DOI 10.15302/J-SSCAE-2021.06.004

Development of Carbon Capture, Utilization and Storage Technology in China

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Abstract: Carbon capture, utilization, and storage (CCUS) is indispensable for achieving carbon neutrality. This study evaluated the technical development level, demonstration progress, costs and benefits, and CO_2 reduction potential of CCUS in China to systematically review the status of CCUS and identify the future direction of development. We indicate that CCUS technology in China has developed rapidly and is at the stage of industrial demonstration overall. Although the overall development is comparable to that of international counterparts, some key technologies are yet to reach advanced international standards. In terms of industrial demonstration, China already has engineering capabilities for large-scale projects; however, there remains a gap between China and advanced countries regarding the scale of demonstration projects, technology integration, offshore storage, and industrial application. In terms of reduction potential and demand, the theoretical storage capacity and the demand for emission reduction in China are large. However, the onshore storage potentials in different regions vary considerably when source–sink matching is considered. In terms of cost and benefit, although the current cost of CCUS technology is high, it remains a cost-effective emission reduction option for achieving carbon neutrality in the future. It is necessary to develop the CCUS technology system, promote full-chain integrated demonstrations, accelerate the pipeline network layout and infrastructure construction, and improve fiscal and tax incentive policies and the legal and regulatory framework.
Keywords: carbon neutrality; carbon capture, utilization, and storage (CCUS); technology research and demonstration; potential of emission reduction; cost and benefit

1 Introduction

Carbon dioxide capture, utilization, and storage (CCUS) refers to the technical means of capturing and separating CO_2 from energy utilization, industrial processes, and other emission sources or air, and transporting it to suitable sites for utilization or storage through tankers, pipelines, and ships (Fig. 1) in order to ultimately achieve CO_2 emission reduction. CCUS is an indispensable part of China's technology portfolio for achieving carbon peaking and carbon neutrality. It can achieve near-zero emissions from fossil energy utilization and promote deep emission reduction in industries that have difficulty in reducing emissions, such as steel and cement manufacturing. It can also enhance the flexibility of the power system under carbon constraints, ensure a safe and stable power supply, and offset the emissions of CO_2 and non-CO_2 greenhouse gases that are difficult to reduce. CCUS is of great significance for achieving ultimate carbon neutrality goals.

In recent years, the Chinese government has emphasized the development of CCUS technology. Therefore, the

Received date: October 21, 2021**; Revised date:** November 13, 2021
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Funding program: CAE Advisory Project "Research on Strategies and Paths for Carbon Peaking and Carbon Neutrality in China" (2021-HYZD-16)
Chinese version: Strategic Study of CAE 2021, 23(6): 070–080
Cited item: Zhang Xian et al. Development of Carbon Capture, Utilization and Storage Technology in China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2021.06.004

maturity of CCUS technology has been rapidly improved, and a series of demonstration projects have been put into operation, showing a trend of continuous emergence of new technologies with continuous improvement in efficiency and gradual reduction in energy consumption costs. Simultaneously, the implications and extensions of the CCUS technology are further enriched and expanded. The China *Outline of the 14th Five-Year Plan (2021–2025) for Economic and Social Development and the Long-Range Objectives Through the Year 2035* clearly proposed to support CCUS as major national demonstration projects. In the future, CCUS technology will play an increasingly important role in achieving carbon neutrality, ensuring national energy security, promoting comprehensive green transformation of economic and social development, and constructing an ecological civilization in China.

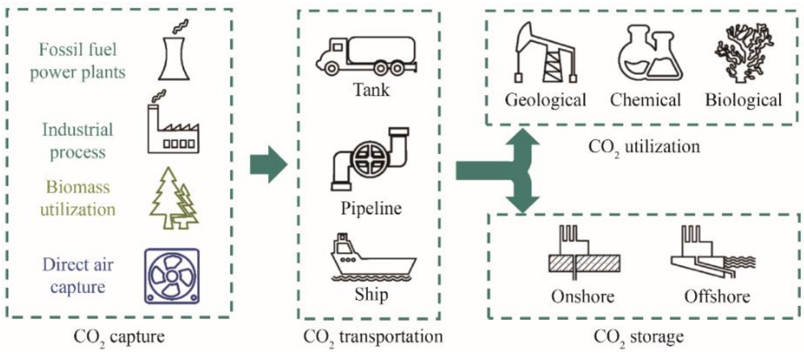

Fig. 1. Technical diagram of CCUS.

The *China Carbon Capture Utilization and Storage Technology Development Roadmap* and *China Status of CO_2 Capture, Utilization and Storage (CCUS) 2021*reviewed and summarized the current status of CCUS technology development in China and proposed policy recommendations with development pathways [1–3]. The *Third National Climate Change Assessment Report* and *China Carbon Dioxide Utilization Technology Assessment Report* describe the maturity, emission reduction potential, and development trend of CO_2 utilization technology from a technical perspective [4]. The Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) have estimated the emission reduction potential of CCUS on a global scale, pointing out that to achieve near-zero emissions in the world in 2070, the cumulative emission reduction of CCUS technology will be approximately 15% [5], and to achieve a 1.5 °C temperature rise control target in 2100, the cumulative emission reduction of global CCUS will be 5.5×10^{11}–1.017×10^{12} t [6]. Under the carbon neutral scenario, CO_2 captured in 2060 will reach approximately 1.6×10^{9} t in China [7].

