China’s pathways of CO₂ capture, utilization and storage under carbon neutrality vision 2060

Guizhen Liu, Bofeng Cai, Qi Li, Xian Zhang and Tao Ouyang

Carbon dioxide (CO₂) Capture, Utilization and Storage (CCUS) is an indispensable part of the carbon removal technologies to achieve carbon neutrality for China. Our study focuses on China’s CCUS pathways, and draws out three key conclusions: (1) in terms of the greenhouse gases emission reductions required to achieve carbon neutrality and based on current technology projections, the CO₂ emission reductions to be achieved by CCUS are 0.6 ± 1.4 billion tonnes and 1 ± 1.8 billion tonnes in 2050 and 2060, respectively; (2) from the perspective of source-sink matching in China, the emission reduction potential provided by CCUS can basically meet the demand of carbon neutrality target (0.6 ± 2.1 billion tonnes of CO₂); (3) with the development of technologies, the cost of CCUS in China has a great potential to be reduced in the future. It is expected that by 2030, the technical cost of the whole CCUS process (according to 250 kilometers transportation) in China will be 310 ~ 770 Chinese Yuan per tonne of CO₂, and by 2060, it will gradually drop to 140 ~ 410 Chinese Yuan per tonne of CO₂.

Introduction

In September 2020, President Xi Jinping announced that China aims to reach the peak carbon dioxide (CO₂) emissions by 2030 and strive to achieve carbon neutrality by 2060 at the general debate of the 75th session of the United Nations General Assembly, which contributes to the global climate governance and the implementation of the Paris Agreement [1]. The announcement of President Xi Jinping opened a new journey for China to tackle climate change. By May 2021, 131 countries, whose greenhouse gas emissions account for more than 65% and gross domestic product (GDP) accounts for more than 75%, have announced the goal of carbon neutrality. With the global carbon neutrality vision becoming clear and mitigation actions being accelerated, the role of CO₂ capture, utilization and storage (CCUS) has become more prominent, and its status is changing significantly [2, 3].

CCUS is a large-scale greenhouse gas emissions reduction technology [4–6]. In recent years, CCUS policies, research and development in China have been gradually improved under the joint promotion of the Ministry of Ecology and Environment, the Ministry of Science and Technology, and the National Development and Reform Commission [7]. What’s more, the scale of pilot demonstration projects continues to grow, and the competitiveness is further enhanced. But overall, China’s green and low-carbon technology systems for carbon neutrality has not yet been established [8–10]. There is still a big gap between the existing technology system for emission reductions and the actual need for carbon neutrality. The studies have shown that CCUS will become one of the indispensable key technologies for China to achieve the goal of carbon neutrality. Therefore, the strategic positioning of CCUS should be rethought and reassessed according to the new situation, and it should be accelerated and deployed in advance on this basis [11].
This study focuses on China’s CCUS pathways, which will play an important role in studying the strategic positioning and development path of CCUS under the carbon-neutral goal in China. This paper introduces the key contents of the CCUS pathways, including the current status, emission reduction needs and potentials, and the cost of CCUS in China. Intelligence gathering and analyzing were the main means to draw the conclusions. Moreover, forty-nine researchers in the CCUS field participated in this research and 12 authoritative experts reviewed the results.

Section “Positioning of CCUS” introduces the position of CCUS in the scenario of carbon neutrality by 2060 and the global theoretical storage capacity; section “Current status of CCUS in China” extracts the current status of CCUS in China from the survey of the CCUS operation enterprises. Section “CCUS needs under the carbon neutrality target” reviewed the CCUS needs of thermal power, steel, cement, petrochemical and chemical industries under the carbon neutrality target, which indicates the role of CCUS in the above industries; section “CCUS potential of China based on source-sink matching” concluded the CCUS potential of China based on source-sink matching, mainly focusing on the utilization and storage technologies; section “CCUS cost assessment in China” forecast the CCUS cost trend to 2060.

The conclusions will support policymakers to carry out CCUS related analyses in strategy, planning, and policy, and help the researchers determine future emissions anchors in different periods based on the current understanding of CCUS. It will further help the public to understand CCUS related knowledge, such as the position and role of CCUS, which will strengthen China’s goal of achieving carbon neutrality.

Positioning of CCUS

To achieve the goal of carbon neutrality, China needs to establish a zero-carbon energy system based on non-fossil energy, and decouples economic development from carbon emissions [12, 13]. CCUS technology, as an important part of the carbon-neutral technologies in China, is the only technology choice for low-carbon utilization of fossil energy and the main technical means to maintain the flexibility of the power system. Moreover, CCUS is a feasible technical solution for difficult emission reduction industries such as steel and cement. In addition, the negative emission technology coupled with CCUS and new energy is also the base technology guarantee to offset the failure to reduce carbon emissions and achieve carbon neutrality [14, 15].

The global onshore theoretical storage capacity is 6 to 42 trillion tonnes (Figure 1), and the offshore is 2 to 13 trillion tonnes [16–26]. Among all the storage types, deep saline formation occupies the dominant position. It is widely distributed and accounts for about 98% of the storage capacity, making it ideal for large-scale CO2 storage [21]. Oil and gas reservoirs have an early opportunity for CO2 storage because of their complete structure and detailed geological exploration basis [27].

In China, the theoretical storage capacity is about 1.21 to 4.13 trillion tonnes [21, 28, 29] (Figure 1). China’s oil fields are mainly concentrated in the Songliao Basin, Bohai Bay Basin, Ordos Basin, and Junggar Basin. 5.1 billion tonnes of CO2 can be sequestered through CO2 enhanced oil recovery (CO2-EOR) technology. China’s gas reservoirs, which are mainly distributed in the Ordos, Sichuan, Bohai Bay, and Tarim Basins, can be used to sequester about 15.3 billion tonnes of CO2 in depleted gas reservoirs, while about 9 billion tonnes of CO2 can be
stored through CO₂ enhanced gas recovery (CO₂-EGR) technology. The CO₂ storage capacity of the deep saline formations in China is about 2.24 trillion tonnes, and its distribution is basically the same as that of the petroliferous basins. Among them, Songliao Basin (694.5 billion tonnes), Tarim Basin (552.8 billion tonnes), and Bohai Bay Basin (490.6 billion tonnes) are the three largest storage areas, accounting for 55.9% of the total storage. In addition, the Subei Basin (435.7 billion tonnes) and Ordos Basin (335.6 billion tonnes) also have large CO₂ storage potential in the deep saline formations. The CO₂ emissions in 2019 is about 9.8 billion tonnes, the theoretical storage capacity would meet the 120~420 years storage capacity demands based on the 2019 total emissions.

