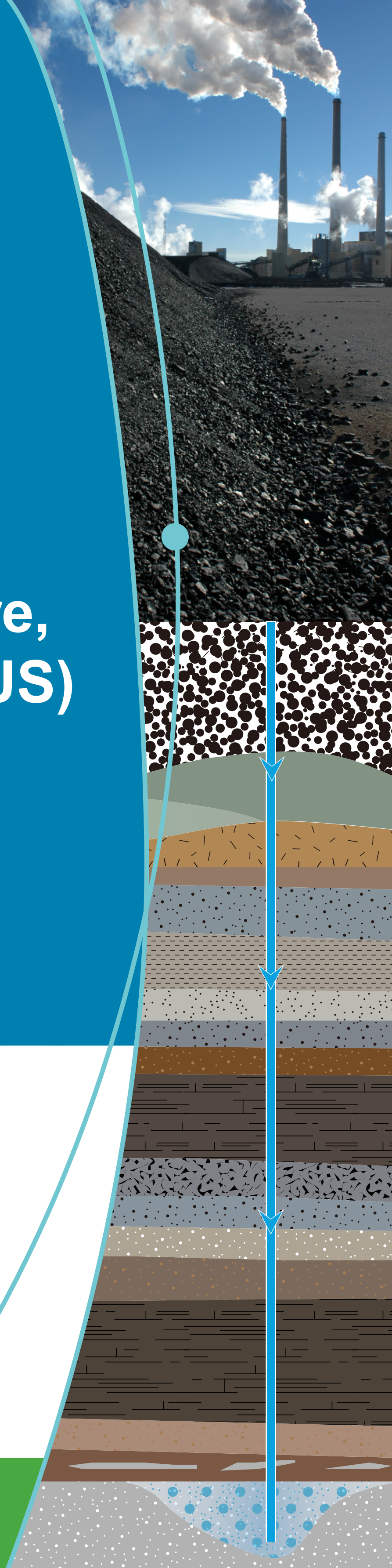
China Status of CO_2 Capture, Utilization and Storage (CCUS) 2019



Forword

Climate change is the most severe challenge facing our planet during the 21st century. It is a major global issue that profoundly affects the economic and social development and environmental sustainability of all countries. Actively addressing climate change has become a global consensus and unavoidable issue. Chinese President Xi Jinping has emphasized many times that addressing climate change should be carried out on our own, rather than someone else's initiative. Achieving sustainable development is not only an internal need but also our responsibility to promote the development of the community with a shared future for mankind. The report of the *19th National Congress of the Communist Party of China* proposed that new economic growth opportunities and drivers should be cultivated in areas such as environmental protection and low carbon development. At the 2018 National Conference on Ecological and Environmental Protection, President Xi Jinping proposed that we should implement a national strategy for actively addressing climate change. This would include advancing and guiding the establishment of a global climate governance system featuring equity, rationality and win-win cooperation. This strategy resonates well with China's image as a responsible country and will promote the building of a human community with a shared future.

China's *Intended Nationally Dete rmined Contribution: Enhanced Actions on Climate Change*, released in 2015, clearly stated that China aims to peak carbon dioxide emissions around 2030, and will use best efforts to peak earlier. By 2030, the CO_2 emissions per unit of GDP should fall by 60% to 65% compared to 2005 levels; non-fossil energy should account for about 20% of primary energy consumption.

Carbon dioxide capture, utilization and storage (CCUS) technology has the great potential to help to achieve near-zero emissions while still using fossil energy, which has received global attention. China attaches great importance to CCUS technology. The *"Thirteenth Five-Year Plan for the Greenhouse Gas Emissions Control,"* issued by the State Council in 2016 clearly stated, "to promote the pilot demonstration of carbon capture, utilization and storage in the industrial sectors." The National Development and Reform Commission, the Ministry of Ecology and Environment, the Ministry of Science and Technology, and other relevant Departments have issued more than 20 policy documents to actively promote the development of CCUS technology. In 2016, the former Ministry of Environmental Protection (now the Ministry of Ecology and Environment) released the "*Technical Guidelines on Environmental Risk Assessment for Carbon Dioxide Capture, Utilization and Storage (Trial)*", which is the first environmental standard for CCUS in developing countries.

China has made a great effort in research, development, demonstration, and commercialization of CCUS technology. This has initially formed a government-led and market-driven environment that led to various technical pathways with active participation by enterprises. " *China Status of CO_2 Capture, Utilization and Storage (CCUS) 2019*" documents the progress of CCUS development in China through field data collection and reviewing existing literature. The report summarizes China's efforts and practices, evaluates the progress and needs, and provides strategic thinking for CCS's future direction in the country. It is hoped that more research institutions and enterprises will join hands to promote the development of CCUS and to address climate change.

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Abstract »»

As an emerging technology for the large-scale mitigation of CO_2 emissions from the use of fossil energy, carbon dioxide capture, utilization, and storage (CCUS or CCS) has received widespread attention from the international community.

There are various CCUS technologies demonstrated in China, including CO_2 storage in deep saline aquifers, CO_2-enhanced oil recovery (CO_2-EOR), and displacement of coalbed methane by CO_2. These projects provide valuable experience and data for the future development of CCUS in China and the rest of the world. As of the end of 2019, China had launched a total of nine capture demonstration projects and twelve geological utilization & storage projects (including 10 full-process demonstration projects). The cumulative volume of geologically-stored CO_2 in all CCUS projects is approximately 2 million tons.

The CO_2 capture projects are mainly concentrated in the coal chemical industry, followed by the thermal power industry. Geological utilization and storage projects are mainly focused on enhancing oil recovery. China's CO_2 capture technology is relatively mature, and several core technologies in geological utilization and storage have made major breakthroughs. CO_2-EOR has entered the initial stage of commercial application.

The economic cost is a major hurdle for the development of CCUS in China. CO_2 capture consumes the most energy and is the most expensive in the entire CCUS process, including capture, transportation, utilization, and storage. Currently in China, the capture cost for the low-concentration CO_2 is 300-900 yuan/ton, and the transportation cost by tanker is about 0.9-1.4 yuan/(ton/km). The cost of flooding and storage technology varies greatly depending on the technical details, reservoir conditions, gas source, and source-sink distance. CO_2-EOR can effectively compensate the cost of CCUS. At the level of 70 USD per barrel of

crude oil, the cost of CO_2-EOR can be balanced in China.

Compared to China's CO_2 emissions reduction requirements, the contribution of CCUS is still very small (the annual storage volume is about one ten-thousandth of annual total emissions). It is recommended to establish a more comprehensive CCUS policy framework as soon as possible to promote the development of CCUS in China. The recommended policy initiatives include：

(1) To establish and improve CCUS regulations and standards.

There are urgent legal and regulatory issues needing to be solved, such as unclear ownership, unclear jurisdiction and approval procedures, and lack of relevant technical specifications. It is necessary to formulate clear and complete CCUS laws and regulations to reduce the concerns of stakeholders. Based on the standard system, a third-party verification system for CCUS from site selection to emission reductions should be established.

(2) To introduce incentives and subsidy policies, explore market-based incentive mechanisms, and improve the investment environment.

Development of CCUS technology requires a huge investment in R&D before commercial application. Therefore, governments urgently need to introduce financial inventives, such as subsidies and government grants. It is also suggested to explore market-based policy mechnisms to attrack bank loans, private capital, and to include CCUS into China's carbon emission trading system. The government should promote infrastructure construction, including building CO_2 transport pipelines, helping reducing the operation cost for CCUS. It is recommended to design reasonable investment and financing mechanisms and policies to overcome the obstacles of high CCUS investment and operating costs.

(3) To establish inter-departmental and cross-industry coordination mechanisms, and gradually promote the commercialization of CCUS technology in stages, with industries, at the same time as setting priorities.

The implementation of a CCUS project requires the cooperation and coordination of multiple Ministries and industries. It is recommended to set up a special inter-department coordination initiative for CCUS led by the Ministry of Ecology and Environment in policy planning, technology research, process evaluation, and project establishment. A policy framework should also be designed to better manage costs and allocate responsibilities. Driven by large-scale geological storage, targeting emission reductions, it is recommended to carry out the overall layout and planning of CCUS in China in the 14th Five-Year Plan period.

CONTENTS

CCUS Overview

CCUS refers to an industrial process that separates CO_2 from emission sources and then utilizes or stores it to achieve CO_2 reductions. As an emerging technology that is expected to help achieve large-scale and low-carbon utilization of fossil energy, CCUS is a vital approach for China to reduce CO_2 emissions, to ensure energy security, and to achieve long-term sustainable development. CCUS adds “utilization” into carbon dioxide capture and storage (CCS). This new concept is introduced as a result of the continuous learning from pratical experieces and has been promoted under Chinese leadership. It has now gained wide recognition in the world. The IPCC's Fifth Assessment Report (2014) highlights the new CCUS technology - bioenergy with

Table 1 Main processes and technical links of CCUS

Components		Content
Capture		The process of separating and enriching CO_2 generated from the use of fossil energy in the chemical, power, steel, cement and other industries; it is usually divided into post-combustion capture, pre-combustion capture, and oxyfuel combustion capture.
Transportation		The process of transporting captured CO_2 to a site for utilization or geological storage. The approaches include onshore or offshore pipelines, ships, railways, and tanks.
Utilization and Storage	Geological utilization	The process of injecting CO_2 into the ground for energy production. It is mainly used to enhance the recovery of resources such as petroleum, geothermal, deep saline water in the formation, and uranium ore.
	Chemical utilization	Chemical conversion is the main approach to convert CO_2 and co-reactants into target products. It excludes the traditional chemical approach that uses CO_2 to generate products but re-releases CO_2 after being consumed (e.g., urea production).
	Biological utilization	In this category, CO_2 is used to facilitate biomass synthesis. The main products are food and feed, biofertilizers, chemicals and biofuels, and gas fertilizers.
	Geological storage	The captured CO_2 is stored in the geological structure through engineering techniques to achieve long-term isolation from the atmosphere. It is mainly divided into onshore saline aquifer storage, offshore geolgocal storage, and depleted oil and gas field storage.

CCUS Overview »»

carbon capture and storage (BECCS) ,which combines biomass energy technology and CCUS, as an important technology for reducing CO_2 emissions. This technology has been gradually receiving more and more attention.

CCUS can achieve nearly zero CO_2 emissions from the use of fossil energy. Among various emission reduction technologies, it will fill the gaps between energy efficiency and renewable energy technology for CO_2 mitigation in the future. The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2014) pointed out that CCS is of great significance for global greenhouse gas reduction. The IPCC believes that CCS technology will play a vital role in achieving the 450 ppm CO_2 equivalent concentration target by 2100 (controlling the temperature increase below 2 ° C). Most models that do not consider CCS technology cannot achieve the 450 ppm target by 2100. The IPCC believes that CCS technology can reduce the cost of mitigating global greenhouse gas emissions. In the report, CCS technology will be more market-competitive than other low-carbon technologies in 2030, and it will play a major role in reducing global greenhouse gas emissions after 2030.

In the IPCC *Special Report on 1.5 °C global warming (2018)*, out of the four reported scenarios for achieving the 1.5 °C target, only one scenario (the end-use energy demand dropped significantly) did not use CCS. Among the other three scenarios, CCS technology will respectively achieve emission reductions of 348 billion tons (including 151 billion tons of BECCS), 687 billion tons (including 414 billion tons of BECCS), and 1218 billion tones (including 1,191 billion tons of BECCS)， and 1218

CCUS Overview

billion tones (including 1,191 billion tons of BECCS) by 2100. The deployment of BECCS will remain limited by 2030 (300 million tons, median level in all scenarios), but reach 3, 5 and 7 billion tons of CO_2 per year by 2050 in the three scenarios (median level in three scenarios).

The IPCC *Special Report on Climate Change and Land (2019)* demonstrates that the emission reduction potential of BECCS in 2050 can reach 0.4 to 11.3 billion tons of CO_2 per year. The IEA (International Energy Agency) published "*Transforming Industry through CCUS" in 2019*, which shows that the cumulative amount of CCUS in the industrial sector will reach 28 billion tons in 2060, under the clean technology scenario (in line with *the Paris Agreement path*). The cumulative CO_2 mitigtion from CCUS in the energy processing and conversion sector will reach 31 billion tons, and the cumulative amount of CCUS in the power sector will reach 56 billion tons in 2060. CCUS will help reduce CO_2 emissions by 38% in the chemical industry and 15% in the cement and steel industries globally.

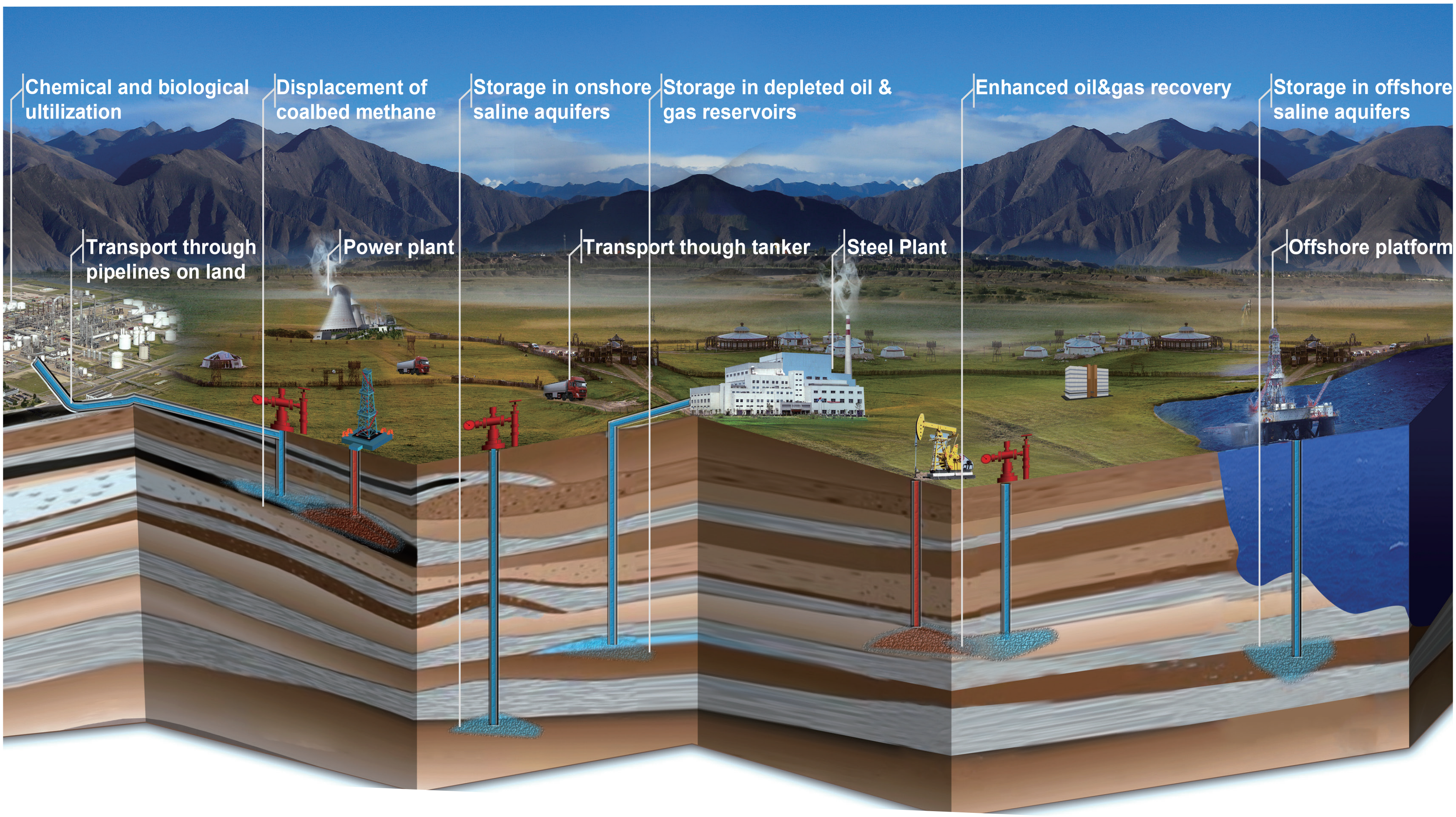


Fig. 1 Schematic of different types of CCUS technology

Many international governments, organizations, and enterprises actively provide strong policy support for CCUS development and deployment.

Table 2 Main CCUS projects and corresponding storage volumes in the world in 2019

Country	Accumulated storage volume	Annual storage volume in CCUS (10,000 tons)	Annual CO_2 emissions (10,000 tons)	Number of projects
USA	More than 58 million tons （1972—2019）	~2100	514520	9
China	About 2 million tons （2007—2019）	10~100	942870	10
Norway	About 22 millions tons （1996—2019）	170	3550	2
Canada	About 44.25 million tons （2000—2019）	~300	55030	4

Note: The source of CO_2 emissions data is the *Statistical Review of World Energy 2019*, which calculates emissions from fossil fuel combustion. CO_2 capture and injection data in the U.S. comes from the U.S. Environmental Protection Agency (EPA, 2016) and the author’s survey. The accumulated storage volume of CO_2 for Norway comes from GCCSI. The scale of Chinese demonstration projects is more than 20,000 tons/year, and those in the United States, Norway and Canada are generally large than 400,000 tons/year.

