E3S Web of Conferences **424**, 04015 (2023) https://doi.org/10.1051/e3sconf/202342404015
ICREE 2023

Current Status and Prospects of Carbon Capture, Utilization and Storage Technology in the Context of International Carbon Neutrality Strategic Goals

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Abstract. China is the world's largest emitter of greenhouse gases, and its huge emissions have attracted strong attention from the world. After accurate calculation, the Chinese government clearly proposed the goal of carbon peak by 2030, carbon neutrality by 2060, from relative emission reduction to absolute emission reduction, and then zero emissions, which became an ambitious "China plan" and road map. Starting with the strategic goals of carbon neutrality in China and other countries in the world, this article introduces in detail the characteristics and practical applications of CCUS (Carbon Capture, Utilization and Storage) technology, as well as the current research status and progress of carbon capture, carbon utilization, and carbon storage technologies. Based on China's national conditions and reality, it analyzes various challenges faced by CCUS technology, including economic, technological, environmental, and policy aspects. Finally, this article places the future vision on the international stage, analyzes and summarizes the development experience of CCUS technology in developed countries, and puts forward suggestions for the development of CCUS technology in China.

1 Introduction

Carbon neutrality refers to reducing the emissions of greenhouse gases such as carbon dioxide to the same level as the carbon dioxide absorbed and stored. In other words, humans need to reduce carbon dioxide emissions to sustainable levels to mitigate the impact of global climate change.This requires various measures in the fields of energy, transportation, construction, and industry, such as using renewable energy, improving energy efficiency, promoting low-carbon transportation, and improving building energy efficiency [1].

The strategic goal of carbon neutrality refers to reducing carbon emissions to almost zero within a certain period in the future (usually decades to hundreds of years), and achieving control and adaptation to global climate change. This requires various measures to be taken globally, including but not limited to strengthening international cooperation, promoting clean energy, improving energy efficiency, improving the energy structure, promoting low-carbon development, and strengthening carbon sink management. The carbon neutrality strategic goal is an important strategic goal for the global response to climate change, and it is also an inevitable choice for countries to address climate change.

The process of storing and long-term isolation from the atmosphere. Carbon capture, utilization, and storage (CCUS) is a process that separates CO_2 from industrial processes, energy utilization, or the atmosphere, and directly uses it or injects it into the formation to transport it to a storage site and isolate it from the atmosphere for a long time to achieve permanent CO_2 emission reduction [2].

On March 13, with the official closing of the two sessions of the NPC and CPPCC, words such as green development and carbon neutrality became hot topics. The Report on the Work of the Government pointed out that in 2023, we should further promote green economic development and promote low-carbon life for residents. Not only that, but the vigorous development of the digital economy also provides choices and avenues for China to achieve its "dual carbon" goals.

The "1+N" economic policy system of China's current "dual carbon" goals roughly covers the implementation of carbon peaking methods in various fields and industries such as energy, industry, transportation, and urban-rural construction, as well as comprehensive guarantees in terms of technology security, energy security, carbon sequestration capacity, fiscal and financial pricing policies, and local government supervision and assessment [3].

With the substantial progress made in China's environmental protection and low-carbon transformation and construction, environmental construction has become one of the most concerning livelihood issues for the people. According to the requirements of China's dual carbon strategy, by 2025, China's new system of green and low carbon cycle development will be basically formed, and energy efficiency in major areas will be significantly improved; By 2030, significant

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breakthroughs will be made in the comprehensive green transformation of China's economic and social development, and the energy efficiency of the main energy consumption areas will exceed the world's advanced level. By 2060, China's new system of green and low carbon cycle development and clean, low carbon, safe and efficient energy system will be fully established, the overall energy efficiency in the field will exceed the world's advanced level, the proportion of non fossil fuels will reach more than 80%, the task of carbon neutrality will be basically completed, and the construction of ecological civilization will achieve fruitful results, creating a new realm of harmonious coexistence between people and nature in China.

Europe is the first to announce absolute emission reduction policies. On September 16, 2020, European Commission Director von der Leyen released the "Union Situation Speech", announcing the European emission reduction plan: by 2030, Europe's total greenhouse gas emissions will be at least 55% lower than in 1990, and by 2050, the EU will become the world's first "carbon neutrality" continent. Since 1990, carbon emissions in Europe will continue to decline, reaching 23.3% [3,4].

After China clearly put forward the carbon peak and carbon neutrality standards, the standards of developed countries such as Japan, the United Kingdom, Canada and South Korea have also been raised to the national commitment to complete the carbon neutrality task by 2050. It was proposed by Japan to convert the total reduction of about 80% previously achieved in 2050 into carbon neutrality. The UK proposes to achieve net zero emissions by 2045 and carbon neutrality by 2050. The Canadian government has long made it clear that it will be carbon neutrality by 2050. Except for the United States and India, most developed countries and low-carbon countries around the world have made commitments to reduce carbon emissions. However, at present, China is still in a period of rising carbon emissions, which is different from countries such as Western Europe and Japan [5].