In 2020 and 2021, the Global CCS Institute summarized the status and development trends of CCUS facilities worldwide [8,9]. Although some of China's demonstration projects have been included, the development of CCUS technology demonstrations in China still needs to be comprehensively reviewed. Therefore, this study conducted a systematic survey of CCUS demonstration projects that have been put into operation or are under construction in China as of July 2021. Based on the basic economic and social development conditions and strategic needs to address climate change in China, this paper summarizes the technical level of China's CCUS and the progress of demonstration projects, carries out a comparative analysis of CCUS technology development between China and foreign countries, and comprehensively and systematically evaluated the development level of CCUS technology in China. Finally, we propose policy recommendations for CCUS technology development with the goals of carbon peaking and carbon neutrality.

2 The development status of CCUS technology in China

Since the 11th Five-Year Plan, the National Natural Science Foundation of China, 973 Program, 863 Program, and National Key Research and Development (R&D) Program have supported CCUS technology R&D. Various technical links, such as CO_2 capture, transportation, utilization, and storage, have developed rapidly, and a series of achievements has been made by strengthening basic research, tackling key technologies, and demonstrating integrated projects. In particular, pre-combustion capture, transportation, chemical utilization, enhanced deep saline water recovery and storage, and integrated optimization technologies have developed rapidly in the past decade. The comparative analysis with international ones shows (Fig. 2) that China's CCUS technology is at the same level as the advanced international level, but there is a certain gap between the domestic and advanced international levels in terms of individual key technologies and the commercial integration of capture, transportation, and storage.

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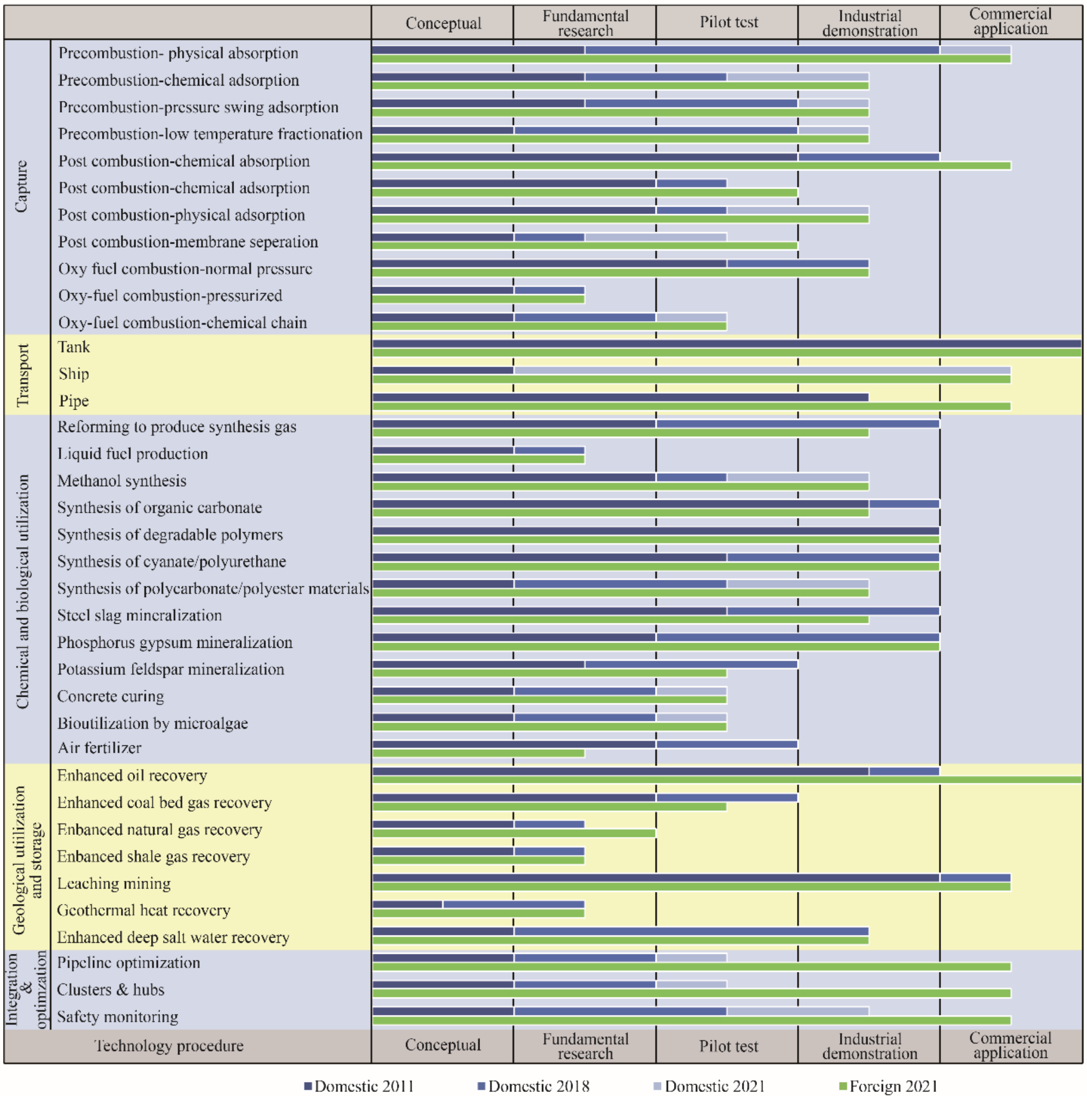

Fig. 2. Development levels of major technologies in each technical link in China and abroad [2].