1 CCUS projects in China »»

1.1 Distribution of CCUS projects in China

By August 2019, nine capture demonstration projects and twelve geological utilization and storage projects had been carried out in China, including 10 integrated demonstration projects (Fig. 2). In addition, dozens of chemical and biological utilization projects have been carried out in China. Geological utilization and storage projects are mainly located in Ordos Basin (4), Bohai Bay Basin (2), Songliao Basin (2), Qinshui-Linfen Basin (1), Hailar Basin (1), Subei and Junggar Basin (1), and involving provinces and cities including Inner Mongolia Autonomous Region (3), Shandong Province (1), Henan Province (1), Shaanxi Province (2), Shanxi Province (2), the Xinjiang Uygur Autonomous Region (1), Jilin Province (1), Jiangsu Province (1).

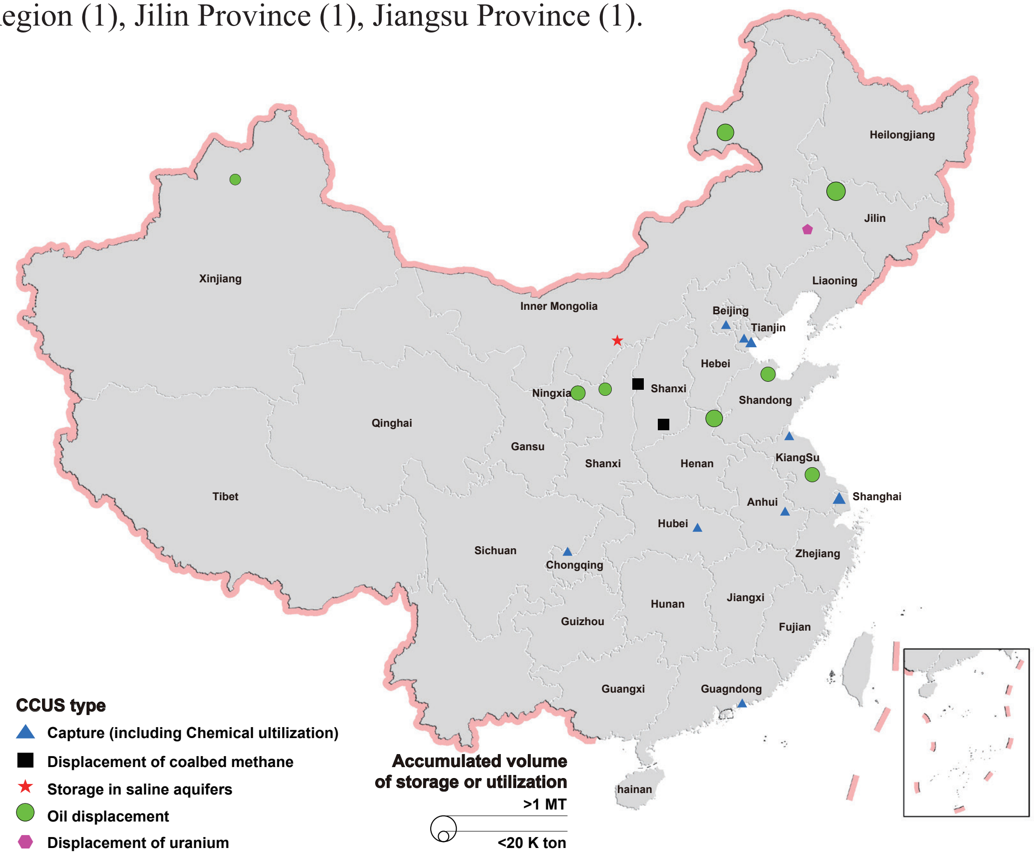


Fig. 2 Types and distribution of CCUS Projects in China

In 2019, 18 CO_2 capture projects were in operation in China, with 1.7 million tons of CO_2 captured in total. Among the 12 geological utilization projects in 2019, the geological, chemical and biological utilization amounts are about 1 million tons, 250,000 tons and 60,000 tons respectively (Fig. 3).

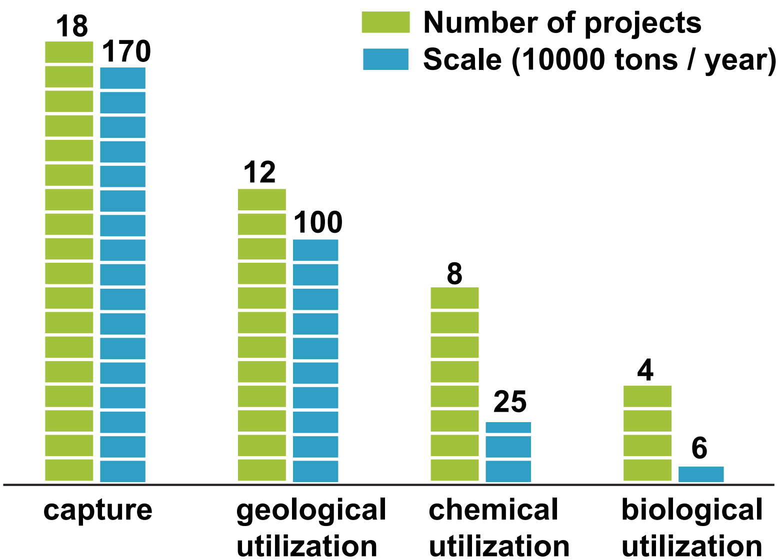


Fig. 3 The numbers of CCUS projects in China in 2019

Note: 1) Shenhua Ordos saline storage project finished injection in 2015, which is not included in the figure above. 2) The number of chemical utilization and biological utilization projects on the figure refers to the statistical number and does not represent the actual level of the whole country. There may be errors due to field collection. 3) The scale of CO_2 from chemical utilization refers to the national scale, which does not directly come from the project idenfied from the report. The data is from *Roadmap for Carbon Capture Utilization and Storage Technology in China (2019).*

1.2 CO_2 Capture demonstration project

China's CO_2 capture demonstration projects are mainly located in north and east China (Fig. 4). Project types mainly include pre-combustion, post-combustion, and Oxyfuel combustion.

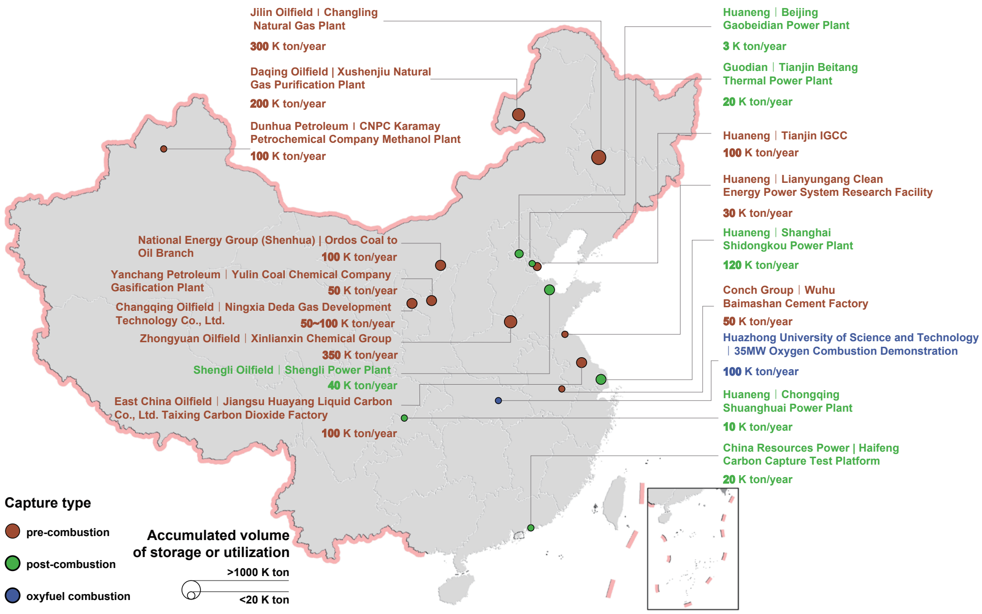


Fig. 4 The distribution of CO_2 capture projects in China

CO_2 capture in China is mainly demonstrated in the coal chemical industry, followed by thermal power, natural gas processing, methanol plants, cement plants, and fertilizer plants (Fig. 4, Fig. 5). The CO_2 concentration of flue gas is often closely related to the cost.

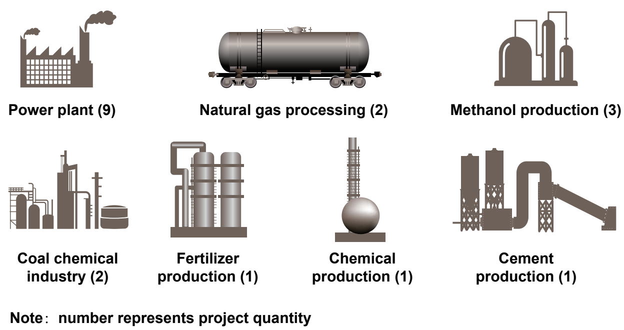


Fig. 5 The project distribution of CO_2 capture project in key industires in China

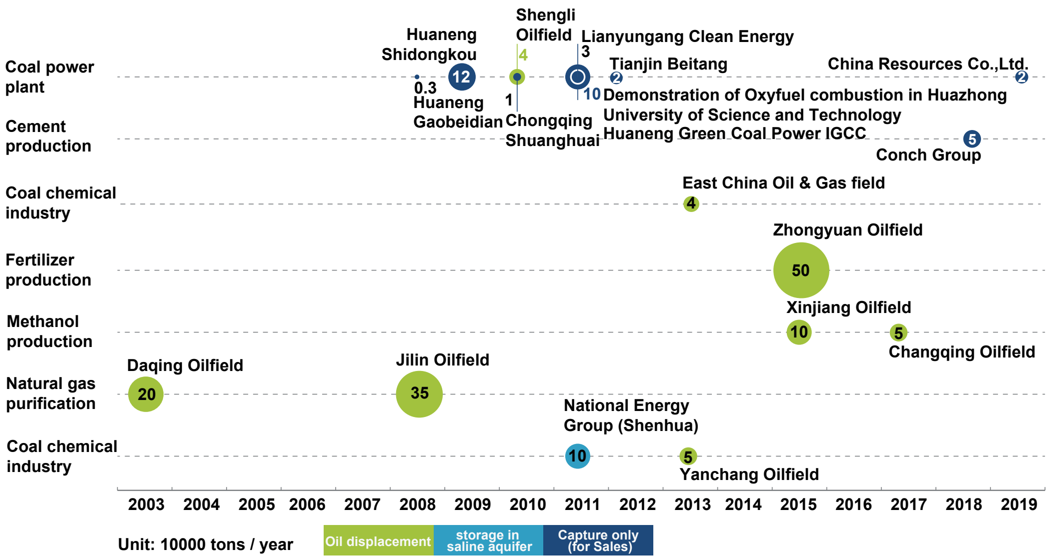
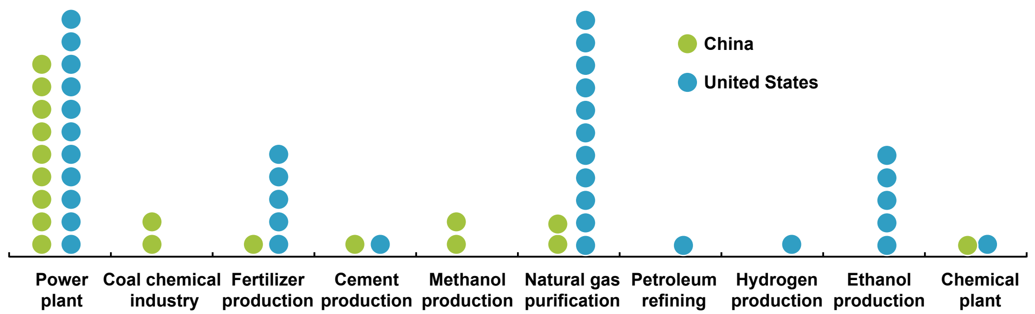


Fig. 6 Type of CO_2 capture industries in China

CCUS projects in the United States cover a wide range of industries, including ethanol production, hydrogen production, petroleum refining, chemical plants, etc. (Fig. 7). The gap between the the United States and China in the power industry is small.



Note: circle number represents project number.

Fig. 7 Comparison of deployment of CO_2 capture projects industries in the US and China

Post-combustion capture

China's post-combustion capture technology mainly uses the chemical absorption method to capture CO_2 from flue gas in coal-fired power plants. China Resources' electric power Haifeng test platform project was officially put into operation in May, 2019. It is the first multi-usage carbon capture test platform in Asia and one of the world's three medium-sized carbon capture technology test platform in parallel with the US National Carbon Capture Center and the Technology Centre Mongstad of Norwary (Fig. 8).

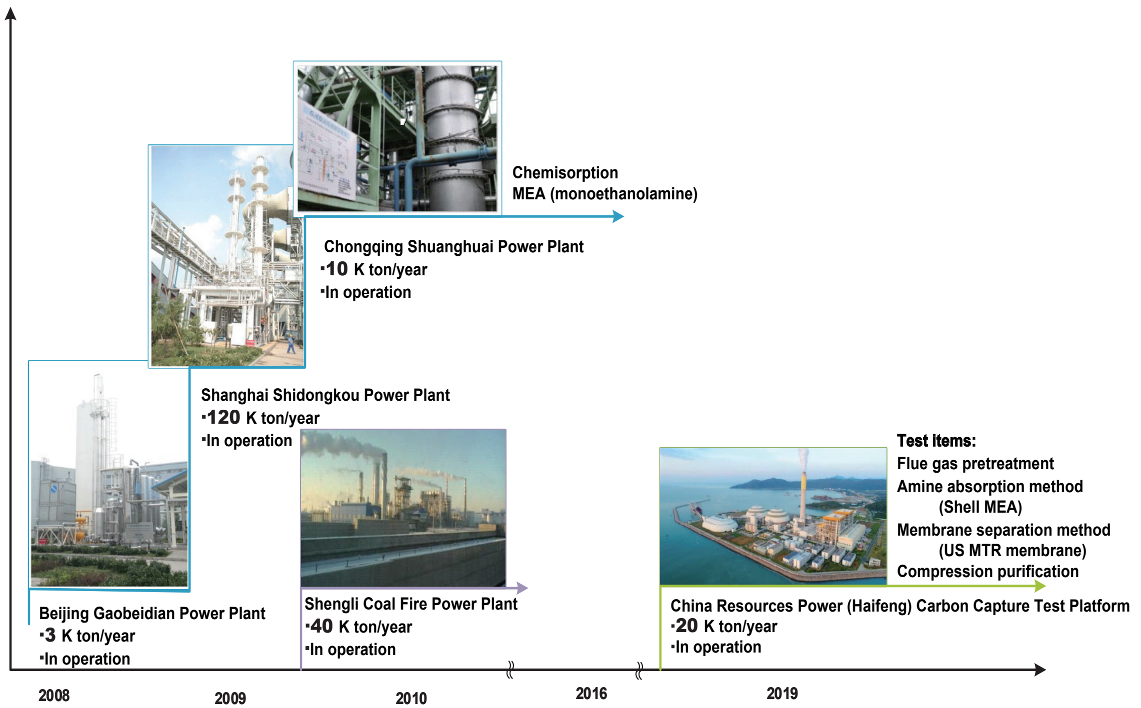


Fig. 8 Scale and history of post-combustion capture projects in China

Pre-combustion capture

China's pre-combustion capture technologies consist of IGCC (integrated gasification combined cycle) and industrial separation. There are two IGCC demonstrations in China, including Huaneng IGCC project in Tianjin and the Clean Energy Power System Research Facility in Lianyungang. China Huaneng IGCC project in Tianjin began operation in November 2012, and its associated CO_2 capture facility started to test in 2018 with an annual CO_2 capture capacity of 60,000 tons. The Tianjin IGCC project is longest continuous IGCC facility in the world.

CO_2 industrial separation projects in China are located in the following sectors, coal-to-oil, coal-to-gas, natural gas processing, cement, methanol, and fertilizer. Shengli CO_2-EOR Project is the only project capturing CO_2 from coal-fired power plants. The others come from industrial separation. At present, the project with the largest capture volume is SINOPEC's Zhongyuan CO_2-EOR project, with a total of 350,000 tons/year. The largest carbon capture project in terms of its total scale is natural gas purification, with a total volume of 500,000 tons/year (Fig. 9).

Oxyfuel combustion capture

Oxyfuel combustion is still largely in the R&D process in the international community. In China, Huazhong University of Science and Technology has been conducting laboratory experiments since 1995. In 2014, a 100,000-ton/year-capture-facility was built in Yingcheng, Hubei. In 2016, the feasibility study of 1 million tons/year oxy project was completed. However, even though the 100,000 tons/year CO_2 capture device has been built, its normal thermal debugging and demonstration operation have not been carried out.