**Current status of CCUS in China**

In China, about 40 CCUS demonstration and pilot projects have been put into operation and under construction with a capture capacity of 3 million tonnes per year. By 2021, these projects mainly focus on the small-scale EOR demonstration in the petroleum, coal chemical and thermal power industries, lacking large-scale and full-chain industrialization demonstration with various technology combinations (Figure 2).

**Ready to scale up and preparing for CCUS cluster**

The engineering capacity in China is ready to capture and store CO₂ on a large scale and is actively preparing for a full-chain CCUS industrial cluster. China Energy Investment Corporation (China Energy) Ordos CCUS Demonstration Project has successfully carried out a full-chain demonstration of CO₂ capture, transportation and storage with a total of 300,000 tonnes of CO₂ injection into deep saline formations. Until 2021, China National Petroleum Corporation (CNPC) Jilin Oilfield EOR project is the only Chinese project among the 21 large-scale CCUS projects currently in operation globally and is presently the largest EOR project in Asia [22, 35], with a total of over 2 million tonnes of CO₂ injected. Besides that, the construction of 150,000 tonnes/year post-combustion CO₂ capture and storage demonstration project of Guohua Jinjie Power Plant (China Energy) started in 2019. It became China’s largest coal-fired power plant CCUS demonstration project. In July 2021, China Petrochemical
Corporation (Sinopec Group) officially launched China’s first million-tonne CCUS project, i.e. Qilu Petrochemical Corporation-Shengli Oilfield CCUS project.

**Diverse types of capture sources and utilization routes**

China’s CCUS projects are distributed in 19 provinces, and the industries of capture sources and the types of storage and utilization are diversifying. The total scale of China’s 13 CO₂ capture demonstration projects involving power plants and cement plants reached 856,500 tonnes/year. The total scale of China’s 11 CO₂ geological utilization and storage projects is 1.821 million tonnes/year, among which the scale of CO₂-EOR is about 1.54 million tonnes/year. China’s CO₂ capture sources cover pre-combustion, post-combustion and oxyfuel combustion capture in coal-fired power plants, gas-fired power plants, coal chemical industries, and cement kiln exhaust. CO₂ storage and utilization involve various options such as saline formation storage, EOR, enhanced coalbed methane recovery (ECBM), enhanced uranium leaching, CO₂ mineralization, biodegradable polymers, reforming of methane to syngas, and microalgae immobilization.

**Having significant progress in all aspects and commercial potential of some technologies**

Significant progress has been made in all technical aspects of CCUS in China, and some technologies have the potential for commercial applications (Figure 3).

**Capture technology**

The maturity of different CO₂ capture technologies varies greatly. At present, the pre-combustion physical absorption technology is already at the commercial application stage. The post-combustion chemical adsorption technology is still at the pilot stage, and most other capture technologies are already at the industrial demonstration stage. The post-combustion capture technology is currently the most mature capture technology, which can be used in the decarbonization transformation of most thermal power plants. For example, the 150,000-tonne-per-year CO₂ capture and storage demonstration project carried out by Guohua Jinjie Power Plant is operating. It is the largest post-combustion CO₂ capture and storage demonstration project in China. The pre-combustion capture system is relatively complicated, and the integrated gasification combined cycle (IGCC) technology is a typical pre-combustion CO₂ capture system. China’s IGCC projects include Huaneng Tianjin IGCC project and Lianyungang clean energy power system research facility. Oxyfuel combustion technology is one of the most potential large-scale CO₂ capture technologies for coal-fired power plants, producing higher concentration (about 90% ~ 95%) of CO₂ and is easier to capture. The oxyfuel combustion technology has developed rapidly and can be used in new and/or retrofitted coal-fired power plants. At present, the first-generation CO₂ capture technology (post-combustion, pre-combustion, oxyfuel combustion) has gradually matured. The main bottleneck is high cost, high energy consumption and lack of extensive large-scale demonstration project experiences. While, the second-generation technology (such as new membrane separation, new absorption, new adsorption, pressurized oxyfuel combustion, etc.) is still in laboratory research or a small-scale test stage. When the second-generation technology is mature, the energy consumption and cost will be reduced by more than 30% compared with the matured first-generation technology. And it is expected to be widely applied around 2035 [36].

**Transportation technology**

Among the existing CO₂ transportation technologies, tanker and ship transportation technologies have reached the commercial application stage, while pipeline transportation is still in the pilot stage. CO₂ land vehicle transportation and inland ship transportation technology has matured, and it is mainly applied to CO₂ transportation with a scale of less than 100,000 tonnes/year. The scale of China’s existing CCUS demonstration projects is relatively small, and most of them are transported by tankers. Jilin Oilfield and Qilu Petrochemical Corporation use land pipeline transportation. Part of the CO₂ from East China Oil and Gas Field and Lishui Gas Field is transported by ship. The cost of submarine pipeline transportation is 40% to 70% higher than that of land pipelines. At present, the technology of submarine pipeline transportation of CO₂ lacks experience, and it is still at the research stage in China.
Utilization and storage technology