Note: The conceptual stage refers to proposing concepts and application ideas. Fundamental research indicates functional verification of components or small systems in a laboratory environment. The pilot test stage refers to the completion of the test of the medium-scale full-process device. An industrial demonstration means that one to four industrial-scale full-process units are in operation or have completed tests. Commercial applications are defined as five or more industrial-scale operations that are in progress or completed.

CO_2 capture technology refers to the process of separating and enriching CO_2 from different emission sources using technologies, such as absorption, adsorption, membrane separation, low-temperature fractionation, and oxy-fuel combustion. This is the basis and premise for the development of CCUS technology. At this stage, China's first-generation capture technology has made significant progress. Most technologies have been developed from the conceptual or basic research stage to industrial demonstration level. Some technologies can be commercialized. However, large-scale system integration optimization lacks engineering experience, and second-generation capture technology is in the laboratory R&D or small-scale test stage[1]. The development of pre-combustion capture technology in China is relatively mature, and it is at the stage of industrial demonstration as a whole, keeping pace with the advanced international level. Post-combustion capture technology is at the pilot-scale or industrial

[1] The first-generation technologies refer to capture technologies that are already capable of large-scale demonstration, such as amine absorbers and atmospheric oxygen-rich combustion. Compared with the first generation, the energy consumption and cost of the second-generation technology can be reduced by more than 30% after the technology is mature, such as new membrane separation, new adsorption, pressurized oxygen-rich combustion, and chemical chain combustion.

demonstration stage, which lags behind the advanced international level. In particular, the post-combustion chemical absorption method with the greatest CO_2 capture potential is already in the commercial application stage worldwide, but is still in the industrial demonstration stage in China. Oxy-fuel combustion technology is in the pilot stage in China and abroad, and its overall development is relatively slow, especially supercharged oxy-fuel combustion technology, which is still in the basic research stage. As second-generation low-cost capture technology continues to develop and mature, its cost and energy consumption will be significantly lower than those of the first-generation capture technology in the future. To further reduce the cost of CO_2 capture, intergenerational replacement of capture technology should be accelerated.

CO_2 transportation refers to the process of transporting captured CO_2 to a utilization or storage site, and includes different transport methods such as tank trucks, ships, and pipeline transportation. Generally, tank trucks are considered for small-scale and short-distance transportation, whereas pipeline transportation is preferred for long-distance large-scale transportation or CCUS industrial clusters. In China, tanker and ship transportation technologies have been put into commercial application, keeping pace with the advanced international level. Pipeline transportation technology with the greatest transportation potential has only been demonstrated, while foreign countries are already at the level of commercial application, which shows a significant gap.

CO_2 biological and chemical utilization technology refers to the process of using different physical and chemical characteristics of CO_2 to produce products with commercial value and realize emission reduction. In this regard, the levels of technological development in China and foreign countries are synchronized at the industrial demonstration stage. In the past ten years, various biological and chemical utilization technologies have been developed, and remarkable progress has been made in some chemical utilization technologies. The technology with the highest level of development is the use of CO_2 to synthesize chemical materials such as organic carbonates, degradable polymers, cyanate esters/polyurethanes, and polycarbonate/polyester materials. It is currently in the industrial demonstration stage in China and other countries.

CO_2 geological storage and utilization technology refers to the technology of geologically utilizing or injecting captured CO_2 into deep geological reservoirs through engineering and technical means to achieve long-term isolation from the atmosphere. Storage technology includes two methods: onshore and offshore storage. The development levels of various geological storage and utilization technologies are uneven both in China and abroad. Globally, CO_2-enhanced oil recovery (CO_2-EOR) and leaching mining technologies have developed rapidly and begun commercial applications. Among the other technologies, except for the enhanced deep saline water recovery and storage technology, which is being demonstrated in industry, all other technologies are in the pilot test and lower stages. In China, geological storage and utilization technology has developed in the past ten years, especially the enhanced deep saline water recovery technology which has developed from the conceptual stage to the industrial demonstration level, but still lags behind the world level as a whole. Although the enhanced coal-bed methane recovery technology is slightly at the leading level, CO_2-EOR technology with better economic benefits is still in the industrial demonstration stage in China, whereas it has been commercialized in foreign countries, and the gap is obvious.

In CCUS integrated optimization technology, China has made great progress in the past ten years. However, foreign CCUS integration optimization technology is generally in the commercial application stage, and the development of related technologies in China still lags behind, especially the pipeline network optimization and technologies for clusters and hubs, which are still only in the pilot stage. The limited development level of the key technologies in each CCUS link makes it difficult to support research on CCUS integration and optimization technologies, which limits the development of large-scale CCUS demonstration projects in China, and the lack of large-scale full-chain integration demonstration projects further restricts the development of integrated and optimization technologies.

3 Progress of CCUS demonstration projects in China

Since the first demonstration project was put into operation in Shanxi Province in 2004, there have been 49 projects in operation or under construction in China by July 2021, mainly located in East and North China, according to the survey results of the nationwide CCUS demonstration projects by the China Ministry of Science and Technology. In all, 38 projects completed construction, with a CO_2 capture capacity of 2.96 million tons per year and an injection capacity of 1.21 million tons per year. To date, more than 2 million tons of CO_2 have been injected or sequestrated in China.

In terms of technological procedures, demonstration projects for capture, chemical and biological utilization, and geological utilization and storage accounted for 39% (15 projects), 24% (9 projects), and 37% (14 projects),

DOI 10.15302/J-SSCAE-2021.06.004

respectively. Among the 15 projects for CO_2 capture, 14 projects capture CO_2 from medium- and low-concentration emission sources, and only one captures CO_2 from high-concentration emission sources.