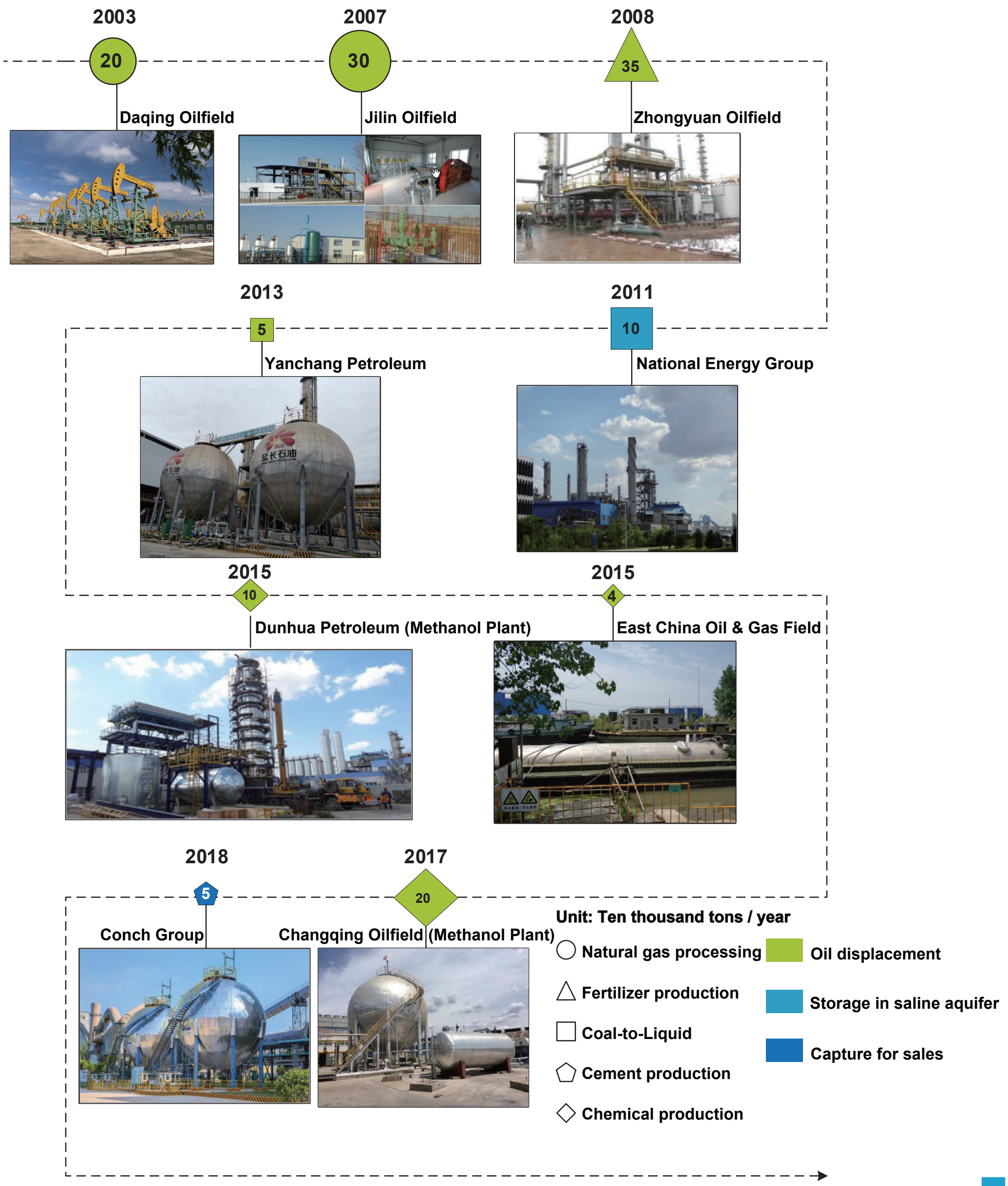


Fig.9 Industrial separation projects of CO_2 in China

1.3 Geological utilization and storage

China's geologic utilization and storage projects, primarily focusing on enhanced oil recovery, are located in several major oil and gas basins, including Songliao basin in northeast China, Bohai bay Basin in north China, and Ordos Basin and Junggar Basin in northwest China. CO_2 Coalbed Methane Recovery is now in the pilot stage, which is demonstrated by China United Coalbed Methane in Liulin and Shizhuang of Qinshui-linfen Basin. The technology for leaching CO_2 for uranium ore recovery is mature, which has been tested by China's National Nuclear Corporation in Tongliao (Fig. 10).

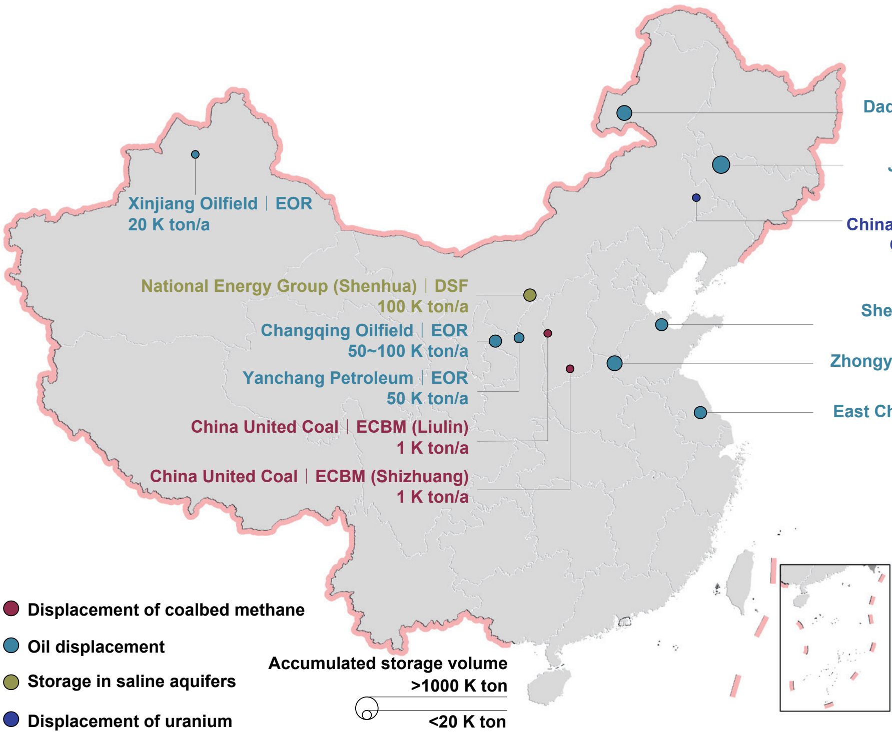


Fig. 10 Distribution of geological utilization and storage projects in China

Carbon dioxide enhanced oil recovery (CO_2-EOR)

CO_2-EOR has been demonstrated by China Petroleum & Chemical (Sinopec), China National Petroleum Corporation (CNPC), and Yanchang Petroleum Group. Specifically, these projects are located in Shengli Oilfield and Zhongyuan Oilfield of Sinopec Daqing Oilfield, Jilin Oilfield, Xinjiang Oilfield, and Changqing Oilfield of CNPC.

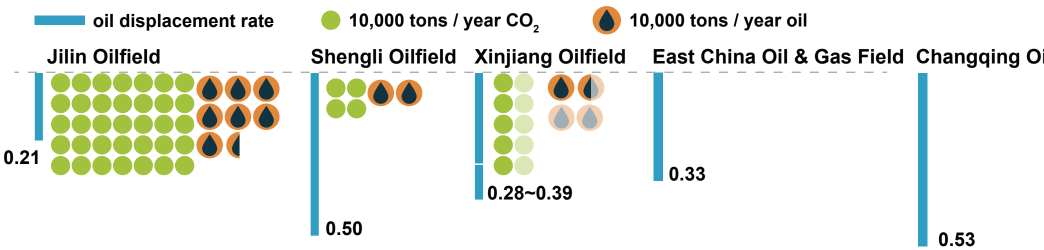


Fig.11 Annual CO_2 injection and annual oil production

The CO_2 utilization rate of Jilin Oilfield is about 4.67:1, that is, injecting 4.67 tons of CO_2 can produce 1 ton of oil. The CO_2 utilization rate of Shengli Oilfield is about 2:1. The total injection over 2 years in Xinjiang Oilfield totals 50,000-100,000 tons, producing 14,000-39,000 tons of oil per year, and the CO_2 utilization rate is about 2.56-3.57:1. To date, a total of 2.4 million tons of CO_2 has been injected into East China Oil field, producing 130,000 tons of oil. The gas-to-oil ratio is about 3.07:1 (Fig. 11, Fig. 12).

CO_2 injection well and producing well in Jilin Oilfield, CNPC

Wellhead injection phase	Liquid phase	Liquid phase	Super critical phase	Liquid phase
Maximum Wellhead Injection Pressure	30MPa	19.7MPa	20MPa	13MPa
Average wellhead injection pressure	15MPa	16.1MPa	18MPa	9MPa
Wellhead injection temperature	1~20 ℃	-17 ℃	38 ℃	-20 ℃
CO_2 concentration	98%	99.99%	99.9%	99.8%

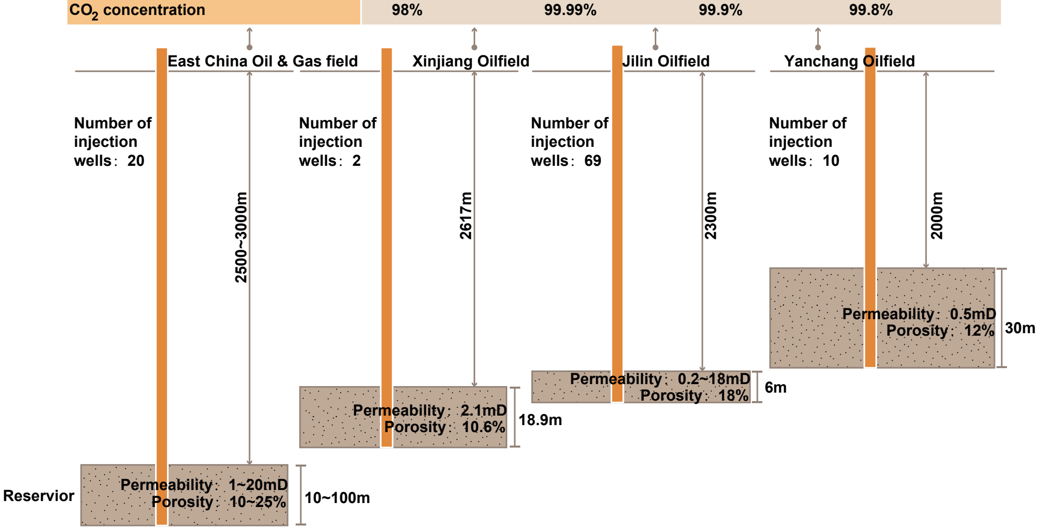


Fig.12 Basic parameters of a typical CO_2-EOR project

CO_2 - Enhanced coal bed methane recovery (CO_2 - ECBM)

The utilization of CO_2 displacement for Coalbed Methane is now in the pilot test phase. The Alberta Research Institute, the Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO), and Wuhan Institute of Rock and Soil Mechanics of the Chinese Academy of Sciences have jointly been conducting a series of pilot injections and monitoring studies in Liulin and Shizhuang in the Qinshui-linfen Basin since 2004 (Fig. 13).

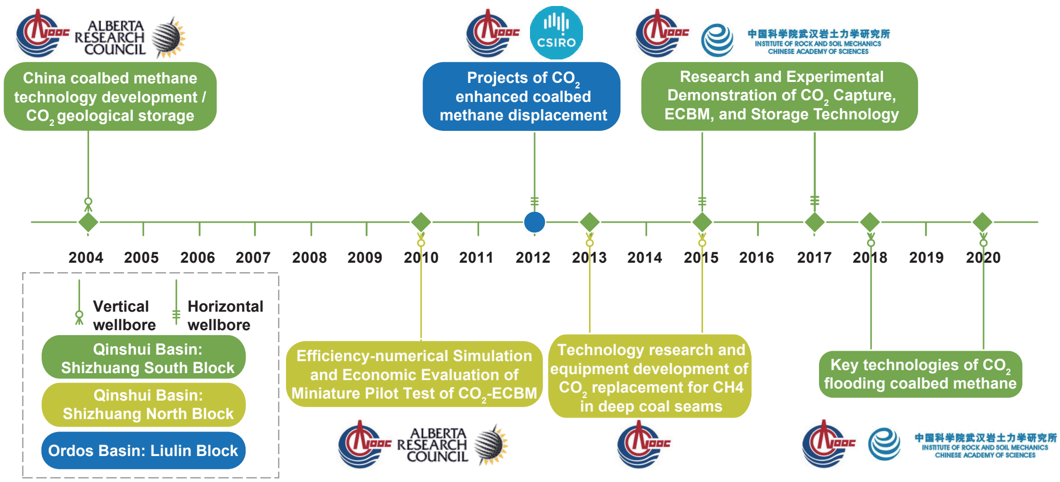


Fig.13 Pilot/demonstration trials of ECBM in China

Saline aquifer storage

The deep saline aquifer CO_2 storage demonstration of China National Energy Investment Group Co., Ltd. (formerly Shenhua) in its coal-to-oil facility in Ordos Basin was the first and largest integrated demonstration facitlity of its kind in China and the world (Fig. 14 and Fig. 15). The project is located about 40 km southeast of Ejin Horo County in Ordos City, Inner Mongolia. This project started injection on May 9, 2011, and completed in 2015. By the end of 2015, the injection target of 300,000 tons had been achieved.

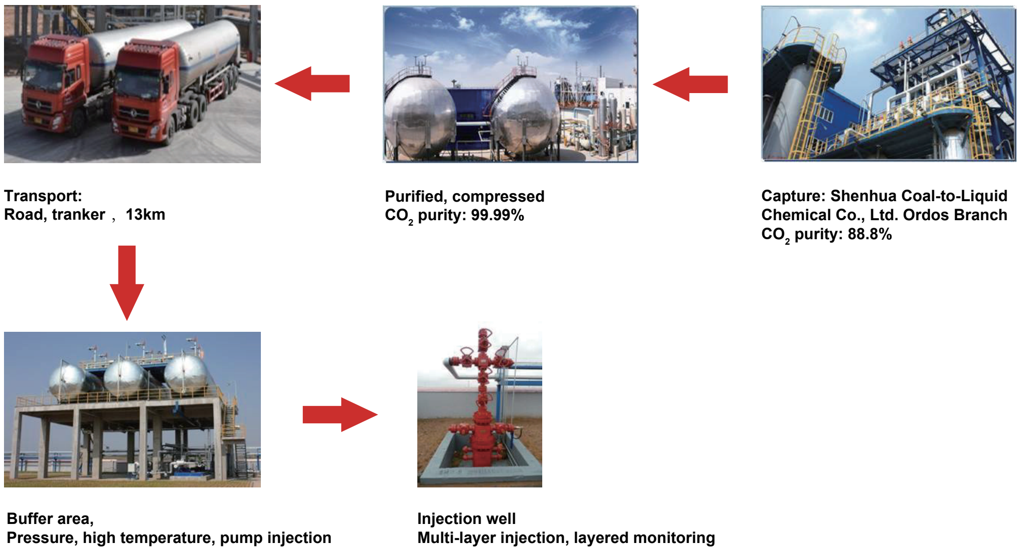
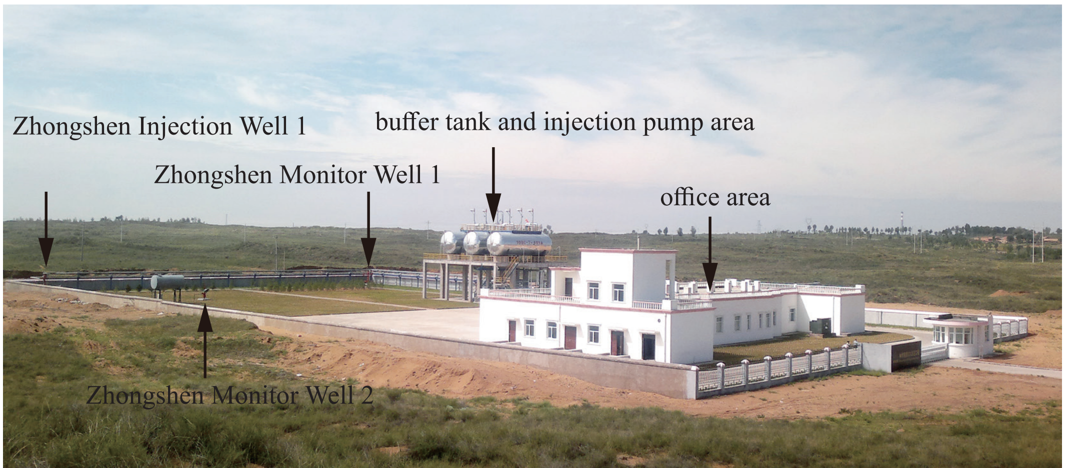


Fig. 14 Schematic diagram of the whole process of National Energy Group (Shenhua) CCS demonstration project

The CO_2 is first separated from the flue gas of the hydrogen production unit and then purified from a purity of 88.8% to more than 99.99% through gas-liquid separation, deoiling, desulfurization, purification, and rectification. A tank truck is thenused to transport CO_2 to the storage area. At the injection site, the captured CO_2 is first stored in the buffer tank, and then injected underground after pressurization and heating (Fig. 14). The pressure and temperature of the buffer tank, injection well, and monitoring well, are all monitored and transmitted to the office building in real-time.