Among CO₂ geological utilization and storage technologies, CO₂ enhanced uranium leaching has reached the commercial implementation stage, CO₂-EOR has been in the industrial demonstration stage, CO₂-EWR pilot test has been completed, ECBM has also completed the pilot-scale research and the CO₂ mineralization has also been in the industrial test stage. CO₂ enhanced natural gas and shale gas recovery are still in the primary research stage. China’s CO₂-EOR projects are mainly concentrated in oil fields and offshore areas in eastern, northern, northwestern and western China. The 100,000 tonnes/year CO₂ storage in deep saline formations implemented by China Energy Investment Corporation has completed the injection target of 300,000 tonnes in Ordos Basin in 2015 and stopped further injection. The 150,000 tonnes/year post-combustion CO₂ capture and storage demonstration project, implemented by China Energy Investment Corporation Guohua Jinjie Power Plant, plans to store the captured CO₂ in saline formations. In July 2021, China Petrochemical Corporation (Sinopec Group) officially launched China’s first million-tonne CCUS project (Qilu Petrochemical Corporation-Shengli Oilfield CCUS project), which is expected to become the largest demonstration project for the

![Figure 3. Types and development stages of CCUS technology until 2021 in China [33, 34, 36, 37].](image-url)
full-chain CCUS technology in China. The Institute of Process Engineering (IPE), Chinese Academy of Sciences, launched a 50,000 tonnes/year steel slag mineralization industrial verification project in Dazhou, Sichuan province. Zhejiang University has carried out a 10,000-tonne industrial test project of CO₂ deep mineralization maintenance for building materials in Henan province. Along with China Petrochemical Corporation (Sinopec Group) and other companies, Sichuan University has made good progress in developing the technology for direct mineralization of phosphogypsum co-production of sulfur-based compound fertilizer from low-concentration CO₂ exhaust gas. In China, significant progress has been made in CO₂ chemical utilization technologies, and many new technologies such as electrocatalysis and photocatalysis have emerged. However, some technical bottlenecks still exist in the post-combustion CO₂ capture system and chemical conversion and utilization device. Biological utilization mainly focused on microalgae fixation and gas fertilizer.

**CCUS needs under the carbon neutrality target**

According to the research of various domestic and foreign research institutions, to achieve the carbon neutralization target, China’s CO₂ emission reduction is 20 million to 408 million tonnes in 2030, 600 million to 1.45 billion tonnes in 2050, and 1 billion to 1.82 billion tonnes in 2060 (Table 1). The scenarios mainly consider China’s achievement of the 1.5°C and 2°C temperature control targets, sustainable development goals, carbon peaking and carbon-neutral targets, CO₂ emission pathways by industry, development of CCUS technology, and scenarios where CCUS can be used or may be used (Figure 4).

**Thermal power industry**

The thermal power industry is the main area of CCUS demonstration in China currently. It is expected that coal-fired power emission reductions will reach 6 million tonnes/year by 2025, peak at 200 million to 500 million tonnes/year in 2040, and then remain unchanged. The CCUS deployment of gas-fired power will be gradually carried out and will remain unchanged after reaching a peak in 2035, with a reduced rate of 20 million to 100 million tonnes/year. Coal-fired power plants equipped with CCUS can capture 90% of CO₂ emissions, turning them into relatively low-carbon power generation technology. China’s current installed capacity of about 900 million kilowatts will still be in operation by 2050. The deployment of CCUS technology helps to make full use of existing coal-fired power generation units, appropriately retain coal-fired power production capacity, and avoid the premature retirement of some coal-fired power assets that may lead to waste. It is an important way to release the emission reduction potential of CCUS by realizing low-carbon utilization and transformation of existing advanced coal-fired power units combined with CCUS technology. Technical suitability criteria and cost are the main factors affecting the installation of CCUS in active coal-fired power units. Technical suitability criteria determines whether a power
plant can be a candidate for transformation. At the present stage, technical suitability criteria that need to be considered in retrofitting coal-fired power plants include implementation year of CCUS, unit capacity, remaining service life, unit load rate, capture rate setting, and valley value/peak value, etc.

**Steel industry**

The emission reduction demand of steel industry is 2 million ~ 5 million tonnes/year in 2030 and 90 million ~ 110 million tonnes/year in 2060. China's iron and steel production process is dominated by the blast furnace-converter technology with high CO2 emissions, and the output of electric furnace steel accounts for only about 10%. About 89% of energy input in blast furnace-converter steelmaking comes from coal, leading to high CO2 emissions per tonne of steel in China. CCUS technology can be applied to many aspects of the steel industry, mainly including hydrogen production and steelmaking processes in hydrogen reduction ironmaking. In addition, the CO2-EOR project is also a vital driving force for the development of CO2 capture technology in China's steel industry.

The CO2 from China’s steel plants is mainly of medium concentration, which can be captured by pre-combustion and post-combustion capture technologies. Coking and blast furnace ironmaking processes have the most significant CO2 emissions in the entire steelmaking process, and these two processes have the largest CO2 capture potential. The mainstream CO2 capture technology in China’s steel industry is post-combustion capture from coking and blast furnace exhaust gas.

In addition to utilization and storage, CO2 captured by the iron and steel industry can also be directly used in the steelmaking process. These technologies have been tested successfully by Shougang Group and promoted to Tianjin Pipe International Economic & Trading Corporation and Xining Special Steel Co., Ltd. Full application of these technologies can reduce the total CO2 emissions by 5% ~ 10%. There are four main development directions for CO2 utilization in the steel industry. (1) It can be used for mixing. CO2 can replace nitrogen (N2) or argon (Ar) for the top/bottom blowing of the converter or for the mixing of molten steel in the ladle; (2) It acts as a reactant and reduces the volatilization and oxidation loss caused by direct collision of oxygen (O2) and molten iron in CO2-O2 mixed spray steelmaking; (3) It can partially replace N2 as a protective gas in steelmaking, thereby minimizing the loss of steel, as well as the nitrogen content and porosity in the finished steel; (4) It also can be used to synthesize fuel. The dry reforming reaction of CO2 and methane can produce synthesis gas (CO and hydrogen), which can then be used in direct reduced iron (DRI) steelmaking or the production of other chemicals.

**Cement industry**

In the cement industry, the CO2 emission reduction demand in 2030 will be 10 million ~ 152 million tonnes/year, and it will be 190 million ~ 210 million tonnes/year in 2060. The CO2 emissions from the decomposition of limestone account for about 60% of the total emissions in the cement industry. CCUS is a necessary technical means for cement decarbonization.