In terms of the industries involved, CCUS is adopted in almost all major industries, including power, coal chemical, petrochemical, cement, steel, and others. Of the 15 capture projects, 11 were from the power industry, three from the cement industry, and one from the coal chemical industry (Fig. 3). Geo-utilization and sequestration projects are often linked to the chemical industry, with five of the 13 projects capturing CO_2 from the coal chemical industry and two from petrochemicals. The CCUS demonstration project in the iron and steel industry is in its initial stage. The key technology and 10 000-ton industrial test project for mineralizing desulfurization slag using CO_2, which was put into operation in Xichang in 2020, will capture and mineralize CO_2 from the sintering flue gas of iron and steel enterprises.

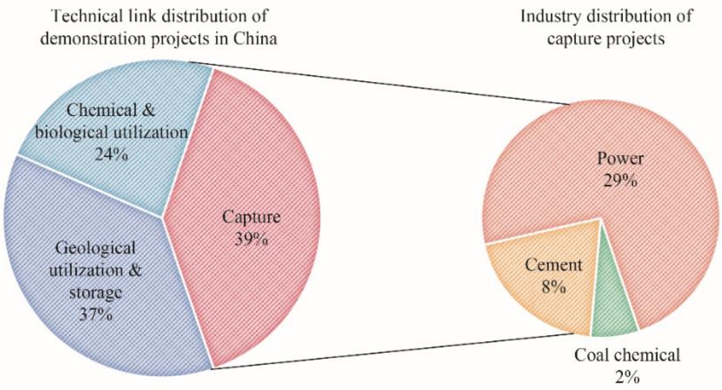

Fig. 3. Distribution of CCUS technical links and industries involved in capture projects

In terms of scale, although the projects currently in operation are generally small, the scale of the projects planned in China is gradually increasing. Among the CCUS demonstration projects that have been put into operation, 29 projects are at the scale of 100 000 tons or less, and only two of them, CO_2-EOR of Zhongyuan Petroleum Exploration Bureau, China Petrochemical Corporation, and CO_2-EOR of Jilin Oilfield Company, China National Petroleum Corporation, are at the scale of 500 000 tons or more, and there are no projects at the megaton scale or more. In July 2021, the CCUS full-process demonstration project of the Shengli Oilfield Branch of Sinopec began construction and is expected to be put into operation by the end of 2021. This will become the first project in China to capture and store more than one million tons of CO_2 annually. The 500 000-ton carbon capture and utilization project of Taizhou Power Generation Co., Ltd., and the 1-million-ton CO_2 capture and EOR project in Hami, Xinjiang, are in the preparatory construction stage. It is worth pointing out that some projects have not been continuously in operation after construction completion, but are in a state of shutdown or intermittent operation. At present, CCUS demonstration projects are costly and have low returns; thus, projects capable of maintaining operations mainly belong to large state-owned enterprises or a few large enterprises with relevant industrial chains.

Currently, CCUS projects are developing rapidly worldwide. As of September 2021, the number of commercial CCUS facilities under planning, construction, and operation has reached 135, which is more than double that in 2020. The total capture capacity can reach approximately 1.5×10^8 t CO_2 every year after completion [9]. Single facility scales show an increasing trend, and several projects exceed one million tons. There is also an obvious trend in industrial cluster development that promotes a reduction in project costs. Compared with the advanced international level, there is a large gap in the overall scale, degree of integration, offshore storage, and industrial application of large-scale demonstration projects in China.

First, only a few large-scale commercial demonstration projects exist in China. There are 31 large-scale CCUS projects under construction or in operation worldwide, located in the United States (13), China (5), Canada (4), Europe (4), the Middle East (3), Australia (1), and Brazil (1) [9]. In 2021, several 10-megaton CCUS clusters were built, the largest of which is the Houston Channel CCUS Innovation Zone, which aims to sequester 1×10^8 t of CO_2 per year in the offshore strata of the Gulf of Mexico by utilizing CO_2 from multiple industrial carbon sources [9]. There are 24 CCUS industrial clusters in the late developing stage or in operation, locating in the United States (6), the United Kingdom (6), the Netherlands (4), Greece (1), Norway (1), Denmark (1), Canada (1), China (1), the Middle East (1), Australia (1), and Brazil (1) [9]. In CCUS clusters, the scale of compression, dehydration, transportation, and sequestration is enhanced, and thus, the unit cost of CO_2 reduction is dramatically lowered, which demonstrates the scale economy effect. The planned construction scale of the CCUS hub in Xinjiang is 2×10^5–3×10^6

t CO_2/a [8].

Second, full-process integrated projects over a one-million-ton scale have not yet been conducted. At present, most domestic projects are aimed at CCUS single-technology procedures, which significantly lag behind developed countries with rich experience in multiple full-process demonstration projects. As of October 2021, there are five commercial full-process integrated facilities over a 1-million-ton scale under construction and in operation in the United States and three in Canada [9]. In addition, CCUS clusters in the United States, the United Kingdom, the Netherlands, Norway, and the United Arab Emirates not only attach importance to the integration of technology links of the whole CCUS chain, but also coordinatively consider the synergistic development of cross-industries by involving multiple industries such as electricity generation, petroleum production, and steel manufacturing.

Third, CO_2 offshore sequestration demonstration lags behind. As of July 2021, no submarine storage demonstration projects are in operation or under construction in China. Up to 2021, offshore storage demonstration projects at different scales have been carried out in Norway, the United States, Brazil, Japan, and other countries, and the total cumulative storage has exceeded 2.5×10^7 t CO_2 [9]. The Longship project, recently approved by the Norwegian government, transports CO_2 captured from trash incinerators and cement plants to an underground storage site in the offshore North Sea for permanent storage, which would inject and sequester 1.5×10^6 t CO_2 per year in the initial stage.