Storage area perspective of CCS demonstration project of National Energy Group (formerly Shenhua)

1.4 Chemical utilization and biological utilization

More and more technologies are being included in CCUS, like chemical, biological and physical utilization, etc. Among them, chemical products include materials, fuels, chemicals, etc.; biological products include fuels, chemicals, food, feed and fertilizers. Overall, chemical utilization and biological utilization utilize less CO_2 than geological utilization and storage.

1.5 The cost

Capture is the most energy and capital intensive among the entire CCUS process. CO_2 emission sources can be divided into two categories: the first being high-CO_2 concentration sources (such as coal chemical industry, refinery, natural gas purification plant, etc.), the second being low-CO_2 concentration sources (such as coal-fired power plants, steel plants, cement plants, etc.). The CO_2 capture cost from high CO_2 concentration sources can be much lower.

At present, post-combustion capture is the most mature technology compared with the other two in China. Post-combustion capture has been demonstrated primarily in coal-fired power plants. The cost of mitigation from the IGCC projects owned by China Huaneng is about 300 yuan/ton of CO_2. The carbon capture test platform of China Resources (Haifeng), which was put into production in 2019, shows mitigation costs of 500 yuan/ton of CO_2. As for oxyfuel combustion, Huazhong University of Science and Technology has carried out lab tests and pilot tests in coal-fired power plants, at a cost of 900 yuan and 780 yuan per ton of CO_2 respectively.

In China, CO_2 transport is mainly carried by tanker, with a cost of about 0.9-1.4 yuan/ton/km. Jilin Oilfield adopts pipeline transportation, the transportation distance is about 20 km, and the cost is 0.3 yuan/ton/km.

China National Energy Group operates China's first CO_2 geological storage demonstration project with the CO_2 from its coal-to-oil facility. The whole process cost is 249 yuan/tonne CO_2. The CO_2-EOR cost varies greatly due to the technical competence, reservoir conditions, gas sources, and sink distance. Generally, the whole process costs between 120 and 800 yuan/ton (Fig. 15). The crude oil produced from CO_2-EOR could provide an economic return for the CCUS project. Specific returns are related to oil prices.

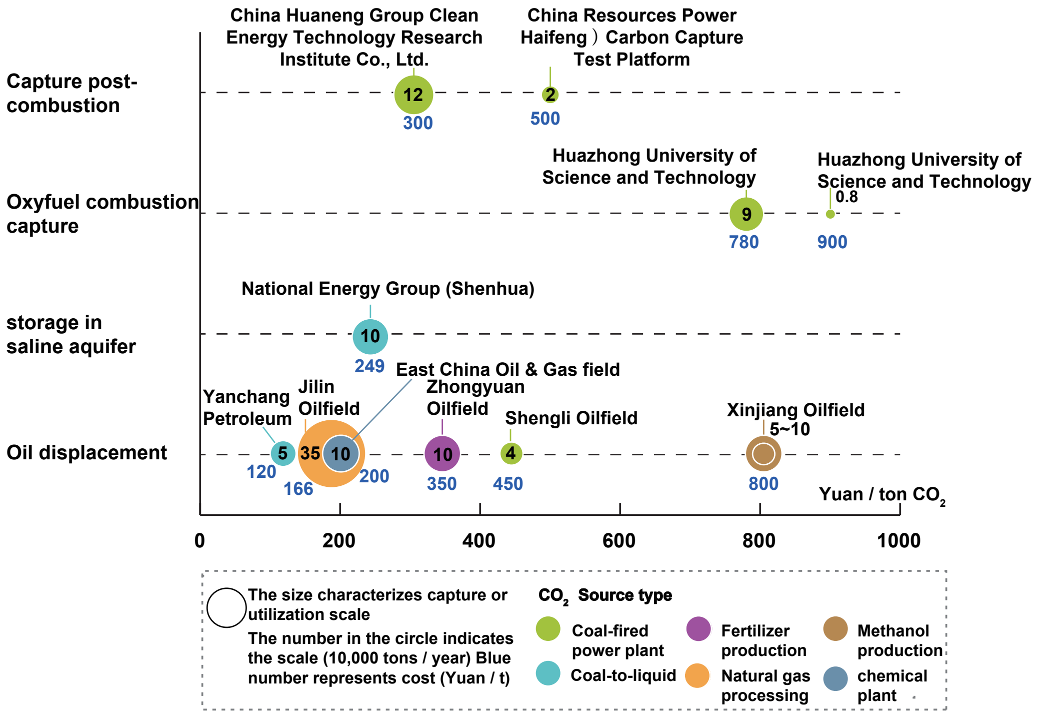


Fig.15 Cost of a typical CCUS project

In the figure above, the cost of Jilin Oilfield refers to the cost of supercritical injection in the gas field, and the total cost from different CO_2 sources and injection phase states is quite different (Table 3). The cost of externally purchased gas is the highest.

Table 3 Injection costs of different gas sources and injection methods in Jilin Oilfield

CO_2 source and injection mode		CO_2 costs from purchasing or processing (yuan/ton)	Injection cost (yuan/ton)	Total injection cost (yuan/ton)
Purchased carbon dioxide	Liquid injection	650.00	32.22	682.22
CO_2 gas Wells	Liquid injection	99.41	32.22	131.63
	Supercritical injection	56.08	62.58	118.66
CO_2 captured by gas fields	Liquid injection	158.59	30.80	189.39
	Supercritical injection	102.38	63.91	166.29

The data above are the actual operating costs of CCUS projects that have been carried out in China from the 300,000 tons/year CO_2-EOR project in Jilin Oilfield. As for large-scale CCUS projects, the cost only can be estimated through desk research.

Taking the Baogang Zhanjiang Steel Plant as an example, with a target of an annual capture scale of 500,000 tons, the economic cost of emission reduction is 448 yuan/ton CO_2 when injected offshore in currently mothballed facilities in the Beibu Gulf Basin within 100 km of the plant. The total investment requirement for this steel industry CCUS project is 360 million yuan. In the one-million-ton carbon capture and offshore storage project at China Resources Haifeng power plant, the CO_2 emission reduction cost is around 396 yuan per ton. The above is based on the research results from the UK-Guangdong CCUS Centre.

2 Survey of typical CCUS projects in China

2.1 CO_2-EOR project in Jilin Oilfield of CNPC

The CO_2-EOR pilot test facility in Jilin Oilfield was completed in April 2008, marking the official establishment of the first CO_2-EOR demonstration zone in China. The CO_2-EOR in the Jilin Oilfield project is the first full-process CCUS project in China. The CO_2 gas came from CNPC's Changling natural gas field and the gas was transported to the demonstration area, a dozen kilometers away from the gas field. Since 2008, Hei 59, Hei 9 south, Hei 79, Yi 59, and Hei 46 areas have been successfully completed and put into operation. There are 69 gas injection well groups in these areas. The annual oil-producing capacity was 120,000 tons, and the annual CO_2 storage capacity was 300,000 tons. At present, 1.45 million tons of gas has been injected and 130,000 more tons of oil have been produced. The CO_2-EOR project of the PetroChina Jilin Oilfield has realized recycled injection of carbon dioxide in the associated gas field, achieving zero carbon dioxide emissions.

The gas separation technology was applied to capture the CO_2 gas. This technology is mature and the cost is relatively low, but a dense phase injection technology with lower cost needs to be developed. Changling natural gas treatment plant is the first natural gas purification plant using CO_2 from CNPC, including gas collection, decarbonization, dehydration, CO_2 compression, storage, and other functions. The daily capture capacity is 1500 tons of CO_2. Because the gas source and the storage site are a dozen kilometers apart, pipelines are used to transport CO_2 and the transport price for one kilometer is about 0.3 yuan each ton. At present, there are two injection methods in Jilin Oilfield: liquid phase injection and supercritical phase injection. The cost of gas-liquid phase injection is about 130 yuan/ton, and that of supercritical phase injection is about 120 yuan/ton. The cost of the associated gas-liquid phase injection is about 190 yuan/ton, the cost of the supercritical phase injection is about 170 yuan/ton. As can be seen, the cost of the supercritical phase injection is lower than that of liquid phase injection.

CO_2 adsorption tower of Jilin Oilfield, CNPC

Demonstrations should be first built to test various CO_2-EOR and CO_2 geological approach, followed by industrial deployment. Only having a single carbon source is a major hurdle which could be solved by cross-sectoral and -boundary trading of CO_2. The pilot test in Jilin Oilfield initially adopted the method of CO_2 liquid injection and water flooding to extract the oil, with an annual carbon storage capacity of 500,000 tons. After that, in order to verify the potential of CO_2-EOR in the water flooding reservoir, an extended test zone, converted from water flooding to CO_2 flooding, was successively built. In 2012, Hei 79 north with a small well within the extended test area was completed to evaluate the oil recovery. The reservoir permeability is only 4.5 mD and the miscible pressure PO/MMP is 23.6/22.1 Mpa. The water content is up to 93.1% and the recovery rate is only 25%. There are 10 injection wells and 27 production wells with a daily CO_2 injection capacity of 600 tonnes. Compared with water flooding, the average recovery increased by 20% and the recovery in the core area increased by 25%. The degree of recovery increased by 15.6%, and the storage rate of CO_2 is up to 95%. In July 2014, the Yi 59 water-sensitive reservoir test zone was established to explore the enhanced recovery rate of CO_2 flooding in water-sensitive reservoirs. In October 2014, the Hei 46 test zone for CO_2 miscible flooding was built, laying the foundation for promoting industrial-scale application. At present, the carbon source of Jilin Oilfield is mainly associated with natural gas production. It mainly solves the problem of carbon emissions from inside the oil field and does not benefit emissions reduction outside the oilfield. There is no cross-industry collaboration with other emission sources.

Jilin Oilfield has the relatively well-developed infrastructure and skills for CO_2-EOR. Its experiences from CO_2-EOR operation in continental low permeability reservoirs need to be promoted. Through more than 10 years of experiments, funded by the National

Major Science and Technology programs, supported by CNPC major science and technology projects and major development tests, Jilin Oilfield has gained five key engineering technologies: low-cost anticorrosive technology for CO_2 flooding; multiple combination injection-production control technology; high gas-oil ratio well-lifting technology; whole-process surface engineering technology; and safety and environmental protection control technology. It has established a national CCS-EOR technology research and development center and the CO_2-EOR and storage test base for CNPC. It has the functions of the CO_2 corrosion evaluation, core evaluation, fluid evaluation and CO_2 storage monitoring. Its CO_2-EOR technology has been applied in Changqing, Hainan and other oil fields.

2.2 CO_2-EOR project in Xinjiang Oilfield of CNPC

There are some problems with high-water content and low recovery rate in the old oilfield, and a high proportion of low permeability and extra-low permeability in the new oilfield in Xinjiang. To solve these problems, the exploitation method in the Xinjiang Oilfield needs to be urgently changed. In 2009, Xinjiang Oilfield started to set up CO_2-EOR pilot tests, such as the evaluation of CO_2 flooding and storage potential in the Junggar Basin. Since 2012, the company has successively adopted methods to increase production and enhanced oil recovery tests such as CO_2 huff and puff, CO_2 flooding and tight oil CO_2 storage fracturing. A total of 56,000 tons of CO_2 was injected, 47,000 tons of oil was produced, and 23,700 cubic meters of steam were saved. Good production results have been achieved.

The CO_2 gas for CO_2-EOR in Xinjiang Oilfield was obtained through high-purity chemical flue gas separation. The capture technology is advanced, but the capture cost is high and the upfront investment is also relatively high. As an integrated process project, the capture and storage process of the CO_2-EOR project in Xinjiang Oilfield was completed in cooperation with external enterprises. Its gas source comes from the industrial exhaust produced by the Karamay Petrochemical Company and was captured by the private enterprise Xinjiang Dunhua Petroleum Technology Company. Dunhua, through converting the hydrogen production unit of the Karamay Petrochemical Company, built a 100,000 tons/year CO_2 capture and liquefaction unit. This device can capture and liquefy the waste gas from the methanol plant of the Karamay Petrochemical Company to obtain high purity CO_2. The initial concentration of CO_2 is 41% and the purity after liquefaction separation is up to 99.96%. The captured CO_2 was supplied to the First and Second Oil

Production Plants of Xinjiang Oilfield Company, Baikouquan Oil Production Plant, Zhundong Oil Field, Shixi operation area, Luliang operation area, Heavy Oil Company and 10 other factories for CO_2 flooding and oil storage. From 2013 to July 2019, a total of 139,500 tons of CO_2 was injected, and more than 60% of CO_2 was sequestered. However, limited by technology and lack of mechanisms for cooperation, the cost of capturing a ton of CO_2 was still as high as 600-800 yuan. For CO_2 flooding pilot tests, the initial investment is huge. Although the oil displacement effect is obvious, the benefits brought by CO_2-EOR is equal to the cost, therefore, the profit for the company is limited.

The pilot tests in Xinjiang have been implemented with various approaches with great technical difficulties. The amount of oil recovery is significant, but the effect of CO_2 storage is still hard to be evaluated. After evaluating geological reservoir conditions, Xinjiang Oilfield conducted a variety of CO_2 flooding pilot tests in the real field. Through comprehensive consideration of CO_2 miscibility, reservoir geological parameters, development parameters and gas sources, the screening criteria for CO_2 miscible flooding reservoirs in Xinjiang Oilfield were established and suitable blocks were selected for the pilot test. So far, progress has been made in the 530th field of the Eighth area, the Ma 18 and Ma 131 field in the Mahu Depression and the Sixth area in the Karamay Oil Field. However, only the pilot test of CO_2 miscible flooding in the Kexia Formation, which consists of the conglomerate reservoir in the 530 well area of the Eighth area, has achieved significant results. Gas injection began in 2012, and 20-30 tons per day were injected into a single well. At present, it has produced accumulatively 650,000 tons of oil, and the storage rate is 83%. It formed an annual CO_2 injection scale of 100,000 tons. Pilot tests in other blocks, such as Ma 18 and Ma 131 well areas, 120 tons of CO_2 were injected into the oilfield per day in Ma 18 well area and 150 tons of CO_2 in Ma 131 well area. As one of the mixed oil recovery methods, synchronous and asynchronous huff and puff methods were applied to inject CO_2, with a small injection amount and low storage efficiency.

Carbon capture apparatus of
Xinjiang Dunhua Petroleum

Rich in oil and coal resources, Xinjiang province contains many chemical enterprises, which create good source-sink matching conditions for developing CCUS. However, it needs further exploration to form a win-win business cooperation model. The complicated geological conditions and the development procedure of Xinjiang Oilfield determine the urgency of implementing CO_2-EOR technology. At the same time, the developed coal chemical industry and petrochemical industry in Xinjiang create huge CO_2 emissions. These form good source-sink matching conditions for the development of CCUS in Xinjiang. At present, Xinjiang Oilfield serves as the end of the CCUS chain. Private enterprises buy gas sourced from Karamay Petrochemical Company and purify it through their own separation technology independently developed by the enterprises. CO_2 with high purity was obtained for oil displacement. To realize benefit sharing and responsibility-sharing amongst the capture side (Karamay Petrochemical Company), collector (Dunhua Petroleum) and sequestration side (Xinjiang Oilfield) is a huge challenge facing CCUS in Xinjiang Oilfield.

2.3 Haifeng Power Plant of CR Power CCUS demonstration project

The CO_2 capture demonstration project in the Haifeng power plant of China Resources Power Holdings Co., Ltd. (CR Power) was put into operation in May 2019. It marks the first post-combustion carbon capture demonstration project based on supercritical coal-fired power plants in China and Asia. This was combined with a platform test area, a CO_2 storage facility, chemical laboratory, and an international technology exchange center.

Aerial View Haifeng Power Plant of CR Power CCUS

Two carbon capture technologies were used: the amine method and membrane method. Both are advanced technologies but with high cost. In the first phase, amine absorption and membrane separation technologies were selected as the first two test technologes. The amine absorption and membrane separation units were constructed in parallel, and the two methods could be tested simultaneously on the carbon capture test platform. The amine method process is mainly composed of two parts: absorption and regeneration. CO_2 gas with a purity of 99% can be obtained with a daily collection capacity of 50 tons. The membrane method mainly depends on the selectivity of the membrane to the gas molecules in the flue gas and the different permeability to separate and purify CO_2. Through the three-stage membrane separation process, the CO_2 gas with a purity of 95% can be obtained and 16.4 tons of CO_2 can be captured per day. At present, the Haifeng testing platform mainly solves the parallel testing problem of multi-threaded carbon capture technology. However, the core technologies of amine liquid and membrane technology are from Shell Oil (Netherlands) and MTR company (US), respectively. Mature technologies have high costs, which is not conducive to large-scale applications. Therefore, it is urgent to further explore solutions for low-cost mature technologies and promote the amplification of innovative technologies.