**Petrochemical and chemical industries**

The petrochemical and chemical industries are the main areas of CO2 utilization, through chemical reactions to convert CO2 into other substances and then for resource reuse. China’s petrochemical and chemical industries have many high-concentration (above 70%) CO2 emission sources. They include natural gas processing plants, coal plants, ammonia/fertilizer production plants, ethylene plants, methanol, ethanol and dimethyl ether production plants, etc. Compared with low-concentration CO2 emission sources, the capture of high-concentration CO2 emission sources has lower energy consumption, lower investment costs, and lower operation and maintenance costs, which have significant advantages. Therefore, high-concentration CO2 emission sources in the petrochemical and coal chemical industries can provide low-cost opportunities for early CCUS demonstrations. Early CCUS demonstration projects in China preferred combining high-concentration CO2 emission sources and EOR to generate revenue through CO2-EOR. When the oil price is high, CO2-EOR revenue can fully offset the cost of CCUS and create additional economic profits for the stakeholders of CCUS, that is, it can achieve CO2 emission reductions at a negative cost. The CCUS demand for CO2 emission reductions in the petrochemical and chemical industries will be about 50 million tonnes in 2030, and will gradually decrease to zero by 2040.
CCUS potential of China based on source-sink matching

In the category of CO₂ geological utilization and storage technologies, the CO₂-EWR technology can achieve large-scale and deep CO₂ emission reductions, with a theoretical storage potential of 2.417 trillion tonnes. Under current technical conditions, both CO₂-EOR and CO₂-EWR can be demonstrated on a large scale and can achieve large-scale CO₂ emission reductions under specific economic incentives. Therefore, this research provides source-sink matching of CO₂-EOR and CO₂-EWR with major industries in China (Table 2).

China has enormous potential for CO₂-EOR. From the perspective of basin scale, Bohai Bay Basin and Songliao Basin have great potential for CO₂-EOR. They are regarded as the priority areas for the implementation of CCUS projects. Combined with the geological characteristics of China’s major basins and the distribution of CO₂ emission sources, the key areas for CO₂-EOR in China are the Songliao Basin in northeast China, the Bohai Bay Basin in north China, the Ordos Basin in central China, and the Junggar Basin and Tarim Basin in northwest China.

The sedimentary basins suitable for CO₂-EWR are widely distributed in China with great storage potential. The Junggar Basin, Tarim Basin, Qaidam Basin, Songliao Basin and Ordos Basin are the most suitable regions for CO₂-EWR. In 2010, the Shenhua Group carried out a CO₂ capture and storage (CCS) demonstration project in Ordos Basin, the first and largest full-chain CCS saline reservoir storage project in Asia. The deep formations in Songliao Basin have good reservoir and caprock properties, which imply potential sites for large-scale CO₂ storage in China.

The sedimentary basins in the east and north, such as Bohai Bay Basin, Ordos Basin and Songliao Basin, match well with the distribution of carbon sources. The geological conditions in northwest China are relatively good, and the Tarim and Junggar basins have great geological storage potential, however, the distribution of CO₂ emission sources is relatively few. In the southern and coastal areas where CO₂ emission sources are concentrated, the sedimentary basins that can be sequestered are small in space and scattered in distribution, with relatively poor geological conditions. The potential of onshore storage is very limited in the southern and coastal areas in China, and offshore geological storage is an important alternative.

CCUS source-sink matching mainly considers the geographical location relationship and environmental suitability of emission sources and storage sites. 250 km is the critical distance of the pipeline that does not require a CO₂ relay compressor station, and the pipeline cost is relatively low. Therefore, it is often used as the distance limit in the analysis of source-sink matching in China, and more than 250 km is generally not considered. The Chinese government attaches great importance to the environmental impacts and risks of CCUS. The Ministry of Environmental Protection released the Technical Guideline on Environmental Risk Assessment for carbon dioxide Capture, Utilization and Storage (On Trial) on June 20, 2016. Considering the regulatory requirements of the Chinese government for the environmental impacts and risks of CCUS projects, the environmental impacts and risks of CO₂ geological storage on water resources (i.e. groundwater and surface water), surface vegetation and human health are mainly considered.

### Chemical utilization & bio-utilization

| Year | 2025 | 2030 | 2035 | 2040 | 2050 | 2060 |
|------|------|------|------|------|------|------|
| Total | 50~120 | 140~280 | 270~660 | 620~1170 | 960~1990 | 1220~2920 |
| Chemical utilization & bio-utilization | 40~90 | 90~140 | 140~260 | 290~370 | 420~560 | 620~870 |
| Geological utilization and storage | 10~30 | 50~140 | 130~400 | 330~800 | 540~1430 | 600~2050 |

Note: The upper limit of CO₂ chemical utilization potential is calculated based on the market share of chemical products. In contrast, the upper limit of geological utilization potential and storage potential is calculated based on the matching result of internal source and sink of 250 km.

### Thermal power

The Junggar Basin, Turpan-Hami Basin, Ordos Basin, Songliao Basin and Bohai Bay Basin are considered as key areas for the deployment of CCUS technologies including CO₂-EOR in the thermal power industry, which are suitable for the early integration demonstration projects to promote the large-scale and commercial development of CCUS technologies.

In 2020, China’s coal-fired power plants in service will be distributed in 798 grids (one grid with a width of 50 km), covering central and eastern China, most of southern China, and parts of northeast and northwest China (Figure 5). There are 51 grids with annual CO₂ emissions of more than 20 million tonnes, mainly distributed in central China and the eastern coastal areas. The suitability of storage sites is particularly medium or low. In particular, there are almost no sites suitable for onshore storage along the eastern coast. There are 99 grids with annual CO₂ emissions ranging from 10 million to 20
million tonnes, which have medium and high suitability for geological storage in Turpan-Hami Basin, Ordos Basin, Junggar Basin, Songliao Basin and Qaidam Basin. However, southern inland provinces, such as Guizhou, Jiangxi, Anhui and other regions with significant CO2 emissions of local thermal power do not have matching storage sites. Hunan and Hubei provinces only have scattered medium and low suitability sites in Dongting and Jianghan Basins. Therefore, source-sink matching is not good within the transportation range of 50 km from the perspective of regional cluster development.