Fourth, the technological foundation of CCUS demonstration in the cement and steel industries is weak. The distribution of existing CCUS demonstration projects in China is unbalanced, most of which are applied to the power and chemical industries. There are no large-scale full-process demonstration projects in the cement and steel industries for long-term stable operation. However, several countries have started large-scale demonstration projects in industries that have difficulty in reducing emissions, such as steel and cement manufacturing. For example, the Al Reyadah CCUS project in the United Arab Emirates, which is a large hub of CCUS in the country, captures CO_2 from the flue gas of steel mills and uses it to enhance oil extraction at a capacity of 8×10^5 t CO_2 per year.

4 Costs and benefits of CCUS technology in China

4.1 Costs

Survey results on the net emission reduction cost of CCUS demonstration projects in operation show that the promotion of CCUS technology in China still faces the challenges of high energy consumption and costs. The energy consumption and cost of CCUS technology differ significantly because of the different emission source types and CO_2 concentrations. Generally, the higher the CO_2 concentration, the lower the energy consumption and cost of capture and the lower the cost of CO_2 avoided. Among the operational CCUS demonstration projects (Fig. 4), capture energy consumption in the cement industry is the highest at 6.3 GJ/t CO_2 owing to technological maturity. The capture energy consumption is 1.6–3.2 GJ/t CO_2 in the power sector. The energy consumption of the coal chemical industry is 0.7–2.5GJ/t CO_2, and the wide range is owing to the differences in capture sources and capture technologies. In the petrochemical industry, the lowest energy consumption was as low as 0.65 GJ/t CO_2.

It is expensive to capture CO_2 in industries such as power and cement production, which can cost 300–600 RMB/t CO_2 and 180–730 RMB/t CO_2, respectively. The net cost reduction of integrated EOR projects in the coal chemical and petrochemical industries can be as low as 120 RMB/t CO_2 (Fig. 5). The costs of CCUS demonstration projects are usually high in industries with high capture energy consumption, the reduction of which is vital for reducing the cost of CCUS demonstration projects in China.

In terms of CCUS whole-process technology, the cost of CO_2 avoided is currently approximately 20–194 USD/t in major global carbon emission sources (coal power plants, gas power plants, coal chemical plants, natural gas processing plants, steel plants, and cement plants) at the present stage [10], and the cost in China is generally at a low level compared to that worldwide (Fig. 6). The cost of CO_2 avoided is 60 USD/t CO_2 and 81 USD/t CO_2 in thermal power plants and integrated gasification combined cycle (IGCC) plants, respectively, which is the lowest in the world compared to the global average costs of 60–121 USD/t CO_2 and 81–148 USD/t CO_2. The costs of CO_2 avoided in steel and fertilizer production in China are 74 and 28 USD/t CO_2, respectively, which are close to the lowest global level compared with the world average cost of 67–119 USD/t CO_2 and 23–33 USD/t CO_2. The costs of CO_2 avoided in natural gas cycle combined power generation (NGCC) and cement industry in China are 99 USD/t CO_2 and 129 USD/t CO_2, respectively, which are at lower levels of the world average costs of 80–160 USD/t CO_2 and 104–194 USD/t CO_2, respectively. The cost of CO_2 avoided in China's natural gas processing industry is 24 USD/t CO_2, which is in the middle position compared with the world average of 20–27 USD/t CO_2.

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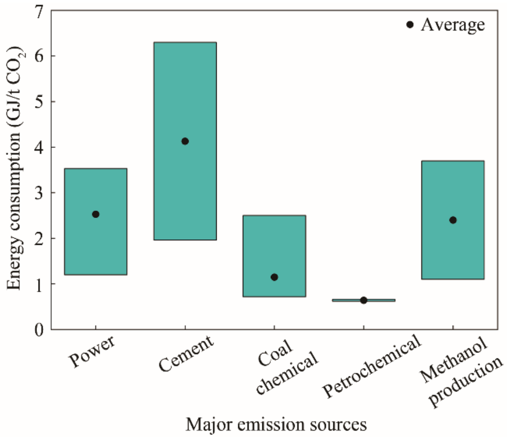

Fig. 4. Energy consumption of demonstration projects of major emission sources in China

Note: Data are from statistics on energy consumption and costs of 38 projects that have been put into operation in China.

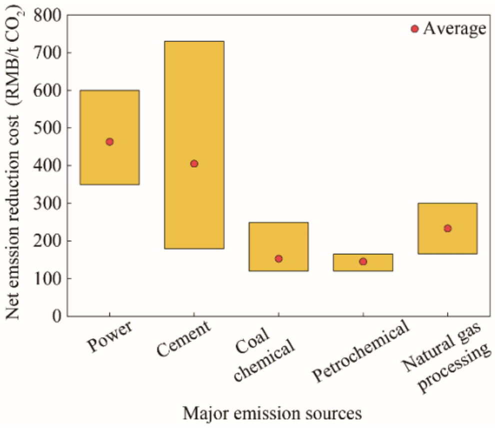

Fig. 5. Net emission reduction costs of demonstration projects of major emission sources in China.

Note: Data are from statistics on energy consumption and costs of 38 projects that have been put into operation in China.