Testing and optimizing capture technology can help gradually promote large-scale industrial applications. However, there are problems of utilization and storage after capture. Barriers of cross-sectoral CO_2 trading, utilization and storage of CO_2 urgently need to be solved, and economic and social benefits need to be improved. Through operating and developing the test platform, the first phase of the project aims to select, test and optimize the most suitable capture technology for the Haifeng power plant. It can also provide support for the following second phase project (Haifeng power plant megaton CCUS demonstration project) and other large-scale carbon capture and storage demonstration and industrial application projects. The carbon capture test platform has been successfully run and the CO_2 source from the power plant has been available. At present, it can be processed into food-grade liquid CO_2 through the compression and purification system. However, due to the lack of follow-up utilization and sequestration of CO_2 and the lack of cross-industry cooperation with other value-chain enterprises, further progress is needed in promoting large-scale emission reductions and improving economic and social benefits of the project.

Haifeng power plant of CR Power has the infrastructure and skills for CCUS technology. The next step can further explore the use of carbon for the cultivation of marine microalgae and offshore CO_2-EOR operation. Haifeng CCUS project has been recognized as a provincial CCUS demonstration project by the Guangdong government. It has built a carbon capture test platform, chemical laboratory, and technology center, with a capability of CO_2 capture separation, storage, and related experiment evaluation. Haifeng power plant is adjacent to the South China sea, which has the natural conditions to use CO_2 for the cultivation of marine microalgae as well as for offshore CO_2-EOR in the Oilfields in the north of the South China sea. The establishment of CCUS industrial or demonstration zones and promotion of the integrated industrial CCUS application can provide support for the low-carbon transformation of the fossil sector in China.

2.4 Integrated CCUS demonstration project in Sinopec East China Oil & Gas Company

Sinopec East China Oil & Gas Company is located in the North Jiangsu plain, covering 11 counties and districts of six cities including Dongtai, Jinhu, and Haian. The exploration and development block is located in the northeast of the North Jiangsu - South Yellow Sea basin. The sedimentary basin provides a large geological storage site consisting of deep saline aquifers and oil & gas fields in the Yangtze river delta region. Zhenwu, Huazhuang, Shuaiduo, Caoshe, and Hai'an oilfields provide storage sites for large-scale CCUS capture in the region. Since 1987, CO_2 flooding tests have been conducted in this area. The pilot project CCUS-EOR for the low permeability reservoir of Taizhou Formation in Caoshe Oilfield was started in 2005. Since

Carbon storage site of Sinopec East China Oil & Gas Company

2012, CO_2-EOR operation has been scaled up and 14 CCUS-EOR units have been built to realize the large-scale application of oil production and storage with annual CO_2 injection of more than 100,000 tons. A total of 400,000 tons of CO_2 has been injected and 130,000 tons of oil has been produced.

The technology of CO_2-EOR and CO_2 storage has been well developed, but monitoring technology after injection still needs to be improved. East China Oil & Gas Company of SINOPEC has undertaken several EOR tests including single well huff and puff and immiscible CO_2-flooding. The learning has obtained five technologies, including (i) physical modelling, (ii) evaluation technology for continental oil field for CO_2 flooding, (iii) tracking adjustment & optimization technology of CO_2 flooding scheme design, (iv) screening technology of CO_2 miscible and (v) immiscible flooding in medium and high permeability oil reservoirs, etc. At present, nine CO_2 development units have been formed to ensure stable oil production and realize the integrated benefits of oil EOR and storage. However, the monitoring system after injection is not complete and the monitoring technology is less-developed.

The developed water syst-em creates convenient water transport, but the dense population brings difficulties in the pipeline construction in the area. There is a high-concentration CO_2 source from the Nanjing Chemical Company of Sinopec, around 150 km away from the adjacent oilfield. CO_2 is transported to the oilfield by ship at 50,000 tons/year. The second-phase plan is to build an integrated CO_2-EOR demonstration project with an annual capacity of 500,000 tons. The project plans to transport the high-concentration gas source of Nanjing Chemical Company to the oil fields in Zhenwu, Huazhuang, Shuaiduo, Caoshe and Haian blocks through pipeline. It is planned to complete the project of 1 million tons/year in the third phase. However, as a necessary condition for implementing large-scale geological storage in the future, the pipeline network will be difficult to build in

the densely populated Yangtze River delta.

The developed industrial system in the Yangtze River delta region has created many potential CO_2 sources , but the cross-sectoral cooperation model and profit-sharing mechanism still need to be developed before commercial promotion. Jiangsu is a big industrial province. There are 22 major coal-fired power plants around the storage site, with an average distance of only 130 km from Subei Oilfield. In addition, a number of steel enterprises such as Sha Steel, Yong Steel, and Zhongtian Iron and Steel are concentrated within 200 km from the Taizhou Oilfield. Capturing CO_2 from steel production will be beneficial to the low-carbon transformation of the steel industry. A large amount of CO_2 emitted from these steel sites provides sufficient gas for CCUS projects. However, the CO_2 concentration in the flue gas, discharged from the steel production process, is low and the flue gas composition is complex, resulting in a relatively high capture cost. How to form a long-term and profitable business model among enterprises remains a question for enterprises with large CO_2 emissions.

3. Scientific Research of CCUS in China

3.1 CCUS Patents in China

The first CCUS-related patent in China was published in 1997, and in the following ten years, the relevant patents were very few, no more than 10 in total (Fig. 16 & Fig. 17). In 2006, the state issued a CCUS-related policy for the first time; and in 2008, China's first carbon capture demonstration at Huaneng Beijing GaoBeidian Power Plant was put into operation. Since then, the number of CCUS patents in China has been increasing every year. During the 12th Five-Year period, China introduced some policies to promote the development of CCUS and invested substantial funds to support CCUS RD&D. In 2015, China produced more patents than in 2013 and 2014 combined. After 2015, with decreasing policy and funding support, the number of patients dropped in 2016, but the trend continued to increase after.

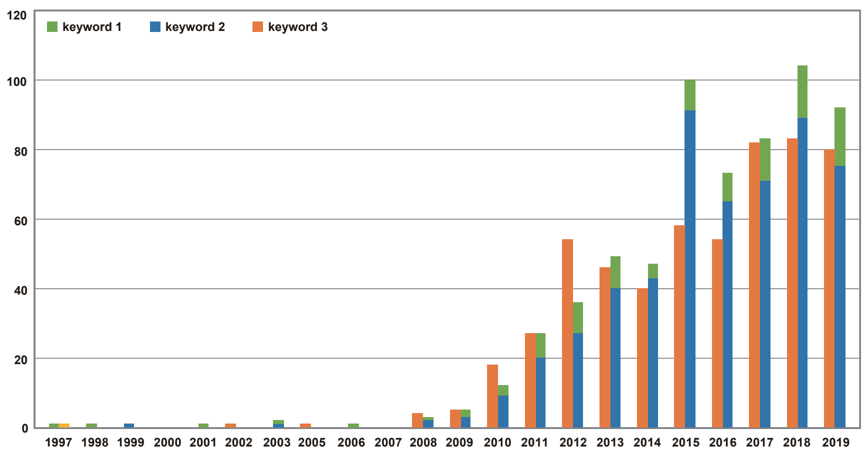


Fig. 16 CCUS invention patent (search date: 3 January 2020).

Keyword 1 searched: carbon dioxide utilization;

Keyword 2 searched: carbon dioxide storage OR carbon dioxide capture OR CCUS;

Keyword 3 searched: Keyword = carbon and dioxide and capture and utilization and storage) OR Keyword = (Carbon and dioxide and Capture) OR Keyword = (carbon and dioxide and sequestration)

Note: Data are all patents filed in China, including the patents filed by other countries in China. 78.22% of the applicants are Chinese.

Fig.17 CCUS patent word frequency analysis (Search Date: 3 January 2020).

According to "word frequency" analysis, CCUS patents in China mainly focus on capture, which primarily involves the preparation of adsorbent/absorber materials, the research and development of capture devices, and the optimization of the capture process, etc. The areas of capture are mainly about flue gas emission from coal-fired power plants and natural gas exploitation. Capture cost is an important part of CCUS economics. The distribution of word frequency above reflects that most patents focus on exploring CO_2 capture sources and reducing energy consumption and capture cost. A small number of patents focus on the geological utilization and storage of CO_2, which has great development potential in the context of commercial development of the whole CCUS industrial chain, in particular, the capture of flue gas from coal-fired power plants. In the field of technology distribution, the first five fields are (1) general physical or chemical methods or devices (34.29%); (2) inorganic chemistry (15.77%); (3) oil, gas and coking industries, industrial gases containing carbon monoxide, fuels, lubricants and peat, (5.2%); (4) combustion equipment and method (4.44%); (5) drilling and mining of soil or rock (3.67%).

3.2 Literature on CCUS in China

In the early stage, CCUS-related SCI articles published by Chinese authors focused on CO_2 utilization. The first article on sequestration appeared in 2007, and the number of acticles increased year by year. It can be seen that national policies have promoted relevant researches. The number has increased rapidly since 2009, mainly because the government has included carbon emission reduction in the national science and technology plan, and made a solemn commitment to achieve carbon emission reductions. Countries and companies have gradually increased their investment in carbon emission reduction. From 2008 to 2019, the number of articles grew at an annual rate of about 24% (Fig. 18).

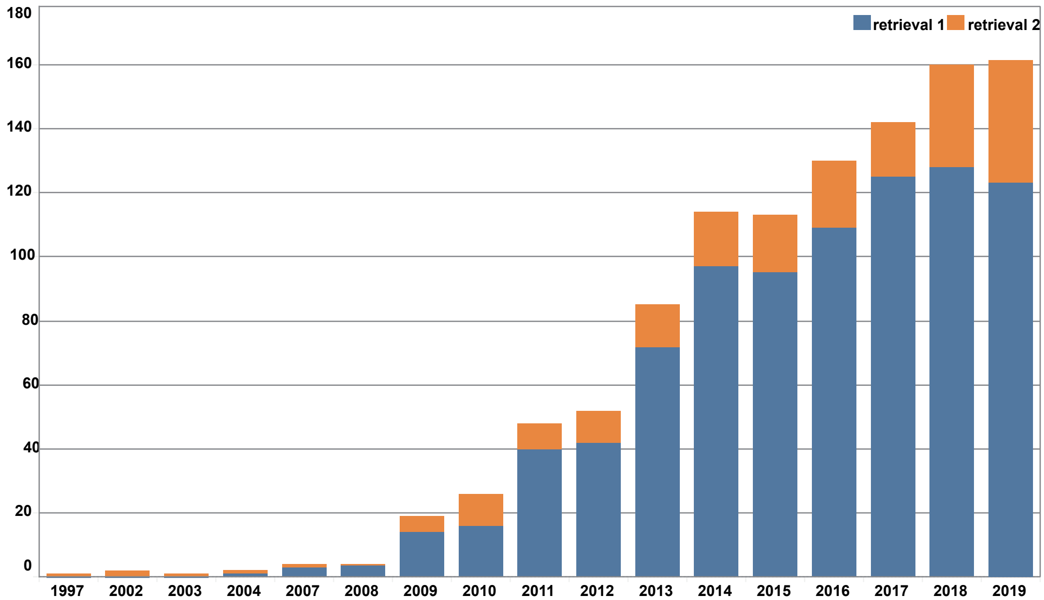


Fig.18 Annual distribution of CCUS research literature in China.

Retrieval type 1: TS=("carbon capture utilization and storage" OR " carbon capture usage and storage " OR (carbon and CCUS) OR ("carbon" and CCS) or "carbon capture and storage") AND CU=CHINA;

Retrieval type 2: TS=("carbon usage" or" Carbon utilization") and CU=China, retrieval date January 3, 2020, database: Web of Science (SCI))

According to the word frequency analysis, other hot words include electric power, coal, enhance, energy, emissions, models, development, etc., indicating that in addition to the CCUS technology itself, its additional effects on energy transformation, industry reduction and the sustainable development also gradually become the research emphasis of relevant scholars, and further reflects the fact that CCUS is an important technology to reduce emissions in the energy sector (Fig. 19).

Fig. 19 Word frequency analysis of Chinese CCUS research literature abstract.

4 Status and Business Model of CCUS Technology in China

4.1 Technical Status

As a responsible developing country, China has made a solemn commitment to achieve carbon emissions peak by 2030, but China's coal-based energy structure cannot be changed in a short term. CCUS, as an effective technology with great potential to realize low-carbon use of fossil energy, has attracted wide attention in recent years. Remarkable achievements have been made in macro planning, technology research and development, promotion and application, and international cooperation regarding CCUS.

The Chinese government has made systematic deployment and carried out a series of work focusing on basic research, technology development and demonstration related to CCUS. The CCUS R&D project on key technologies was deployed, and a national key project on "clean and efficient utilization of coal and new energy-saving technologies" was established. The country has also issued *the National Special Plan for the Development of Carbon Capture, Utilization, and Storage Technology During the 12th Five-Year Plan Period*, and *the CCUS Technology Roadmap* for China in 2011 and 2019. On the basis of a comprehensive assessment of the technical status of CCUS in China, its strategic position, development objectives, and R & D policies at different stages are defined. In collaboration with universities, enterprises, research institutes and other organizations, the China Industry Strategic Alliance for CO_2 Capture, Utilization and Storage Technology Innovation has been established to explore the government-university-industry collaboration mechismism and share knowledge and experiences.

Chinese enterprises have actively carried out CCUS RD&D activities and made great progress. Huaneng Group has developed thefirst CO_2 capture device in China's coal power plant and built the world's first industrial application of post-combustion carbon capture project at a scale of 120,000 tons CO_2 captured per year, which has been in operation steadily for more than 10 years. In 2008, China National Energy Group Co., Ltd. (Shenhua) Coal-to-Oil Co., Ltd. launched China's first 100,000-ton/yr CO_2 saline storage demonstration project, which has achieved a total 300,000 tons of CO_2 injection ahead of schedule. Jilin Oilfield has built 53 kilometers of CO_2 transport pipeline and a storage facility with an annual capacity of 300,000 tons. CNPC, Sinopec, Yanchang Petroleum and other companies have carried out engineering tests of 50,000-100,000 tons/year CO_2 flooding to enhance oil recovery in different oil fields.

China has continuously strengthened international cooperation and exchanges. In the China-EU and China-US joint statements, CCUS technology has been listed as one of the important areas of cooperation, the China-UK (Guangdong) CCUS Center and China-USA Clean Energy Research Center have been established successively. Extensive cooperation with the International Energy Agency (IEA), Carbon Capture Leaders Forum (CSLF), Innovation Mission (MI), Clean Energy Ministerial Conference (CEM), Global CCS Institute (GCCSI) and other international organizations has been carried out; China has actively participated in the preparation of international standards and conducted bilateral and multilateral scientific and technological cooperation at various levels with the European Union, the United States, Australia, Canada, Italy and other countries and regions around CCUS.

The main technologies of CCUS in China are developing rapidly, and a variety of new technologies are emerging.

Regarding CO_2 capture, some technologies have reached or nearly reached the stage of commercial application. At present, the cost and energy consumption of the first-generation* CO_2 capture technology is still high, and the experience of large-scale demonstration projects is limited. The second-generationtechnology is still in the stage of laboratory research & development or pilot test. The second-generation technology needs to realize intergenerational connection around 2035.

Regarding CO_2 transportation, CO_2 transportation by truck tanks and inland vessels is mature; and the technology of CO_2 transportation by land pipeline is the most economical. China has gained experience in designing pipelines for the capacity of 1 million tons/year and is in the process of publishing relevant technical specifications. The technology of offshore pipeline is still in the stage of conceptual research.

In the area of CO_2 utilization, chemical utilization has made great progress. Some techniques, such as reforming the preparation of syngas, synthetic biodegradable polymers and synthetic organic carbonate, have been demonstrated Bio-utilization products with high added-value have good economic benefits; currently, the technology for food and feed production has achieved large-scale commercialization, while other technologies are in a stage of R&D or small-scale demonstration. Compared with chemical and biological utilization, geological utilization technology has the largest development potential and is relatively mature. CO_2-EOR has been applied to a number of oil recovery and storage demonstration projects.

With respect to storage, China has finished the national assessment of theoretical storage potential of CO_2, the total theoretical capacity of onshore geological utilization and storage is over one trillion tons, the demonstration of onshore saline aquifer storage technology has been completed on a scale of 100,000 tons; and the pilot project design and demonstration of offshore saline aquifer storage, exhausted oil fields, and exhausted gas fields storage technology has been completed. The main technological development status of each approach from 2011 to 2018 is shown in Fig. 20.