Iron and steel

Iron and steel enterprises are mainly located in provinces with rich iron ore and coal resources, such as Hebei, Liaoning, Shanxi, Inner Mongolia, etc., and the coastal areas with port resources. These regions have developed economies and enormous demand for iron and steel.

In 2020, China’s iron and steel enterprises were distributed in 253 grids. There are 26 grids with annual CO2 emissions more than 20 million tonnes, mainly distributed in Hebei, Liaoning and Shanxi provinces (Figure 6). 28 grids with annual CO2 emissions ranging from 10 million to 20 million tonnes, mainly distributed in Hebei, Shanxi, Liaoning, Shandong provinces, etc. In addition, there are 1 grid or 2 grids in Fujian, Hunan, Hubei, Guangdong, Jiangxi, Jiangsu, Xinjiang and other provinces. There are scattered medium and low suitability sites in Bohai Bay Basin, Shandong province, among these high CO2 emission areas. Shanxi iron and steel plants should increase the transportation distance in the Ordos, Linfen and other basins to find suitable geological storage sites. Under the condition of 250 km matching distance, more than 79% of steel plants can find suitable geological utilization and storage sites.

Steel plant can carry out CO2-EOR and CO2-EWR joint projects or single CO2-EOR projects, and the levelized cost is low, and even some projects can be profitable. Due to the minimal CO2 storage capacity of oil fields and the competition with CCUS in chemical, thermal power, cement and other industries, it is difficult for the steel industry to obtain enough oil fields to carry out CO2-EOR to achieve deep CO2 reduction. Therefore, the CO2-EWR project must be carried out.

Figure 5. The distribution of CO2 emissions of thermal power enterprises in 2020 and the suitability of geological storage in China. Note: The 50 km grid emission data of China thermal power enterprises in 2020 came from China High Spatial Resolution Emission Grid Data (CHRED). Data on storage suitability came from Cai et al., 2017.
The higher the net CO2 capture rate of the steel plant, the lower the levelized cost of large-scale CCUS projects. Under the same net CO2 capture rate, the larger the matching distance, the more matched CCUS projects, and the more significant the cumulative CO2 emission reductions. Under the same CO2 capture rate and matching distance scenarios, the levelized cost of CO2-EWR projects is much higher than that of CO2-EOR projects. There are many steel plants in Bohai Bay Basin, Junggar Basin, Jianghan Basin, Ordos Basin and nearby regions, large CO2 emissions, high suitability of storage sites, and good source-sink matching. In contrast, the higher cost of steel plants in southern, coastal and other regions is due to longer transportation distances and the lower estimated CO2 emissions. The main reason for the project’s failure is that the steel plants are far from the onshore basins.

**CCUS cost assessment in China**

The overall scale of CCUS demonstration projects in China is small, and the cost is high [33]. The cost of CCUS mainly includes economic costs and environmental costs. Economic costs include fixed and operation costs, while environmental costs include environmental risk and energy consumption emission.

The primary component of economic costs is operation costs, which is the input costs required by each link of CCUS technology in the whole process of actual operation. The operation costs mainly include four segments: capture, transportation, storage and utilization. It is estimated that the capture costs will be 90~390 Chinese Yuan/tonne in 2030 and 20~130 Chinese Yuan/tonne in 2060. Pipeline transportation is the main transportation mode for future large-scale demonstration projects. It is estimated that the cost of pipeline transportation in 2030 and 2060 will be 0.7 Chinese Yuan and 0.4 Chinese Yuan/(tonne-km), respectively. The storage cost in 2030 is 40~50 Chinese Yuan/tonne, and in 2060, it is 20~25 Chinese Yuan/tonne (Table 3, Figure 7).

The extra cost caused by installing a CO2 capture device is 0.26~0.4 Chinese Yuan/kWh for thermal power. The cost per kilowatt-hour of electricity for power plants with large installed capacity, the increased cost of power generation after the
installation of capture devices, and the cost of CO₂ net emission reduction and capture will be lower. In terms of cooling appliances, compared with air-cooled power plants, the net CO₂ emission reduction costs and capture costs of wet-cooled power plants are lower. According to the cooling device, wet-cooled power plants have lower net CO₂ emission reduction costs and capture costs compared with air-cooled power plants, but higher water consumption. The total water consumption of the cooling system increases approximately 49.6% after installing a capture device in power plants, which causes more serious water resource pressure to local areas, especially areas with water shortages. The capture and compression costs are the main sources of CCUS operating costs in the petrochemical

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

Note: Costs include fixed and operating costs (in constant 2021 prices). Data source: Wang Feng et al., 2016; Liu Jiajia et al., 2018; The Ministry of Science and Technology, 2019; Fan Jing-Li et al., 2019; Cai Bofeng et al., 2020; Wei Ning et al., 2020; Wang Tao et al., 2020.

Figure 7. CCUS economic costs in China from 2025 to 2060. The color of the bars represents different periods.
and chemical industries. Higher CO₂ production concentration usually means CO₂ capturing rate is high and compression costs will reduce, so increasing CO₂ production concentration is an effective way to reduce the total cost of CCUS operation.

After adopting CCUS processes, the coal gasification costs increase 10% ~ 38%. And when the carbon tax is higher than $15/tonne of CO₂, the production cost of CCUS is more advantageous than that of traditional coal gasification processes. In the CCUS project of Yanchang Petroleum Group, CO₂ is derived from the pre-combustion process of coal-to-gas (the production of syngas from coal-to-gas). As a result, compared to other CO₂ capture and transport projects, the capture and operation costs of the Yanchang CCUS project decreased by approximately 26.4%, only $26.5/tonne, with capture costs of $17.52/tonne and transport costs of $9.03/tonne.

Another component of the economic cost is the fixed costs, which is the upfront investment of CCUS technology, such as equipment installation, land footprint investment, etc. It costs about $27 million for a steel plant to install a CO₂ capture and storage facility with an annual capacity of 100,000 tonnes. Starting a CCUS project at Baosteel's Zhanjiang plant with an annual capture capacity of 500,000 tonnes (stored in the Beibu Gulf Basin, within 100 km of the plant) will require an investment of $52 million. The economic assessment of Baosteel's Zhanjiang plant shows that combining with fixed and operating costs, the total cost of emission reduction is $65 per tonne of CO₂, which is similar to the costs in Japan ($54 per tonne of CO₂) and Australia ($60 ~ $193 per tonne of CO₂).