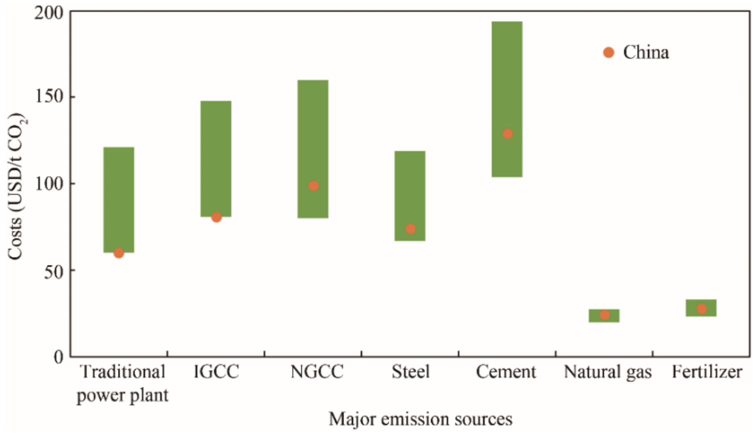

Fig. 6. Costs of CO_2 avoided in major emission sources worldwide [10].

4.2 Benefits

According to the IPCC, in most models, global warming cannot be controlled within 2 °C by the end of the 21st century if the CCUS technology is not adopted. Even if the global warming control target can be achieved without CCUS, the cost of mitigation is estimated to increase dramatically by 138%, on average [11]. For a long time, the economy of CCUS technology has not been able to compete with other low-carbon technologies in most scenarios owing to its high energy consumption, high cost, immature technology level, and other factors. However, from the perspective of overall emission reduction cost, the combination of CCUS with energy efficiency improvement, terminal energy saving, energy storage, and hydrogen energy is the most economically feasible solution for achieving carbon neutrality [12]. CCUS technology shows great potential for future economic and social benefits, mainly in the following five aspects.

First, there are early opportunities for CCUS technology to reduce CO_2 emissions at negative costs, and a reasonable carbon-pricing mechanism can facilitate the economic feasibility of CCUS technology. Under certain conditions, the considerable economic benefits of the chemical, biological, and geological utilization of CO_2 can offset the costs of capture, transportation, and storage, which could realize CCUS application at a negative cost [13]. For example, geological use of CO_2 can reduce carbon emissions and generate benefits by injecting CO_2 to displace or replace oil, gas, and water products. Under appropriate source–sink matching conditions, the cost of some CCUS projects in China is lower than the benefits brought by the EOR, which has the potential to reduce emissions with negative costs. In the case of external benefits, such as carbon trading, CCUS can also achieve economy by offsetting part of the cost through additional emission-reduction benefits [14,15]. With reasonable carbon prices, CCUS technology has the potential to generate profits [16].

Second, the application of CCUS technology can avoid large-stranded energy infrastructure costs. Upgrading infrastructures in the energy and industrial sectors with CCUS can reduce the CO_2 emissions of existing facilities on a large scale and avoid the high stranded costs caused by the early retirement of a great number of infrastructures under the carbon emission constraint. China is the world’s largest producer of coal power, steel, and cement, and the existing infrastructures of these major emission sources have been operating for only a relatively short time. Given that these infrastructures typically have service lives of more than 40 years, it is almost impossible to operate them until the end of their lives under carbon-neutral targets without mitigation measures. Retrofitting with CCUS technology not only avoids early decommissioning of facilities already in production, but also reduces the additional investment required to build other low-carbon infrastructure, significantly reducing the economic cost of achieving carbon neutrality. It is estimated that the stranded assets of coal power plants in China may be as high as 3.08–7.2 trillion RMB, equivalent to 4.1%–9.5% of China’s GDP in 2015 [17].

Third, in specific regions and conditions, the generation cost of thermal power plants with CCUS is lower than that of gas power and renewable energy. First, when coal-fired power plants are coupled with CCUS technology to achieve the same emission levels as gas-fired power plants, a low capture rate and appropriate transport distance and mode can make coal-fired power generation more economical than gas-fired power generation. According to the analysis of the total levelized cost of electricity (TLCOE) of retrofitting 36 coal-fired power plants with whole-process CCUS in China National Energy Investment Group Co., Ltd., the TLCOE of 75% coal-fired power plants was lower than the floor level of China’s benchmark feed-in price of gas power plants (77.5 USD/MW·h) in 2018, and 100% coal-fired power plants were lower than the upper limit of the benchmark feed-in price of gas power plants (110 USD/MW·h) with a net capture rate of 50% after conducting source–sink matching of the power plants and the storage site with the constraints of the lowest cost. Therefore, coal-fired power plants equipped with CCUS have more competitive advantages than gas-fired power plants in terms of cost [18]. Considering technological progress and the incentive policy effect, it is possible for CCUS to achieve a cost-competitive advantage with a higher capture rate. Second, the LCOE of China’s coal-fired power plants coupled with CCUS is 0.4–1.2 RMB/kW·h under different coal prices, which is generally equivalent to that of solar, wind, and biomass power generation [19]. When coal-fired power plants coupled with CCUS are in ideal conditions of abundant coal resources and short CO_2 transport distance, there is a competitive advantage for coal-fired power plants coupled with CCUS compared with renewable energy generation technology. A cost-economic study on the CCUS retrofit of coal-fired power plants of China Energy Investment Group Co., Ltd. showed that, compared with wind power, the electricity prices of 44% of retrofitted power plants are lower than the minimum wind power price, and the electricity prices of 56% of retrofitted power plants are lower than the maximum wind power price, with a net CO_2 capture rate of 85% [18]. Coal-fired power generation coupled with CCUS technology is currently in the demonstration stage, and the cost of CCUS technology will gradually decrease with technological progress, improved infrastructure, business model innovation, and sound policies [5]. After the continuous decline of renewable energy subsidies, the possibility that the generation costs of coal-fired power plants with CCUS will be lower than those of renewable energy generation technologies will further increase in the future.