*First-generation capture technology refers to the technology that can be demonstrated on a large scale at present, such as amine-based absorbents, atmospheric pressure Oxyfuel combustion, etc. The second generation capture technology refers to the new technology that can reduce energy consumption and cost by more than 30% compared with the first generation technology after technology maturity, such as a new type of membrane separation technology, the new type of absorption, adsorption, pressurization oxyfuel combustion technology, chemical looping combustion technology (Source: *Roadmap for Carbon Capture Utilization and Storage Technology in China(2019)*).

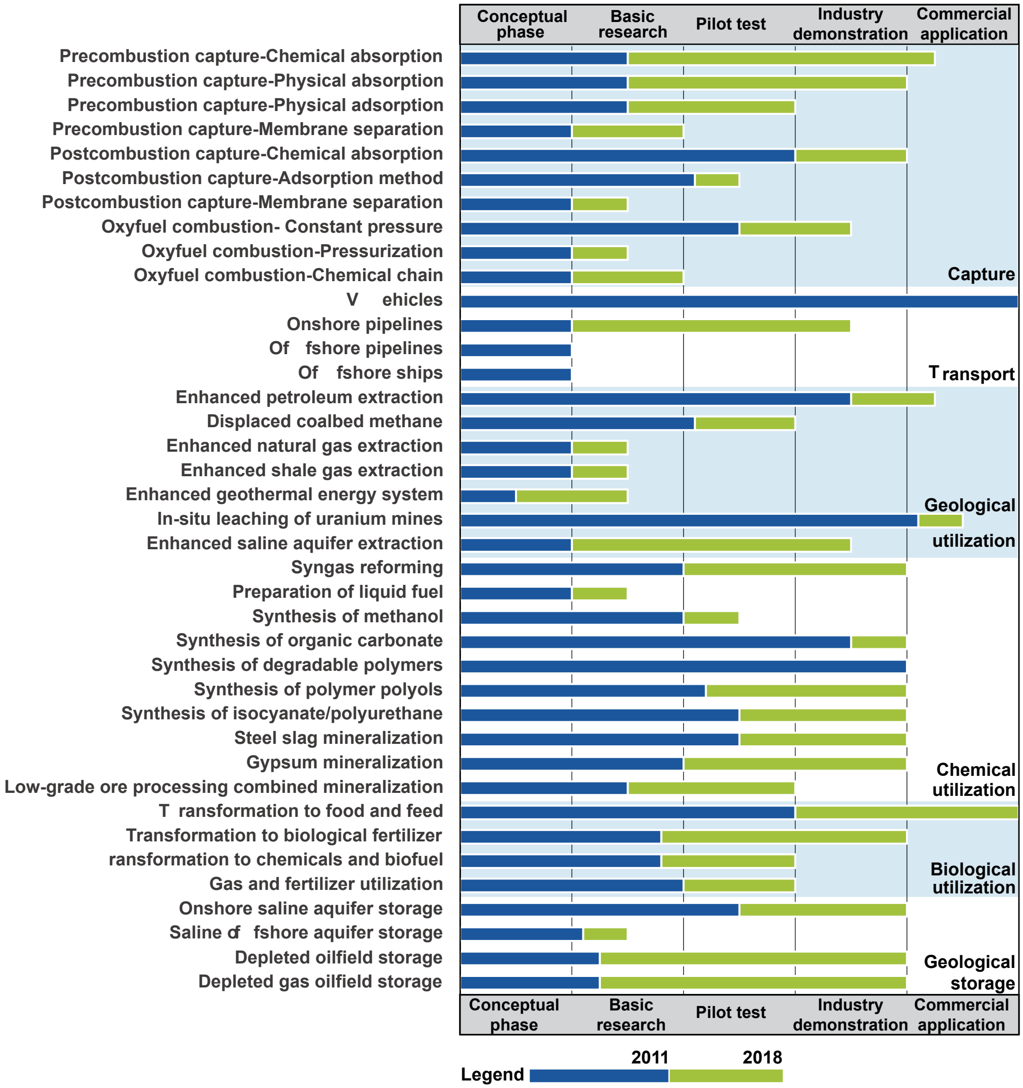


Fig. 20 Schematic diagram of CCUS technology development stage in China.

Note:data from *Roadmap for Carbon Capture Utilization and Storage Technology in China(2019)*

At present, geological utilization technology still faces the following problems:

First, the scientific process or mechanism of some key CCUS technologies is not fully understood, and the evaluation of technical feasibility and effectiveness is not well-developed. For example, CO_2-EOR technology is faced with challenges, like the continental sedimentary reservoir and high density & high viscosity crude oil. CO_2 for coalbed methane recovery has not been tested at an industrial scale anywhere in the world and the test results vary greatly. Some applicable conditions of this technology are not fully understood. Understanding of the technical mechanism of CO_2 flooding to improve shale gas recovery is still inadequate; the feasibility of CO_2 as a heat-conducting medium has not been thoroughly studied, and the efficiency of power generation technology and the feasibility of largescale deployment have not been proved. These are the key technical problems restricting the development of geological utilization of CO_2.

Second, it is diffic-ult to monitor the CO_2 after injection into the ground, and it is d-ifficult to predict the risk. For example, the monitoring of CO_2 injection during the process of CO_2 flooding as well as the prevention & control of anti-corrosion technologies in abandoned wells are still immature. When CO_2 displaces coalbed methane, it is difficult to monitor the gas migration in the coal seam. CO_2 enhanced geothermal systems are still immature for the prediction, monitoring, and control of earthquakes and leakage risks induced by pressure injection. Research and development of monitoring and verification technology are still insufficient; coupled with the high cost of monitoring technology, potential environmental hazards, leakage from geological utilization is difficult to predict and control.

Third, there is no breakthrough in key technologies in the process of geological utilization, making it impossible to scale up. The large-scale pipeline network and well spacing strategy for CO_2 flooding to improve the recovery rate are still immature; the breakthrough in the injection into lowpermeability coalbeds to produce coalbed methane has not yet been achieved. The technology of CO_2 flooding to improve the recovery of natural gas and shale gas has not solved the problem of mixing of carbon dioxide and natural gas. Premature mixing not only affects the sequestration effect of CO_2 but also may cause natural gas pollution and increase the cost and difficulty of the ground treatment process. The CO_2 enhanced geothermal approach is also faced with some technical problems, such as thermal storage reformation and unpredictable fracture networks, which may cause CO_2 leakage or induce earthquakes.

4.2 Business Model

CCUS Financing Model

(1) Costs and Financing Needs

CCUS is a technology with a complex process, involving the capture, transportation, storage and utilization of CO_2, which can be deployed in power, oil, transportation, coal, chemical industry, steel, food and many other industries. The development of CCUS require a great amount for capital and often also face complicated financial models. At the same time, the coordination of the various value chains of the CCUS project will bring greater investment risks. The development of CCUS is a long-term process, which requires a stable investment environment supported by the government and enterprises. Sustained and substantial capital investment is the pre-condition for the further development of the CCUS industry.

CCUS cannot develop without the support of huge capital. According to different emission source concentrations, the financing needs for CCUS projects can be divided into two categories: 1) high-concentration CO_2 emission sources. Because the carbon dioxide concentration of the flue gas is higher, the capture cost is lower than that of the low-concentration CO_2 flue gas. Therefore, the difficulty of getting financing for CCUS projects with high CO_2 concentration emission sources will be relatively low if they can be combined with CO_2 utilization technologies with certain economic returns (such as CO_2 enhanced oil recovery). 2) low concentration CO_2 emission source. Low-concentration emission sources, mainly coal-fired power plants, are the main source of total emissions, and their relatively high capture cost is also a major obstacle to CCUS financing.

In addition to cost, other financing barriers include: 1) technical uncertainty. Geological exploration of storage is one of the biggest uncertainties in the development of CCUS technology. China's geological conditions are complex, geological exploration work is relatively less-developed, and the information support for CO_2 storage is insufficient. The enterprise is also unable to make a comprehensive assessment of the formation structure, storage potential, storage risk and monitoring scheme, which increases the operational risk of the enterprise. 2) lack of policy guidance and incentive mechanism. The country has not given a clear development target for CCUS like it has for renewable energy, and the lack of relevant laws and regulations means multiple risks to the enterprise's financials and goodwill. At present, it is difficult for CCUS to bring benefits to investors through commercial channels, which makes it difficult for enterprises to adopt CCUS technology and directly hinders enterprises' enthusiasm to participate in CCUS projects. 3) lack of effective cross-sector coordination and cooperation mechanism. The industrial chain of CCUS covers almost every part of energy production and consumption, which brings with it the problem of cooperation between multiple enterprises on the complicated benefit chain. The existing market environment and policy framework doesn't lead to an effective profit distribution mechisnism among coal, oil, power, chemical, and other enterprises. If this problem cannot be quickly solved, it will greatly impact the interest of enterprises in CCUS.

(2) Review and Analysis of the Existing Financing Channels for CCUS Projects

From the five successful CCUS demonstration projects in the international community (Table.4), the key to success lies in the active participation of the government, including direct investment, carbon tax, FIT (Feed-in-Tariff), and other incentive policies. The two demonstration projects in Norway are more visible by gaining government policy support. Second, a good cooperative relationship between the government and enterprises is also critical. The success of the Boundary

Dam project in Canada is mainly due to the close cooperation between the local energy company and the government, and the public support for the project is relatively high. However, from the perspective of the failed CCUS demonstration projects, the most critical factors causing the failure are the uncertainty in both cost and technology. For example, the two IGCC/CCUS projects of pre-combustion capture in Australia were both caused by the failure in site selection of CO_2 storage, which resulted in the cost greatly exceeding the project expectation. The government's role also remains important. The Killingholme CCS project's failure in Britain was largely due to a competitive bidding mechanism that did not include funding for pre-combustion capture.

Table 4 Analysis of success factors of typical cases of international CCUS demonstration projects

Project Name	Country	Type	Government Participation in Financing and its Proportion	Private Capital Contribution	Government Incentive Policy	Other Economic Benefits	Financial Institution Participation
Mongstad	Norway	Post-combustion	75.12%	3 energy companies	Guarented purchase of power generation	/	No
Snøhvit	Norway	EGR	Share	1 private company	Carbon tax	/	No
Weyburn-Midale	Canada	EOR	None	12 international companies	None	EGR recovery is high	No
Boundary Dam	Canada	Post-combustion	19.35%	SaskPower works with the government	Electricity market control	/	No
Schwarze Pumpe	Germany	post-combustion	None	Self-financing Vattenfall energy	None	/	No

Table 5 Chinese typical CCUS project financing models

CCUS Project	Scale (10,000 tons / year)	Financing Model / Funding Sources	Features / Advantages & Disadvantages / Issues
CO_2 Geological Storage Demonstration Project in Deep Aquifer of China National Energy Investment Group Co., Ltd. (Shenhua) coal-to-liquids Branch	10	Self-fund, plus funding from by the Ministry of Science and Technology, the estimated investment is 210 million CNY	Due to funding and technology maturity issues, the project is currently operating intermittently
China Huaneng Group Shanghai Shidongkou Power Plant Carbon Capture Project	12	Self fund, the estimated investment is 150 million CNY. The Government subsidies by the form of adding the hours of power generation. The captured CO_2 is used in the industrial and food industries and has a certain income	The main problem is that no subsequent storage was carried out. The captured CO_2 was put into industrial and food utilization. The project is currently operating intermittently
China Huaneng Group Tianjin Green Coal Power Project	10	Self-fund, plus funding from the Ministry of Science and Technology, estimated investment of 100 million CNY	Because the technology is in the research and development stage, the cost is too high to form a suitable commercialization model
CO_2 Capture and Flood Demonstration Project of Sinopec Shengli Oilfield	4	Self-fund, plus funding from the Ministry of Science and Technology	Self-developed efficient CO_2 capture solvent
China Resources Haifeng Carbon Capture Test Platform	2	Self-funded, the estimated investment is 150 million CNY. The Government subsidies by the form of adding the hours of power generation.	It aims to reduce CCS cost by testing different carbon capture technologies, focusing on technological innovation and the expansion and promotion of innovative technologies
CO_2-EOR Project of Sinopec Zhongyuan Oilfield	10	Self-fund, the project combined with CO_2-EOR can bring certain economic returns	This was one of the earliest CO_2-EOR projects in China, and it achieved good results. The project has cumulatively increased the recovery rate by about 10%-15%

Table 5 Chinese typical CCUS project financing models (continued)

CCUS Project	Scale (10,000 tons / year)	Financing Model / Funding Sources	Features / Advantages & Disadvantages / Issues
Yanchang Petroleum CCUS Demonstration Project	5	Self-fund, plus funding from the Ministry of Science and Technology and the Asian Development Bank	The Asian Development Bank provides front-end design and feasibility study support for a large-scale projects at a scale of 1 million tons/year CCUS.
CO_2-EOR Demonstration Project of PetroChina Jilin Oilfield	30	Self-fund, plus funding from the Ministry of Science and Technology, PetroChina	After CO_2 flooding, the output increased by 30%, and the recovery rate can be increased by more than 10% compared with water flooding
CPIC Chongqing Shuanghuai Power Plant Carbon Capture Demonstration Project	1	Self-funded by the enterprise, the estimated investment is 12.5 million CNY	All the equipment of the project is purchased domestically, thus greatly reducing the investment and construction costs. The current facility, serving as a research and development platform, handles less than 1% of the total amount of flue gas of the plant.
Huazhong University of Science and Technology 35 MW Oxygen-Enriched Combustion Project	10	Research funding	/
Carbon Capture Project of Xinjiang Dunhua Petroleum Technology Co., Ltd.	6	Self-funded	CO_2 flooding based on CCUS technology has become a stable production approach for the low-cost and high-efficiency development in Karamay Oilfield
CCUS Demonstration Project of PetroChina Changqing Oilfield	10	Self-funded by the enterprise, Ministry of Science and Technology, PetroChina special funding	The CO_2 source comes from Ningxia Ningdong Deda gas company, and the long transportation distance leads to high CO_2 cost

Over the past 20 years, more than 20 CCUS pilot projects have been launched in China, and some technical preparation work has been done. However, due to the small scale or short operating time of each project, the overall CCUS technology development in China is still in its infancy. At present, most of the CCUS projects that have been carried out in China are self-funded by enterprises. The first motivation is to actively respond to the call for emission reduction and to demonstrate decarbonization technologies with the potential for promotion. The second is to accelerate the development of CCUS technology and make technical preparation for the potential of large-scale CCUS deployment in the future. We have not seen domestic CCUS industrial projects using commercial loans or equity investment financing models.

Since the 12th Five-Year Development Period, the Ministry of Science and Technology, the National Development and Reform Commission, and local governments have repeatedly called on enterprises, research institutions, and universities to actively carry out CCUS demonstration research work by establishing corresponding scientific research projects and corresponding funding programs. However, due to the large gap between the overall funding support and the funding required, government support funding is still primarily used for technical feasibility studies or laboratory-scale technology research.

So far, most of CCUS projects' initial investment has been realized through the company's own funds and a high proportion of government grant, with almost no debt financing (Table 5). To deploy CCUS at the speed needed to meet climate change goals, the proportion of private sector investment must increase. Banks play a key role in providing debt financing to project developers. At present, the difficulty of bank debt financing model is because that CCUS project cannot make profits and are unwilling/unable to accept bank debt financing. The further improvement of national incentive policies, the maturity of the carbon market, and the cluster deployment of transport and storage infrastructure are critical to reducing the debt financing risk for CCUS projects.

CO_2-EOR Business Model

Learning from international CCUS demonstration project business models (Val Verde Natural Gas Plants project in the United States, Coffeyville Gasification Plant project in the United States, Quest project in Canada, Uthmaniyah CO_2-EOR full-process demonstration project in Saudi Arabia, etc.) and business models of energy projects (coalbed methane, shale gas, desulfurization projects, etc.), combined with the business model of the CO_2-EOR project currently operating in China, we can summarize the two main CCUS business models that currently exist in China:

(1)The whole process independently operated by an oil company

The core feature of this business model is that the oil company is an independent operator of the whole process CCUS (Fig. 21). This vertically-integrated business model allows risks and profits to be shared more flexibly among multiple departments, and coordination is easier to implement than the cross-enterprise business model. This model also has lower transaction costs, which can be well adapted to conditions at the beginning of CCUS technology development. This business model is represented by PetroChina Jilin Oilfield and Sinopec Shengli Oilfield, with the following characteristics:

Oil and gas companies are both CCUS operators and CO_2 end consumers. Although this model involves different companies (CO_2 capture, transportation) and oil production plants (CO_2 storage, enhanced oil recovery) in oil and gas companies, they all belong to the same oil and gas company. For example, in the CO_2-EOR gas project of the PetroChina Jilin Oilfield, the source comes from the associated gas in the Changling gas field. Carbon dioxide flooding is carried out in the oil production field by a CCS-EOR development company, both of which belong to the PetroChina Jilin Oilfield Branch.