The environmental costs are mainly due to the environmental impacts and risks of CCUS. First, it is the environmental risk of CCUS technology. CO₂ may leak during the process of capture, transportation, utilization and storage, which will have a certain impact on the nearby ecological environment and personal safety. Second, environmental pollution is caused by the additional energy consumption of CCUS technology. Most CCUS technologies have the characteristics of additional energy consumption, and the increase in energy consumption will inevitably bring the emission pollutants. Considering the storage scale, environmental risk and supervision, it is generally required that the safety period of CO₂ geological storage should be no less than 200 years. The energy consumption is mainly concentrated in the capture stage, wherein the impact of energy consumption on the cost and environment is very significant. For example, alkanolamine absorbent is the most widely used absorbent to capture CO₂ from coal-fired flue gas. However, the chemical absorption technology based on alkanolamine absorbent still has obvious limitations in large-scale commercial applications. One of the main reasons is that the energy consumption of operation is too high, reaching 4.0 ~ 6.0 MJ/kg CO₂.

Conclusions and suggestion

Conclusions

CCUS is one of the indispensable key technologies for China to achieve the goal of carbon neutrality. China attaches great importance to the development of CCUS technology and steadily promotes its research, development and implementation plan. The CCUS in China is on the way to the commercialization with significant emission reduction contribution after 2035.

In terms of the emission reductions required to achieve carbon neutrality and based on current technology projections, the CO₂ emission reductions to be achieved by CCUS are 0.6 ~ 1.4 billion tonnes and 1 ~ 1.8 billion tonnes in 2050 and 2060, respectively. Among them, BECCS and DACCS need to reduce CO₂ emissions by 0.3 ~ 0.6 billion tonnes and 0.2 ~ 0.3 billion tonnes in 2060, respectively. From the perspective of source-sink matching in China, the emission reduction potential provided by CCUS can basically meet the demand of carbon neutrality target (0.6 ~ 2.1 billion tonnes CO₂).

At present, China's CCUS technology is at the industrial demonstration stage, but the scale of the existing demonstration projects is small. The cost of CCUS is an important factor discouraging its large-scale implementation. With the development of technology, the cost of CCUS in China has a great potential to be reduced in the future. It is expected that by 2030, the cost of the whole CCUS process (according to 250 kilometers transportation) in China will be 310 ~ 770 Chinese Yuan per tonne of CO₂, and by 2060, it will gradually drop to 140 ~ 410 Chinese Yuan per tonne of CO₂.

Suggestion

To promote the development of CCUS technologies in China and better support the realization of peak CO₂ emissions and carbon neutrality, the following suggestion can be made:

1. Clarify the development routes of CCUS for the carbon neutrality target. Taking full
account of the industrial structure and emission pathway of key industries under the carbon neutrality target, a comprehensive and systematic assessment about the emission reduction demands and potential of CCUS in China from 2021 to 2060 needs to be made.

2. Improve the support and standard system for CCUS policy. It should promote the commercialization of CCUS, including but not limited to include CCUS in the catalog of industrial and technological development, improve and optimize the framework of laws and regulations, and formulate a scientific and reasonable standard system for construction, operation, supervision and termination.

3. Plan and layout of CCUS infrastructure construction. Increase the investment and construction scale of CCUS infrastructure, improve the management level of technical facilities, establish the cooperation and sharing mechanism of related infrastructure, and promote the coupling and integration of CCUS with different CO2 emission fields and industries.

4. Carry out large-scale CCUS demonstration and industrial cluster construction in an orderly manner. It should improve the compatibility, integration, and optimization of full-chain technology units, accelerate the breakthrough of related bottlenecks of large-scale full-chain CCUS demonstration, and promote the construction of CCUS industrial clusters.

Given the uncertainty of CCUS emission reduction demand and potential assessment in the academic community, it is urgent to carry out in-depth analyses under more clear boundary conditions such as technology, capital, and policy in the future to obtain a more reasonable potential assessment and development path.

Acknowledgements

The authors appreciate the contribution from the participants during the preparation of “China Status of CO2 Capture, Utilization and Storage (CCUS) 2021”.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Appendix

The latest status [2003-2021] of CCUS projects in China.

Funding

This research was partially supported by Chinese Academy for Environmental Planning (Grant No. CAEP2021A004), and Shanxi Provincial Key Research and Development Project (Grant No. 202102090301009).

ORCID

Qi Li  http://orcid.org/0000-0003-0679-4385

Data availability statement

The data may be available on request from the corresponding author.

References

1. Xu S, Dai S. CCUS as a second-best choice for China’s carbon neutrality: an institutional analysis. Climate Policy. 2021;21(7):927–938. doi:10.1080/14693062.2021.1947766.

2. Jiang K, Ashworth P, Zhang S, et al. China’s carbon capture, utilization and storage (CCUS) policy: a critical review. Renewable Sustainable Energy Rev. 2020;119:109601. doi:10.1016/j.rser.2019.109601.

3. Jiao N, Liu J, Shi T, et al. Implement negative ocean carbon emissions and perform the carbon neutral strategy. Scientia Sinica Terrae. 2021;51(4):632–643. doi:10.1360/SSTe-2020-0358.

4. Cao C, Liu H, Hou Z, et al. A review of CO2 storage in view of safety and cost-effectiveness. Energies. 2020;13(3):600. doi:10.3390/en13030600.

5. Vaughan N, Lenton T. A review of climate geoengineering proposals. Clim Change. 2011;109(3–4):745–790. doi:10.1007/s10584-011-0027-7.

6. Wei Y-M, Kang J-N, Liu L-C, et al. A proposed global layout of carbon capture and storage in line with a 2°C climate target. Nat Clim Chang. 2021;11(2):112–118. doi:10.1038/s41558-020-00960-0.

