO_2 purity (%)	CO_2 total production (Kilotonnes)	Transportation type	Transportation distance (km)
Sinopec Qilu Petrochemical CCS Project	Zibo, Shandong	Chemical plant	China Petroleum & Chemical Corporation Ltd		Pre-combustion	350					Pipeline	
Field pilot experiment of CO_2-EWR in Zhundong, Xinjiang	Changji Hui Autonomous Prefecture, Xinjiang Uygur Autonomous Region	-			Post-combustion	-					Vehicle	
China Energy Investment Corporation Guohua Jinjie Power Plant post-combustion CO_2 capture and storage demonstration project	Yulin, Shaanxi	Coal-fired power plants	China Energy Investment Corporation		Post-combustion	150						
Huaneng natural gas power generation flue gas post-combustion CO_2 capture experimental device	Beijing	Coal-fired power plants	China Huaneng Group Co. Ltd		Post-combustion	1						
Huaneng Changchun Thermal Power Plant Post-combustion capture project	Changchun, Jilin	Coal-fired power plants	China Huaneng Group Co. Ltd		Post-combustion	1						
Beijing Liulihe cement kiln flue gas carbon capture and application project	Liulihe, Beijing	Cement plant	Beijing liulihe cement co. LTD		Pre-combustion	1						
Lishui 36-1 gas field CO_2 separation, liquefaction and dry ice production project	Wenzhou, Zhejiang	Natural gas production	China National Offshore Oil Corporation Ltd		Pre-combustion	250					Vehicle/Ship	
300Nm3/h flue gas CO_2 chemical absorption pilot test platform	Hangzhou, Zhejiang	Oil burning boiler			Post-combustion	0.5						
Qilu Petroleum and Chemical Corporation Shengli Oil Field CCUS project	Zibo, Shandong	Chemical plant	Shengli Oilfield Company, Sinopec	Fertilizer plant	Rectisol	1000	-	-	99	1000	Vehicle	80

Utilization and Storage								Cost per tonne of CO_2 (yuan/ tonne)	First year of operation	Status in 2021,
Disposal enterprise	Disposal site	Disposal technology	CO_2 Annual utilization/ injection (Kilo-tonnes)	CO_2 total utilization (Kilo-tonnes)	Product	Capacity (Kilotonnes/ year)	Total resource production (Kilotonnes)			
		EOR							2017	In operation
		Experiment							2018	Experiment
		Saline aqui-fer storage							2020	Under construction
									2012	Suspended
									2014	Intermittent operation
		Industrial application							2017	In operation
		merchandise							2019	Intermittent operation
		Experiment							2017	Intermittent operation
Shengli Oilfield Company, Sinopec	Dongying and Zibo, Shandong	EOR	1000	1000	Crude oil	300	-	-	2022	Under construction

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