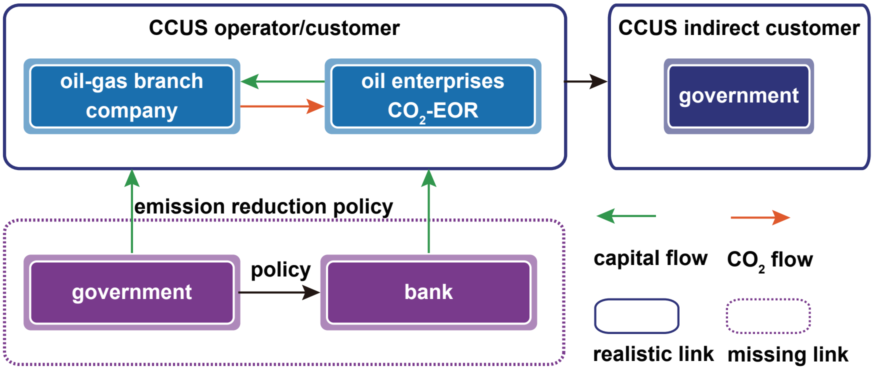


Fig. 21 CCUS independent operation model of whole process of oil companies.

CCUS costs include the process of separation and pressurization, transportation, and other operating costs. The advantage of natural gas associated gas compared with the tail gas from large-scale exhausters such as chemical plants, power plants, and steel mills is firstly high purity, which can be directly used for flooding. Secondly, the distance between the gas source and the storage site is close, usually within 200 km, which can reduce transportation costs.

(2) CCUS Operator Model

Under this model, independent operating companies participate in the operation of the CCUS project. CCUS operators can flexibly sell the captured CO_2 to CO_2 users (oil fields), or directly store CO_2 for storage subsidies. According to different contract rules, the price of CCUS operators' purchase and sale of CO_2 may be at risk (based on price targets). CCUS projects in PetroChina Changqing Oilfield, Xinjiang Oilfield, and Sinopec Zhongyuan Oilfield all adopt this model.

Under the CCUS operator model, independent market operators have emerged (Fig. 22), that is, a CO_2 capture company, such as Ningxia Deda Gas Development Technology Co., Ltd., which supplies gas to the CO_2-EOR project in Changqing Oilfield, and Xinjiang

Dunhua Petroleum Technology Co., Ltd., which supplies CO_2 to the CO_2-EOR project of PetroChina Xinjiang Oilfield. They purchase low-purity CO_2 from coal chemical companies, and rely on the company's own technology for capture, separation, and purification, and deliver it to the oilfield storage site. This is because the important part of transportation in operation is still inseparable from the participation of oil companies, especially when it involves the construction of pipelines. Due to the huge cost, operators might not have the capacibility to build the pipeline newwork, but state-owned oil companies with huge government support can achieve this. This business model covers the upstream and downstream cooperation of "exhaust gas production", "CO_2 capture and separation", "CO_2 utilization", and "CO_2 storage", involving multi-party companies of waste gas generating enterprises (such as coal chemical industry, fertilizer plants, etc.) CO_2 capture service companies, and oilfields that ulilize and storage CO_2.

The captured CO_2 purchased by the CCUS operators can be sold to CO_2 consumer companies for food, chemical, and oil production. Under this model, in addition to direct subsidy policies such as fiscal tax reductions and subsidies, the government should also introduce carbon tax policies or emission reduction requirements for emission sources such as chemical companies and coal-fired power plants.

CCUS costs include the purchase of coal chemical flue gas, flue gas treatment, transportation costs, and other operating costs. Because the cost of CO_2 capture and separation from coal chemical companies accounts for a large proportion of the cost of carbon dioxide sources, CCUS operators, namely carbon dioxide capture companies, are committed to reducing the cost of capture through the development of new capture technologies. Transportation costs are subject to the type of transportation mode, distance and scale. Currently, tanker transportation is commonly used in the demonstration project stage. In the large-scale application phase of CCUS, pipeline will have to be used for CO_2 transportation.

Under this model, in order to settle disputes, government should define clearly the rights, obligations, and social responsibilities among operators, cooperative relationships and customers, through the laws, standards, and systems. Responsibilities, economic and social benefits should be reasonably distributed among the various business sectors and promote effective cooperation in various industries related to the CCUS project.

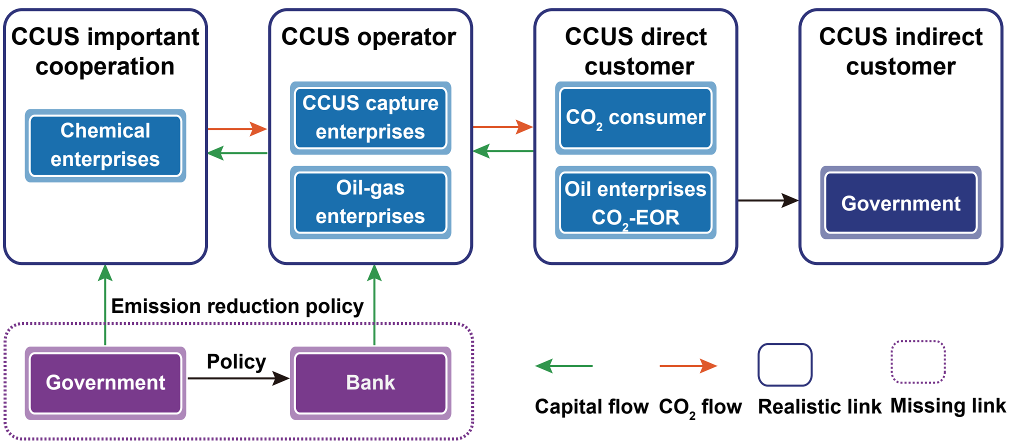


Fig. 22 CCUS operatior model

5. CCUS policy in China »»

As a special emissions-reducing technology, CCUS involves multi-industry collaboration and huge investment. So, its development requires national policies to match its strategic position. The Chinese government attaches great importance to climate change and has issued a series of CCUS policies and plans to promote the R&D and demonstration of CCUS. Since 2006, sixteen national Ministries, including the National Development and Reform Commission, Ministry of Ecology and Environment, Ministry of Science and Technology, Ministry of Finance, Ministry of Foreign Affairs, Ministry of Industry and Information Technology, Ministry of Land and Resources and other ministries, have been involved in formulating and publishing more than 20 national policies and development plans (Fig. 23). These related policy documents, such as *Outline of the National Plan for Medium - and Long-Term Scientific and Technological Development (2006-2020)*, *the national climate change plan (2014-2020)* and *the*

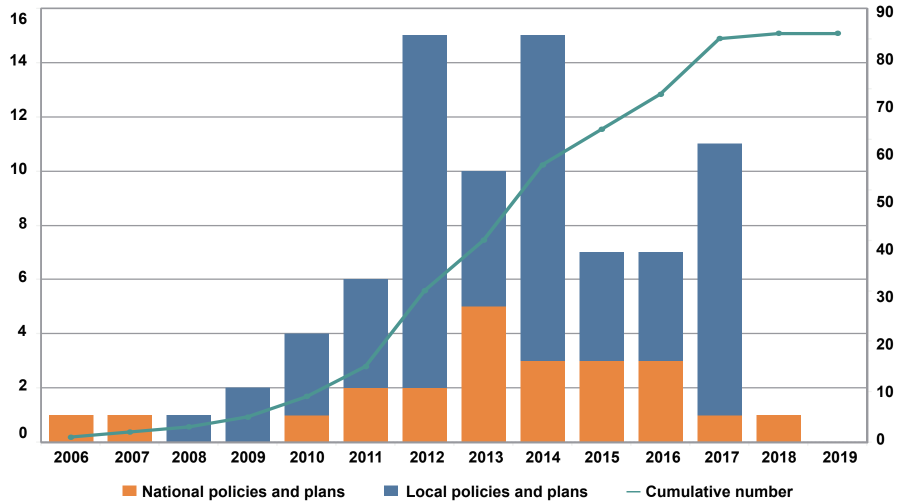


Fig. 23 China's main policy statistics on CCUS

13th Five-Year Plan for greenhouse gas emission control, are listed in table 6. These development plans not only provide the national strategical direction, but also present the steps to the specific, operational, executable, demonstrable CCUS delveopment actions.

Table 6 CCUS policies in China

Issue Organization	Pub-date	Title	Main content
State Council of the People's Republic of China	February 07, 2006	Outline of the National Plan for Medium - and Long-Term Scientific and Technological Development (2006-2020)	Proposed to develop efficient, clean and near-zero carbon dioxide emissions of fossil energy development and utilization technology.
A total of 14 ministries and commissions, including the Ministry of Science and Technology, National Development and Reform Commission, Ministry of Foreign Affairs and Ministry of Education, jointly issued the statement	June 13, 2007	A Specific Project of Science and Technology Initiative in China to Address Climate Change	'Carbon dioxide capture, utilization, and storage technology' has been listed as a key technical field, which has been supported, tackled and demonstrated.
Ministry of Science and Technology	July 4, 2011	The 12th Five-Year Plan for Science and Technology Development	The document proposed to develop technologies for carbon dioxide capture, utilization, and storage
Ministry of Land and Resources	September 13, 2011	Science and Technology Development Plan for The 12th Five- Year Plan of Land and Resources	It proposed to tackle key problem on a technologically innovative of geological carbon sink and carbon dioxide geological storage. It is mentioned in detail that the "geological carbon storage method, CCS process and monitoring technology needs to be developed to explore artificial carbon sequestration technology and ways. To prepare the national geological carbon storage potential evaluation map, with the basin (plain) as the unit and the deep saline aquifer, oil-bearing basin, natural gas-bearing basin and coalbed methane bearing basin as the focus. And then, select strategic prospect areas, and carry out scientific and technological demonstration project of geological carbon storage project".

Table 6 CCUS policies in China (continued)

Issue Organization	Pub-date	Title	Main content
Jointly issued by 16 ministries and commissions including the Ministry of Science and Technology, the Ministry of Foreign Affairs, the National Development and Reform Commission, the Ministry of Education, the Ministry of Industry and Information Technology	May 04, 2012	National "12th Five-Year Plan" Special Plan for Scientific and Technological Development in Response to Climate Change	It calls for developing of CCUS technical and demonstration. The development and demonstration fields of CCUS technology are proposed. The key processes and technologies of low energy consumption pre-combustion, post-combustion, oxyfuel combustion, and carbon capture need to be studied. It is necessary to establish methods and systems for the siting of the storage, carbon dioxide flow monitoring and simulation, leakage risk assessment and treatment, measurement and monitoring. Besides, it makes sense to develop and demonstrate technologies for carbon dioxide utilization, including carbon dioxide enhanced oil recovery, microalgae for oil production, and chemical utilization. The technical route, legal and regulatory of CCUS need to be built. It is necessary to carry out comprehensive integration and demonstration of CCUS technology in key industries such as power generation, steel, cement and chemical industry.
Jointly issued by the Ministry of Industry and Information Technology, the National Development and Reform Commission, the Ministry of Science and Technology and the Ministry of Finance	December 31, 2012	Action Plan On Climate Change in the Industry (2012-2020)	Demonstration projects for the integration of carbon capture, utilization and storage will be implemented in the chemical industry, cement, steel, and other industries. It is necessary to accelerate the demonstration and application of CCS technology with independent intellectual property rights and develop technologies and methods for the resource utilization of carbon dioxide. A roadmap of CCUS technology suitable for China's national conditions needs to be explored, and industrial carbon capture, utilization and storage capacity construction constantly strengthened
Ministry of Science and Technology	February 16, 2013	The 12th Five-Year Plan for Science and Technology Development	The document identifies technical bottlenecks and weaknesses around CCUS. It is proposed that basic research, technology R&D, equipment R&D and integrated demonstration deployment should be coordinated to break through CCUS key technology development. The whole process of CCUS demonstration project construction should be promoted in an orderly way.
National Development and Reform Commission	February 22, 2013	Catalog Of Key Products and Services for Strategic Emerging Industries	The document identifies key products of advanced environmental protection industries, including carbon emission reduction, carbon conversion technologies, carbon capture and storage technologies, and other technologies to reduce or eliminate greenhouse gas emissions.

Table 6 CCUS policies in China (continued)

Issue Organization	Pub-date	Title	Main content
National Development and Reform Commission	April 27, 2013	Notice on the Promotion of Carbon Capture, Utilization and Storage Pilot Demonstration	(1) Pilot demonstration projects need to be carried out by combining the realities of carbon capture and storage processes. (2) Carry out demonstration projects and base construction of CCUS. (3) Explore and establish relevant policy incentive mechanisms. (4) Strengthening strategic research and planning for CCUS development (5) Promote the formulation of CCUS standards and specifications (6) Strengthening capacity building and international cooperation
State Council	May 06, 2013	National Medium- and Long-Term Plan for Major Science and Technology Infrastructure Construction (2012-2030)	Research and build facilities for carbon dioxide capture, utilization, and storage in advance to provide technical support for tackling global climate change
Ministry of Environmental Protection	November 05, 2013	Notice on Strengthening Environmental Protection Work of Carbon Capture, Utilization, and Storage Test Demonstration Project	It pointed out the need to strengthen environmental protection in CCUS pilot projects, including environmental impact assessment, environmental impact monitoring, environmental risk prevention, and control system, environmental standards formulation, basic research and technology demonstration, capacity building and international cooperation
National Development and Reform Commission	August 25, 2014	National Key Promotion of Low-Carbon Technology Catalog	Key technologies promoted by the state include low-carbon technologies involving carbon capture, utilization, and storage.
State Council	Setember 19,2014	National Climate C hange Plan (2014-2020)	Carbon capture test demonstration projects should be carried out in coal-fired power, chemical industry, oil and gas exploration, cement, steel and other industries. Storage test projects and integrated demonstration projects of carbon dioxide capture, oil displacement and storage need to be carried out in areas with appropriate geological conditions. It is necessary to actively explore ways, technologies and methods of recycling carbon dioxide

Table 6 CCUS policies in China (continued)

Issue Organization	Pub-date	Title	Main content
National Energy Administration, Ministry of environmental protection and Industry and Information Ministry	December 26, 2014	Opinions of the National Energy Administration, the Ministry of Environmental Protection and the Ministry of Industry and Information Technology on Promoting the Safe and Green Development and Clean and Efficient Utilization of Coal	It is pointed out that carbon dioxide capture, utilization, and storage technology research and demonstration need to be carried out actively.
National Energy Administration	April 27, 2015	Action Plan for Clean and Efficient Utilization of Coal (2015-2020)	It is noted that CCUS technology research and demonstration need to be carried out actively. Cooperation among modern coal chemical enterprises, petroleum enterprises and related industries is encouraged. Oil displacement, microalgae absorption, geological storage and other demonstrations need to be complemented. Experience should be accumulated for other industries to implement a wider range of carbon emission reduction.
National Development and Reform Commission	December 06, 2015	National Key Promotion of Low-Carbon Technology Catalog (The Second Batch)	Key technologies promoted by the state include low-carbon technologies, involving carbon capture, utilization, and storage.
Ministry of Environmental Protection	December 24, 2015	Technical Policy for Pollution Control of Synthetic Ammonia Industry	One of the new technologies encouraging development is carbon capture and integrated utilization technology.
Ministry of Environmental Protection	June 20, 2016	Technical Guidelines on Environmental Risk Assessment forF Carbon Dioxide Capture, Utilization and Storage (Trial)	The terms and definitions of carbon dioxide capture, utilization and storage, environmental risk assessment procedures, major environmental risk sources, environmental risk receptors, determination of environmental background value, and environmental risk assessment were proposed.

Table 6 CCUS policies in China (continued)

Issue Organization	Pub-date	Title	Main content
State Council	July 28, 2016	"13th Five-Year Plan" for National Science and Technology Innovation	It is pointed out that the research and development of CCUS in coal-burning should be strengthened. At the same time, it is proposed that post-combustion carbon dioxide capture should be carried out to achieve a large-scale demonstration of million tons/year.
State Council	October 27, 2016	"13th Five-Year Plan" for Greenhouse Gas Emission Control	In order to control carbon emission in the coal chemical industry and other industries, it is proposed to carry out a large-scale industrial demonstration of CCUS in coal-based, oil and gas exploitation industries. It is proposed to promote the CCUS pilot demonstration in the industrial field and complete the environmental risk assessment. Relevant standards need to be formulated, including greenhouse gas emission accounting standards for key industries and products, low-carbon operation standards for buildings, carbon capture, utilization and storage standards, etc. Standards, labeling and certification systems for low-carbon products need to be improved.
Ministry of Science and Technology, Ministry of Environmental Protection, China Meteorological Administration	April 27, 2017	"13th Five-Year Plan" for Scientific and Technological Innovation in Response to Climate Change	It pointed out the need to promote the development and demonstration of mitigation technologies and set up a column on key technologies of CCUs with large scale and low cost. It is necessary to continue to promote the R&D and application demonstration of large-scale, low-cost CCUS technology and other low-carbon emission reduction technology
Ministry of Housing and Urban-Rural Development	September 11, 2018	Engineering Design Standard for Carbon Dioxide Capture And Purification of Flue Gas	The design of carbon dioxide capture and purification of flue gas is put forward.