7. Zhang X, Fan J-L, Wei Y-M. Technology roadmap study on carbon capture, utilization and storage in China. Energy Policy. 2013;59:536–550. doi:10.1016/j.enpol.2013.04.005.

8. Li Q, Chen ZA, Zhang JT, et al. Positioning and revision of CCUS technology development in China. Int J Greenhouse Gas Control. 2016;46:282–293. doi:10.1016/j.ijggc.2015.02.024.

9. Liu H, Were P, Li Q, et al. Worldwide status of CCUS technologies and their development and challenges in China. Geofluids. 2017;2017:25. doi:10.1155/2017/6126505.

10. Cai B, Li Q, Liu G, et al. Environmental concern-based site screening of carbon dioxide geological storage in China. Sci Rep. 2017;7(1):7598. doi:10.1038/s41598-017-07881-7.

11. Fan J-L, Xu M, Li F, et al. Carbon capture and storage (CCS) retrofit potential of coal-fired power plants in China: the technology lock-in and cost optimization perspective. Appl Energy. 2018;229:326–334. doi:10.1016/j.apenergy.2018.07.117.
12. Jiang K, Ashworth P. The development of carbon capture utilization and storage (CCUS) research in China: a bibliometric perspective. Renewable Sustainable Energy Rev. 2021;138:110521. doi:10.1016/j.rser.2020.110521.
13. Wang P-T, Wei Y-M, Yang B, et al. Carbon capture and storage in China’s power sector: Optimal planning under the 2°C constraint. Appl Energy. 2020;263:114694. doi:10.1016/j.apenergy.2020.114694.
14. Huisingh D, Zhang Z, Moore JC, et al. Recent advances in carbon emissions reduction: Policies, technologies, monitoring, assessment and modeling. J Cleaner Prod. 2015;103:1–12. doi:10.1016/j.jclepro.2015.04.098.
15. Zhang Z, Huisingh D. Carbon dioxide storage schemes: Technology, assessment and deployment. J Cleaner Prod. 2017;142:1055–1064. doi:10.1016/j.jclepro.2016.06.199.
16. Bradshaw J, Allinson G, Bradshaw BE, et al. Australia’s CO2 geological storage potential and matching of emission sources to potential sinks. Energy. 2004;29(9–10):1623–1631. doi:10.1016/j.energy.2004.03.064.
17. Cook PJ. Demonstration and deployment of carbon dioxide capture and storage in Australia. Energy Proc. 2009;1(1):3859–3866. doi:10.1016/j.energyproc.2009.02.188.
18. Flett MA, Beacher GJ, Brantjes J, et al. Gorgon project: Subsurface evaluation of carbon dioxide disposal under Barrow Island. SPE Asia Pacific Oil and Gas Conference and Exhibition. 2008. SPE-116372-MS. doi:10.2118/116372-MS.
19. Global CCS Institute. Global status of CCS report 2018. Melbourne, Australia: GCCSI; 2018.
20. Global CCS Institute. Global status of CCS report 2019. Melbourne, Australia: GCCSI; 2019.
21. Global CCS Institute. CO2RE storage data. Melbourne, Australia: GCCSI; 2019. 9 October 2019. [Available from: https://CO2re.co/StorageData.
22. Global CCS Institute. Global status of CCS report 2020. Melbourne, Australia: GCCSI; 2020.
23. Kim AR, Cho GC, Lee JY, et al. editors. Potential site characterization and geotechnical engineering aspects on CO2 sequestration in Korea. In: The 2016 World Congress on Advances in Civil, Environmental, and Materials Research (ACEM16). Jeju Island, Korea; 2016.
24. Kim A-R, Cho G-C, Kwon T-H. Site characterization and geotechnical aspects on geological storage of CO2 in Korea. GeoSci J. 2014;18(2):167–179. doi:10.1007/s12303-013-0065-4.
25. Takahashi T, Ohsumi T, Nakayama K, et al. Estimation of CO2 aquifer storage potential in Japan. Energy Proc. 2009;1(1):2631–2638. doi:10.1016/j.energyproc.2009.02.030.
26. Wei N, Li X, Wang Y, et al. A preliminary Sub-basin scale evaluation framework of site suitability for onshore aquifer-based CO2 storage in China. Int J Greenhouse Gas Control. 2013;12:231–246. doi:10.1016/j.ijggc.2012.10.012.
27. Li X, Liu YF, Bai B, et al. Ranking and screening of CO2 saline aquifer storage zones in China. Chinese J Rock Mech Engin. 2006;25(5):963–968.
28. Li X, Wei N, Liu Y, et al. CO2 point emission and geological storage capacity in China. Energy Proc. 2009;1(1):2793–2800. doi:10.1016/j.energyproc.2009.02.051.
29. Guo J, Wen D, Zhang S. Carbon dioxide geological storage suitability evaluation and demonstration project in China. Beijing: Geology Press; 2014.
30. Vishal V, Verma Y, Chandra D, et al. A systematic capacity assessment and classification of geologic CO2 storage systems in India. Int J Greenhouse Gas Control. 2021;111:103458. doi:10.1016/j.ijggc.2021.103458.
31. Vishal V, Chandra D, Singh U, et al. Understanding initial opportunities and key challenges for CCUS deployment in India at scale. Resour Conserv Recycl. 2021;175:105829. doi:10.1016/j.resconrec.2021.105829.
32. BP. Statistical review of world energy. 2021. [accessed on 18 August 2021]. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.
33. Cai B, Li Q, Lin Q, et al. China status of CO2 capture, utilization and storage (CCUS) 2019. Beijing: Center for Climate Change and Environmental Policy, Chinese Academy of Environmental Planning; 2020.
34. Cai B, Li Q, Zhang X. China status of CO2 capture, utilization and storage (CCUS) 2021——China CCUS pathway research. Beijing: Center for Climate Change and Environmental Policy, Chinese Academy of Environmental Planning, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, The Administrative Centre for China’s Agenda 21; 2021.
35. Global CCS Institute. Global status of CCS report 2021. Melbourne, Australia: GCCSI; 2021.
36. ACCA21, MOST. Technology roadmap study of carbon capture, utilization and storage technologies in China. Beijing: The Administrative Centre for China’s Agenda 21 (ACCA21); 2019.
37. Huang J. National assessment report on development of carbon capture utilization and storage technology in China. Beijing: Science Press; 2022.
38. ADB. Roadmap for carbon capture and storage demonstration and deployment in the People’s Republic of China. Metro Manila, Philippines: ADB; 2015. p. 68.
39. BCG. Climate paths for China. Boston: Boston Consulting Group (BCG); 2020.
40. DNV. Energy transition outlook 2021 - A global and regional forecast to 2050. Norway: DNV; 2021.
41. Energy Transitions Commission, Rocky Mountain Institute. China 2050: a fully developed rich zero-carbon economy. Beijing: Energy Transitions Commission, Rocky Mountain Institute; 2019.
42. Energy Foundation. Synthesis report 2020 on China’s carbon neutrality. San Francisco: Energy Foundation; 2020.
43. GEIDCO, Report on China’s carbon neutrality by 2060. Beijing: Global Energy Interconnection Development and Cooperation Organization (GEIDCO); 2021.
44. GEIDCO, Report on China’s carbon peak by 2030. China’s carbon peak and carbon neutralization achievement release and workshop (2021-03).
Beijing: Global Energy Interconnection Development and Cooperation Organization (GEIDCO); 2021.