Fourth, the coupling of bioenergy with CCUS (BECCS) and direct air capture (DAC) can effectively reduce the marginal cost of emissions reduction to achieve carbon neutralization. As important negative emission technologies, BECCS and DAC technologies can reduce the total cost of carbon neutrality in the process of deep decarbonization

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[20]. The cost of BECCS technology is 100–200 USD/t CO_2 and that of DAC technology is approximately 100–600 USD/t CO_2 [21,22]. A case study of the United Kingdom shows that deep decarbonization of the power sector using BECCS and DAC technology can reduce the total investment by 37%–48% compared with a system dominated by intermittent renewable energy and energy storage [4]. With more aggressive CO_2 emission reduction targets, the deployment of negative emission technologies can achieve a cost reduction of 35%–80% by replacing more expensive emission reduction measures in the medium and long term [23]. Therefore, the deployment of negative emission technologies led by BECCS is an important guarantee for achieving China's carbon neutrality goal [24].

Fifth, CCUS technology not only achieves carbon emission reduction, but also has good social benefits. CCUS technology has synergistic benefits in reducing climate change losses, increasing industrial output value and employment opportunities, ensuring energy security, improving comprehensive ecological environment management, and solving regional development bottlenecks [25–28]. A study by the Oil and Gas Industry Climate Initiative showed that CCUS deployment could create cumulative $4×10^6$–$1.2×10^7$ jobs by 2050 [29].

5 Emission reduction potential of CCUS technology in China

5.1 Theoretical CO_2 storage capacity and distribution

Overall, China's northeastern, northern, and northwestern regions are considered relatively ideal for the geological utilization and storage of CO_2. In China, the total theoretical capacity of geological utilization and storage on land is $1.5×10^{12}$ to $3.0×10^{12}$ tons of CO_2, and the theoretical storage capacity under Chinese territorial waters is in the order of trillions of tons [30]. Although the theoretical storage potential of CCUS technology is large, owing to the constraints of external conditions such as the cost of CCUS technology, distance to emission sources, and environmental factors, the emission reduction potential of CCUS is unsatisfactorily fulfilled. China's geological utilization and storage sites are mainly distributed in the Songliao, Bohai Bay, Junggar, and Tarim basins, and other sedimentary sites in the northeastern, northern, and northwestern regions.

5.2 Sector-wise emission reduction demand and potential of CCUS technology

Based on the results of relevant studies in China and other countries and considering the application and future emission reduction potential of CCUS technology in the power and industrial sectors, the overall emission reduction demand for CCUS under China's carbon neutral target is $2×10^7$–$4.08×10^8$ tons of CO_2 in 2030, $6×10^8$–$1.45×10^9$ tons of CO_2 in 2050, and $1×10^9$–$1.82×10^9$ tons of CO_2 in 2060 [3]. First, the future emission reduction contribution of CCUS technology to the energy and power sectors is expected to gradually increase as China's overall demand for electricity increases and the low-carbon transition process accelerates. Reportedly, China's electricity demand will grow to $1.2×10^{13}$–$1.5×10^{13}$ kW·h by 2050 [31,32], while the share of thermal power (coal-fired and gas-fired) will shrink significantly to less than 15% [7]. Thus, the power system would account for $4.32×10^8$–$1.64×10^9$ tons of CO_2 by then. According to the IEA's *Energy technology perspectives 2020: Special report on carbon capture, utilization and storage*, under the sustainable development scenario, the CCUS emission reduction capacity in China is expected to grow rapidly, with the CCUS capture capacity in the power sector growing to ~$1.9×10^8$ tons of CO_2 per year by 2030 and ~$7.7×10^8$ tons of CO_2 per year by 2050. By 2070, it is predicted to exceed $1.2×10^9$ tons of CO_2 per year [5]. Second, the contribution of CCUS technology will be more prominent in sectors in which it is difficult to reduce emissions, such as steel and cement manufacturing. According to the data analysis of medium-to-long-term forecasts, CCUS technology will continue to contribute to carbon emission reduction in the industrial sector until 2070. The emission reduction contribution of CCUS to China's industrial sector is expected to be approximately $8×10^7$–$2×10^8$ tons of CO_2 per year by 2030, reaching $2.5×10^8$–$6.5×10^8$ tons of CO_2 per year by 2050, and slowly rising to $6.7×10^8$–$6.8×10^8$ tons of CO_2 per year by 2070 [5,33–35]. Third, high-concentration sources in petrochemical and chemical industries can provide low-cost opportunities for early CCUS development and demonstrations. The emission reduction demand for CCUS in the petrochemical and chemical industries is expected to be approximately $5×10^7$ tons of CO_2 by 2030, which is predicted to remain at the same level and gradually decrease after 2040 [3]. Fourth, CO_2 removal technologies, such as BECCS, are highly important. The potential yield of typical biomass fuels in China, including agricultural residues, forestry residues, and energy crops, is expected to reach $6×10^8$ tce by 2050 [36], corresponding to a CO_2 removal potential of $3.6×10^8$–$5.9×10^8$ t [37,38].