5.1 The achievement of China's CCUS Policy

(1) CCUS has been identified as a key technology for addressing climate change

In 2007, the Ministry of Science and Technology and thirteen other ministries jointly issued *China's special action on climate change science and technology*, which listed 'carbon dioxide capture, utilization, and storage technology' as a key technology that needs to be supported, developed and demonstrated. It has confirmed the important position of CCUS in the field of addressing climate change. Subsequently, national and local science and technology development special plan, as well as the *Medium - And Long-Term Planning* further clarified the need to vigorously develop carbon capture and storage technology. *China's 12th Five-Year Plan for Scientific and Technological Development* emphasized the necessity of developing CCUS. The Catalogue of *Key Products and Services for Strategic Emerging Industries*, formulated by the National Development and Reform Commission, recognized CCUS as the quintessential products of the advanced environmental protection industry.

In 2011, the development roadmap of CCUS in China, compiled by the Ministry of Science and Technology, proposed the objectives and main tasks of China's development of CCUS technology. In 2014, the Ministry of Science & Technology evaluated the status of CO_2 utilization technology in China and its potential for environmental, social and economic benefits. In 2019, the Ministry of Science and Technology released a new roadmap to adapt to the changing environment and the development of CCUS technology. CCUS technology in China was also evaluated.

(2) CCUS demonstration projects and the related technolo-

gies have been actively promoted.

In addition to clarifying the important role of CCUS in tackling climate change and energy transition, national and local governments have stressed the importance of accelerating integrated CCUS demonstration, as well as proposing the requirements and targets for the development of CCUS technologies. In 2013, *Industrial Action Plan On Climate Change*, jointly issued by the Ministry of Industry and Information Technology, the National Development and Reform Commission, the Ministry of Science and Technology, and the Ministry of Finance, calls for accelerating CCUS integration demonstration projects and encouraging key industries to promote the application of low-carbon technologies. The State Council introduced *National Climate Change Plan (2014-2020)*. This document pointed out 'It is necessary to carry out carbon capture pilot demonstration projects in thermal power, chemical industry, oil and gas exploitation, cement, steel, and other industries. In addition, storage pilot projects and demonstration projects for the integration of carbon dioxide capture, oil displacement and storage need to be carried out in areas suitable for geological conditions. It is important to actively explore the ways, technologies and methods of carbon dioxide resource utilization.' In 2015, *Action Plan for Clean and Efficient Use of Coal (2015-2020)* issued by the National Energy Administration, calls for vigorously developing clean coal technology, promoting efficient & clean use of resources, and actively carrying out CCUS research and demonstration. It encourages coal chemical companies to cooperate with petroleum companies and and related industries to carry out demonstration projects such as oil production, demonstration projects such as oil production, microalgae absorption, and geological storage. In 2017, *'Special Plan for Science, Technology and Innovation in Addressing Climate Change During the 13th Five-Year Plan Period'* further emphasized the research, development and demonstration of life-cycle emission reduction technologies in key industries, such as energy, power, construction, transportation and agriculture. At the same time, the country will continue to promote the R&D, and application and demonstration of large-scale, low-cost CCUS technology. In view of the development conditions of CCUS in these regions, Beijing, Shanghai, Shaanxi, Guangdong and other places have proposed some specific targets regarding the deployment of demonstration projects and the development of key CCS technologies.

(3) Environmental protection related to CCUS project has been strengthened

In 2013, *Notice on Strengthening Environmental Protection in Pilot Demonstration Projects for Carbon Capture, Utilization and Storage* was issued by the former Ministry of Environmental Protection. It puts forward such requirements as "strengthening the environmental protection work of CCS projects, strengthening environmental impact assessment and detection, exploring the establishment of environmental risk prevention and control system, and promoting the development of environmental standards and specifications". In response to this request, the Ministry of Ecology and Environment has prepared the *'Technical Guidelines on Environmental Risk Assessment for Carbon Dioxide Capture, Utilization and Storage (Trial-Version))'.* This guideline, which was released in 2016, is China's first environmental technical guideline and specification for CCUS projects.

5.2 Policy recommendations

Although both the central and local governments have issued a series of policies to encourage the development of CCUS demonstration projects and technology, the policy framework is still not perfect for accelerating the commercial application of CCUS. This report makes the following recommendations:

(1) To establish and improve CCUS regulations and standards.

Urgent legal and regulatory issues need to be solved, such as unclear ownership, unclear jurisdiction and approval procedures, and lack of relevant technical specifications. It is necessary to formulate clear and complete CCUS laws and regulations to reduce concerns of stakeholders. Based on the standard system, a third-party verification system for CCUS from site selection to emission reductions should be established.

(2) To introduce incentives and subsidy policies, explore market-based incentive mechanisms, and improve the investment environ-ment.

Development of CCUS technology requires the huge investment in R & D before commercial application. Therefore, governments urgently need to introduce financial inventives, such as subsidies and government grants. It is also suggested to explore market-based policy mechnisms to attrack bank loans, private capital, and to include CCUS in China's carbon emission trading system. The government should promote infrastructure construction, including building CO_2 transport pipelines, helping reducing the operation cost for CCUS. It is recommended to design reasonable investment and financing mechanisms and policies to overcome the obstacles of high CCUS investment and operating costs.

(3) To establish interdepartmental and cross-industry coordination mechanisms, and gradually promote the commercialization of CCUS technology in stages, industries, and priorities.

The implementation of a CCUS project requires the cooperation and coordination of multiple ministries and industries. It is recommended to set up a special inter-department coordination initiative led by the Ministry of Ecology and Environment in policy planning, technology research, process evaluation, and project establishment of CCUS. It is recommended to design a policy framework to better manage costs and allocate responsibilities. Driven by large-scale geological storage, targeting at emission reductions, it is recommended to carry out the overall layout and planning of CCUS in China in the 14th Five-Year Plan period.

References

BP. Statistical Review of World Energy. 2019.

China Environmental Risk Research Group of Carbon Sequestration. Environmental Risk Assessment of Geological Sequestration of Carbon Dioxide in China (2nd edition). Beijing: Chemical Industry Press. 2018.

Department of Science and Technology for Social Development, Ministry of Science and Technology of PRC, The Administrative Centre for China's Agenda 21. Roadmap for Carbon Capture Utilization and Storage Technology in China(2019). Beijing, 2019.

GCCSI (Global CCS Institute), 2019. Policy Priority for Incentivise Large Scale Deployment of CCS. https://www.globalccsinstitute.com/wp-content/uploads/2019/04/TL-Report-Policy-prorities-to-incentivise-the-large-scale-deployment-of-CCS-digital-fnal-2019-1.pdf

IEA. Carbon capture and storage: Legal and regulatory review, 3rd edition. Paris, OECD/IEA, 2012

IEA. 20 Years of Carbon Capture and Storage Accelerating Future Deployment. Paris, OECD/IEA, 2016.

IPCC. IPCC Special Report on Carbon Dioxide Capture and Storage. Metz B, Davidson O, de Coninck H C, Loos M, Mayer L A, eds. Cambridge, UK, and New York, USA, Cambridge University Press, 2005.

IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press, 2014.

The Administrative Centre for China's Agenda 21. An assessment report on CO_2 utilization technologies in China. Beijing: Science Press, 2014.

Glossary

Abbreviation	Meaning
BECCS	Bio-energy with carbon capture and storage
CCS	Carbon dioxide capture and storage
CCUS	Carbon dioxide capture, utilization and storage
CO_2-ECBM	Carbon dioxide enhanced coalbed methane recovery
CO_2-EOR	Carbon dioxide enhanced oil recovery
IEA	International energy agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental panel on climate change
ppm	One part per million by volume
ton	Metric tonne
t/d	Tonnes per day

China CCUS project basic information table

Project name	Location	Carbon dioxide capture									Transportation	
		Type of catching industry	The business entity	The business entity	Technology of capture	The size of the capture (k tons/ year)	Energy consump-tion (GJ)	Water consump-tion (t/t)	CO_2 purity (%)	Total output of CO_2 (k tons)	Transpor-tation	Transmi-ssion distance (km)
Carbon dioxide storage project of the saline aquifer in the Ordos of National Energy Group	Ordos, Inner Mongolia	Coal-to-liquids	Ordos coal to oil branch of State Energy Investment Group Co., Ltd		Pre-combustion (physical adsorption)	100	1.23	0	99.5	302.6	Tank car	~13
50000 t / a CO_2 Capture and demonstration project of coal chemical industry in Northern Shaanxi of Yanchang Petroleum	Yulin, Shaanxi province	Coal-to-gas	Gasification plant of Yulin coal chemical company of Shaanxi Yanchang Petroleum		Pre-combustion (physical adsorption)	50	NA	NA	99.8	50	Tank car	200
Tongliao uranium leaching project of China National Nuclear Corporatio	Tongliao, Inner Mongolia	–	–	–	–	–	–	–	–	–	Tank car	_
CCS-EOR demonstration project of Jilin Oilfield, PetroChina	Songyuan, Jilin province	Natural gas processing	Songyuan gas production plant of Jilin Oilfield Company of PetroChina		Pre-combustion (associated gas separation)	800	NA	NA	99.9	1600	Pipeline transpor-tation	12.6
Huaneng Gaobeidian Power Plant	Beijing	Coal-fired power plant	Huaneng Gaobeidian power plant		Post-combustion (chemical absorption)	3	0.972	NA	> 99.9	NA	_	_
Capture, utilization, and storage project of Huaneng green coal power IGCC power plant	Tianjin	Coal-fired power plant	Demonstration unit of 400 MW Coal Gasification Combined Cycle Power Generation in Binhai New Area, Tianjin		Pre-combustion (chemical absorption)	100	NA	NA	NA	NA	Tank car	_
Tianjin Beitang thermal power plant of Guodian Cooperation	Tianjin	Coal-fired power plant	Tianjin Beitang power plant		Post-combustion (chemisorption)	20	NA	NA	NA	NA	Tank car	_
Clean energy power system research facility in Lianyungang	Lianyungang, Jiangsu province	Coal-fired power plant	Lianyungang clean energy innovation industrial park	400IGCC megawatt unit	Pre-combustion	30	NA	NA	NA	NA	_	_
Huaneng Shidongkou power plant	Shidongkou, Shanghai	Coal-fired power plant	Huaneng Shanghai Shidongkou No.2 Power Plant	600MWe supercritical unit	Post-combustion (chemical absorption)	120	0.738	NA	NA	NA	_	_
EOR project of Shengli Oilfield, Sinopec	Dongying City, Shandong province	Coal-fired power plant	Shengli Power Plant		Post-combustion (chemical absorption)	40	NA	NA	99.997	NA	Tank car	_
CO_2-EOR project of Zhongyuan Oilfield, Sinopec	Puyang, Henan province	Chemical fertilizer plant		Tail gas of synthetic ammonia in fertilizer plant	Pre-combustion (chemical absorption)	500	NA	NA	NA	5000	Tank car	NA

Note: The data comes from the voluntary reporting by the enterprise, which has not been strictly verified and is for reference only.

Project name	Location	Carbon dioxide capture									Transportation	
		Type of catching industry	The business entity	The business entity	Technology of capture	The size of the capture (k tons/ year)	Energy consumption (GJ)	Water consumption (t/t)	CO_2 purity (%)	Total output of CO_2 (k tons)	Transpor-tation	Transmi-ssion distance
Carbon capture demonstration project of Chongqing Shuanghuai power plant, China Power Investment Corporation	Chongqing	Coal-fired power plant	Chongqing Hechuan shuanghuai power plant	Two 300MW units	Post-combustion	10	NA	NA	$>$ 99.9	NA	–	–
coal-seam gas drive project of China United Coalbed methane Co. Ltd (Shizhuang)	Qinshui, Shanxi province	–	–	–	–	–	–	–	–	–	Tank car	NA
35MW oxyfuel combustion demonstration project of Huazhong University of Science and Technology	Wuhan, Hubei province	Coal-fired power plant	Hubei Jiuda (Yingcheng) Company	Thermoelectric Workshop II	Oxyfuel combustion	100	15.48	40	95	NA	Tank car	–
coal-seam gas drive project of China United Coalbed methane Co. Ltd (Liulin)	Liulin, Shaanxi province	–	–	–	–	–	–	–	–	–	Tank car	NA
EOR project of Karamay Donghua Petroleum - Xinjiang Oilfield	Karamay, Xinjiang province	Methanol plant	Xinjiang Dunhua Petroleum Technology Co., Ltd	Methanol plant of Karamay Petrochemical Company, PetroChina	Pre-combustion (chemical absorption)	100	2.5	45	99.96	NA	Tank car	26
EOR project of Changqing Oilfield	Yulin, Shaanxi, province	Methanol plant	Ningxia Deda Gas Development Technology Co., Ltd	Shenning coal chemical methanol plant	Pre-combustion	50	NA	NA	NA	NA	Tank car	NA
EOR project of Daqing Oilfield	Daqing, Heilongjiang Province	Natural gas treatment	Xushenjiu natural gas purification plant of Daqing natural gas branch company	Xu Shen gas field	Pre-combustion (associated gas separation)	NA	NA	NA	NA	NA	Tank car (Outsourcing gas)+ Pipeline transportation (Xushenjiu natural gas purification plant)	NA
The 50,000-ton CO_2 capture and purification demonstration project of Wuhu Baimashan cement plant of conch group	Wuhu, Anhui Province	Cement plant	Wuhu Baimashan cement plant		Pre-combustion (chemical absorption)	50	NA	NA	99.99	–	–	–
Haifeng Carbon capture test platform of China Resources	Haifeng, Guangdong Province	Coal-fired power plant	China-UK (Guangdong) CCUS Center	Unit 1 of China Resources Haifeng power plant	Post-combustion	20	3.24	20 t/h	99.99	NA	–	–
CCUS full process demonstration project of East China Oil & Gas Company	Dongtai, Yancheng, Jiangsu Province	Chemical plant	Taixing carbon dioxide plant of Jiangsu Huayang Liquid Carbon Co., Ltd	Sinopec Nanjing Chemical Company	Pre-combustion	40	124 Yuan/ton	8.6 Yuan/ton	99	100	Tanker and vessel	100

Utilization and storage								ton of CO_2 (RMB)	the year	2019
Department/Enterprise	Place of disposal	Technology of disposal	CO_2 annual utilization/ injection volume (K tons)	The total utilization of CO_2 (K tons)	Products	Production capacity (K tons)	Total resource output (K tons)			
Coal to oil branch of State Energy Investment Group Co., Ltd	Ordos basin	Saline aquifer seal up	100	302.6	_	_	_	249	2011	Stopped injections in 2015. Now under monitoring
Yanchang Oilfield	Oilfield in Jingbian, Yulin, Shanxi province	EOR	50	130	Crude oil	NA	NA	120	2013	In operation
Tongliao uranium industry	Qianjiadian uranium deposit	EUL (in-situ leaching of uranium)	NA	NA	NA	NA	NA	NA	NA	NA
CO_2 capture and storage and EOR development company---Jilin Oilfield Company of PetroChina	Daqing zi well oil field	EOR	300	1450	Crude oil	75	NA	166	2008	In operation
Gaobeidian power plant	NA	NA	_	_	_	_	_	_	2008	In operation
_	_	Emptying	_	_	_	_	_	_	The capture unit was completed in 2015, but the utilization and storage project was delayed	In operation
_	Market sales	Food applications	_	_	_	_	_	_	2012	In operation
_	_	Emptying	_	_	_	_	_	_	2011	In operation
Shidongkou Power Plant	Market sales	Industrial utilization and food application	_	_	_	_	_	_	2009	Intermittent operation
Shengli Oil Field	Block G89, Shengli Oilfield, Dongying	EOR	40		Crude oil	NA	NA	4500	2010	In operation
Zhongyuan Oil Field	Zhongyuan Oil Field	EOR	100	740	Crude oil	NA	NA	350	2015	In operation
_	self use	Used for welding protection, generator hydrogen cold replacement and so on	_	_	_	_	_	NA	2010	In operation
China United Coalbed methane co. LTD	Shizhuang block, qinshui basin	ECBM	1	NA	Coal Seam Gas	NA	NA	NA	2004	In operation
_	Market sales	industrial application	_	_	_	_	_	780~900	2014	Intermittent operation
China United Coalbed methane co. LTD	Liulin block, ordos basin	ECBM	1	NA	Coal Seam Gas	NA	NA	NA	2012	In operation
Xinjiang Oil Field	Xinjiang Oilfield, junggar basin	EOR	20	1239	Crude oil	14~39	495.1	800	2015	In operation
Changqing Oil Field	Jiyuan oil area, Changqing Oilfield, dingbian county, shaanxi province	EOR	50	376	Crude oil	NA	NA	NA	2017	In operation
Daqing Oil Field	Block 101 of trees outside changyuan and block 14 of Hailarbei oilfield	EOR	200	NA	Crude oil	NA	NA	NA	2003	In operation
_	Market sales	_	_	_	_	_	_	NA	2018	In operation
China Resources (haifeng) Co. Ltd	NA	_	_	_	_	_	_	500	2019	In operation
East China Oil & Gas Company, Sinopec	Zhenwu, Huazhuang, Shuaiduo, Caoshe and Hai 'an blocks in east China oilfield	EOR	100	400	Crude oil		130		2005	In operation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