45. Goldman Sachs. Carbonomics-China net zero: the clean tech revolution. New York: Goldman Sachs; 2020.

46. He J. Low carbon transformation of energy and economy aiming for the peaking of carbon emission and carbon neutrality. J Environ Econ. 2021;6(1):1–9.

47. IEA. CCUS in clean energy transitions. Paris: IEA; 2020.

48. IEA. Net zero by 2050: a roadmap for the global energy sector. Paris: IEA; 2021.

49. IEA. CCUS global progress and China’s policy suggestions. Petroleum Geol and Recovery Efficiency. 2020;27(1):20–28.

50. Tang Q, Yang J, Tian C, et al. In-situ leaching for sandstone type uranium deposit in Songliao basin and ecological conservation. Geol Survey and Res. 2016;39(2):136–139.

51. WRI. Accelerating the net-zero transition: Strategic action for China’s 14th five-year plan. Washington, DC: World Resources Institute (WRI); 2021.

52. Xu J, Yi B, Fan Y. A bottom-up optimization model for long-term CO2 emissions reduction pathway in the cement industry: a case study of China. Int J Greenhouse Gas Control. 2014; 20:27–36. doi:10.1016/j.ijggc.2013.11.004.

53. Bao W, Li H, Zhang Y. Progress in carbon dioxide sequestration by mineral carbonation. J Chem Industry and Engin (China). 2007;58(1):1–9.

54. Chen M. Effects of microalgae-biochar on sand fixation and improvement of desert soil. Henyang, Hunan Province: University of South China; 2019.

55. Fang Y, Wang D, Wang Q, et al. A review on carbonation of steel slag and its application in building materials. Mater Rep. 2020;34(3):3126–3132.

56. Zhang X, Li Y, Ma Q, et al. Development of carbon capture, utilization and storage technology in China. Strategic Study of CAE. 2021;23(6):70–80. doi:10.15302/J-SSCAE-2021.06.004.

57. Hou Z. Study of controlled-release CO2 gas-fertilizer system effected by multiple factors in greenhouse. Heilongjiang: Heilongjiang Bayi Agricultural University; 2015.

58. Jang W-J, Shim J-O, Kim H-M, et al. A review on dry reforming of methane in aspect of catalytic properties. Catal Today. 2019;324:15–26. doi:10.1016/j.cattod.2018.07.032.

59. Li W, Wang H, Jiang X, et al. A short review of recent advances in CO2 hydrogenation to hydrocarbons over heterogeneous catalysts. RSC Adv. 2018;8(14): 7651–7669. doi:10.1039/c7ra13546g.

60. Qin J, Li Y, Wu D, et al. CCUS global progress and China’s policy suggestions. Petroleum Geol and Recovery Efficiency. 2020;27(1):20–28.

61. Wang C, Bao W, Xu D, et al. Reaction characteristics of steelmaking slag carbonation in dilute alkali medium. Iron & Steel. 2016;51(6):87–93.

62. Ye R, Ding J, Gong W, et al. CO2 hydrogenation to high-value products via heterogeneous catalysis. Nat Commun. 2019;10(1):5698. doi:10.1038/s41467-019-13638-9.

63. Zhou W, Cheng K, Kang J, et al. New horizon in C1 chemistry: Breaking the selectivity limitation in transformation of syngas and hydrogenation of CO2 into hydrocarbon chemicals and fuels. Chem Soc Rev. 2019;48(12):3193–3228. doi:10.1039/c8cs00502h.

64. Xu J, Yi B, Fan Y. A bottom-up optimization model for long-term CO2 emissions reduction pathway in the cement industry: a case study of China. Int J Greenhouse Gas Control. 2016;44:199–216. doi:10.1016/j.ijggc.2015.10.028.

65. Fan J-L, Wei S, Yang L, et al. Comparison of the lcoe between coal-fired power plants with CCS and main low-carbon generation technologies: Evidence from China. Energy. 2019;176:143–155. doi:10.1016/j.energy.2019.04.003.

66. Liu J, Zhao D, Tian Q, et al. Modeling and optimization of the whole process of CO2 capture, transportation, oil displacement and storage. Oil-Gas Field Surface Engin. 2018;37(10):1–5.

67. Wang F, Zhu D, Ju F, et al. Technology and economy analysis of 660 MW coal-fired power unit with 1 Mt/a CO2 capture system. Clean Coal Technol. 2016;22(6):101–105.

68. Wang T, Liu F, Fang M, et al. Research progress in biphasic solvent for CO2 capture technology. Proceedings of the CSEE. 2021;41(4):1186–1196.

69. Wei N, Jiang D, Liu S, et al. Cost competitiveness analysis of retrofitting CCUS to coal-fired power plants. Proceedings of the CSEE. 2020;40(4):1258–1265.