5.3 Source-sink match for CCUS

The source-sink match for CCUS focuses on the geographic relationship and environmental suitability between the CO_2 source and storage site; that is, assessing the availability of geologically suitable and cost-effective CO_2 storage sites for each source. Source-sink matching plays an important role in the application and commercialization of CCUS technology. In the absence of a national primary pipeline and public pipeline network, 250 km is the maximum length for a CO_2 pipeline that does not require a midway compressor station (i.e., lower cost) and is therefore used as an upper limit for source-sink matching in designing CCUS projects. In terms of regional distribution, fossil resources are abundant in the central and western provinces of China, such as Xinjiang, Inner Mongolia, and Shaanxi. In these regions, CO_2 emissions involved in energy and industrial raw material production can be matched with onshore storage sites in the northeastern, northern, and northwestern regions, resulting in lower decarbonization costs through CCUS. Energy and industrial raw materials are mainly consumed in the eastern and coastal regions, especially in Fujian, Guangdong, and Guangxi provinces, where the sedimentary basins suitable for CO_2 storage are small in scale, scattered in distribution, and relatively poor in geological conditions. Coupled with the relatively limited onshore storage potential, the CO_2 sources and sinks hardly match in these regions. Therefore, offshore CO_2 storage in sediment basins adjacent to the sea is a viable option.

In terms of industrial distribution, the Junggar, Turpan-Hami, Ordos, Songliao, and Bohai Bay basins are key areas for CCUS deployment (including CO_2-EOR) in the thermal power industry. Early CCUS integration demonstration projects should be conducted in these areas to promote the large-scale commercial development of CCUS technology. However, within the 50-km transportation range, CO_2 sources in the thermal power industry are poorly matched with storage sites, and challenges remain for the future development of CCUS clusters and hubs. For the steel and cement industries, CO_2 sources currently located in the Bohai Bay, Junggar, Jianghan, and Ordos basins are large in number and scale, have suitable storage sites, and are suitable for onshore storage. In contrast, CO_2 sources in the southern and coastal regions are far from onshore basins and must be considered for offshore CO_2 storage at a later stage [3].

6 Suggestions for CCUS development in the context of carbon neutrality

6.1 Establishing overall development framework for CCUS technology under the carbon neutral target

It is necessary to conduct the early deployment of R&D projects on second-generation CCUS technologies to significantly reduce costs and energy consumption, striving for the commercialization of second-generation carbon capture technologies by 2035. We should fully understand the needs of CCUS technology under the carbon neutral goal and conduct research on key technologies for carbon capture, transportation, utilization, storage, and monitoring. Bring into full play the key role of CCUS in decarbonization of multi-energy complementary energy systems and the industrial sector, including combining CCUS with emerging energy and industrial systems, fostering new techno-economic paradigms for CCUS development, identifying the feasibility and development potential of integrating CCUS with renewable energy and energy storage systems, and exploring new directions for “renewable energy/energy storage + CCUS” integration technologies, to design a comprehensive multi-functional CCUS technology system.

6.2 Promoting integrated full-chain demonstration and commercialization of CCUS technology

It is necessary to prioritize the deployment of demonstration projects for offshore CO_2 storage and carry out CCUS demonstration projects in the industrial sector to complement the shortcomings of CCUS demonstrations. China should also carry out integrated large-scale full-chain CCUS demonstration projects, accelerate the deployment and construction of CCUS clusters and hubs, accelerate breakthroughs in the optimization of full-chain technology, and strive to build 3–5 million ton-scale full-chain CCUS demonstration projects during the 14th Five-Year Plan. Based on large-scale demonstration projects for CO_2 utilization technologies, including enhanced oil/gas recovery, solid waste mineralization, and chemical utilization, the deployment of CCUS demonstration zones should be actively supported in oil and gas, energy, chemicals, and other related industries, and gradually incorporate CCUS technologies into the technology supporting system for green transformation of energy and mining industries, as well as the catalogue of strategic emerging industries.

6.3 Accelerating pipeline network planning and infrastructure construction for CCUS hubs

It is imperative to increase investment in CCUS-related infrastructure, strengthen the construction of the CO_2 transportation pipeline network, optimize the facility management model, and establish a cooperation and sharing mechanism to drive the formation of CCUS clusters and hubs based on pipeline networks and storage sites. China

DOI 10.15302/J-SSCAE-2021.06.004

should accelerate the planning of future CCUS clusters and hubs, improve CCUS clusters and hubs that were initially formed based on the geographical characteristics of the source-sink match, and fully utilize the advantages of CCUS clusters in infrastructure sharing, systematical integration of projects, interactive use of energy resources, and connection between industrial demonstration and commercial application to reduce emission reduction costs.

6.4 Completing financial incentive policies and legal and regulatory systems

Learning from the promotion of the development of solar, wind, biomass, and other clean energy technologies, we should explore financial incentives and subsidies suitable for China’s national conditions under the carbon-neutral goal, and grant equal policy incentives to the early development of next-generation low-cost, low-energy-consumption CCUS technologies and carbon removal technologies coupled with clean energy sources. China should accelerate CCUS-related investment and financing to promote commercialization, incorporate CCUS into industry and technology development catalogs, and explore a CCUS commercialization investment and financing mechanism that links government and market. The advantage of green finance, climate bonds, low-carbon funds, and other financial tools should be utilized to support CCUS demonstration projects. Stable and continuous policy support should be provided to lower costs and enhance the maturity and safety of CCUS technologies, especially the R&D of advanced CCUS and carbon removal technologies. It is necessary to develop legal systems and regulatory framework for CCUS, and establish standards systems and technical specifications required for construction, operation, supervision, and termination of CCUS projects.

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