With mature technological development, CCUS has the opportunity to achieve near zero emissions and become an important part of global environmental solutions. CCUS is of great significance in promoting the clean use of coal, and it is likely to have a significant driving effect on the optimization and transformation of industries such as petroleum, fuel power generation, and coal chemical industry. It also has strategic significance for global fuel supply.

2 Research status and progress of CCUS technology

2.1 Research progress and status quo of carbon capture technology

Carbon capture technology mainly refers to the process of capturing CO_2 from emission sources such as power generation and industry and separating, collecting, and compressing the captured CO_2. The carbon emission industries suitable for CCUS in China mainly include thermal power plants, cement, steel, coal chemical industry, etc. [6].

According to the sequence of carbon source capture and combustion processes, carbon capture technologies can be divided into post-combustion capture, pre-combustion capture, oxygen-enriched combustion, and air capture. Post-combustion capture technology is mainly used in coal-fired power plants to capture CO_2 in the flue gas after combustion using physical and chemical methods. Pre-combustion capture technologies include integrated gasification combined cycle power generation (IGCC) and industrial separation. IGCC is a technology that gasifies fuels such as coal, biomass, and petroleum coke, and uses the purified gas for gas-steam combined cycle power generation.Industrial separation refers to CO_2 separation in industries such as coal to oil, coal to gas, natural gas processing, cement, methanol, and fertilizer [6]. Currently, most carbon capture technologies in China's CCUS projects are industrial separation technologies. Yanchang Petroleum uses methanol as a solvent at low temperatures and utilizes the excellent carbon dioxide solubility of cold methanol to remove CO_2 and other acidic impurities from the feed gas of coal to methanol units. This carbon capture process is currently recognized as the most economical and highly purified gas purification technology at home and abroad. The purity of CO_2 captured by the extended petroleum low-temperature methanol process can reach 99% [6].

Compared to China's first-generation carbon capture technology (as of 2011), significant progress has been made in the research on the second-generation carbon capture technology (2011-2021). China's pre-combustion capture technology is basically in sync with the international advanced level and is generally in the industrial demonstration stage. However, the development of post-combustion capture technology in China lags slightly, especially for the post-combustion chemical absorption method with the greatest potential for carbon capture, which is still in the pilot test or industrial demonstration stage, while the international advanced level is already in the stage of commercial application. The oxygen-rich combustion technology is currently in the demonstration stage. The CO_2 mass concentration of carbon emission sources is the main factor affecting the cost of carbon capture. The higher the carbon source mass concentration, the lower the carbon capture cost.

For industries such as ethanol, synthetic ammonia, and natural gas processing with high carbon source mass concentration The CO_2 emitted during production does not require physical or chemical absorption treatment, and carbon capture can be achieved directly through dehydration and compression equipment. Low-concentration carbon sources such as power plants and cement plants must first undergo physical or chemical separation methods to capture CO_2, with a long process and integrated carbon capture. Carbon capture costs account for 60% to 85% of the total cost of CCUS projects.

2.2 Research progress and current status of carbon utilization technology

CO_2 utilization technology refers to the process of producing CO_2-related products with commercial value and achieving carbon emission reduction. CO_2 can be used to produce inorganic chemical products such as soda ash, baking soda, white carbon black, borax, various metal carbonates, and high-value-added carbon-containing chemicals such as energy, fuels, and macromolecular polymers. For example, CO_2 and methane are used as catalysts to prepare synthesis gas, and oxygen-containing organic compound monomers such as alcohols, ethers, organic acids, polymer polymers, etc. In addition, CO_2 can also mineralize with large amounts of solid wastes rich in calcium and magnesium such as steel-making slag, cement kiln ash, fly ash, phosphogypsum, etc., achieving carbon emission reduction while also obtaining valuable inorganic chemical products. Currently, chloride-based mineral carbonation reaction technology, wet mineral carbonation technology, dry carbonation technology, and biological carbonation technology have been developed.

The development level of CO_2 utilization technology at home and abroad is synchronized, and it is generally in the industrial demonstration stage. China has made particularly prominent progress in CO_2 mineralization and utilization technologies such as steel slag and phosphogypsum. Breaking through the bottlenecks in high-temperature and high-pressure environments and finding suitable catalysts to improve carbon utilization efficiency are the key research directions in the next stage of CO_2 utilization technology.

2.3 Research progress and status quo of carbon storage technology

Carbon storage technology refers to the technology of injecting captured CO_2 into deep geological reservoirs through engineering and technical means to achieve long-term isolation from the atmosphere. The storage methods are divided into onshore storage and offshore storage.

The CO_2-enhanced oil recovery technology has entered commercial application. This technology can achieve CO_2 storage while also improving oil recovery. The economic benefits achieved by the additional extracted crude oil can effectively reduce the cost of CCUS projects. Every 1 t of CO_2 injected can produce 0.1~0.6 t of crude oil. Due to the favorable conditions such as complete geological data and infrastructure of oil and gas reservoirs, developing CCUS in oil fields is currently the mainstream direction for the large-scale promotion of CCUS. In addition to CO_2-enhanced oil recovery projects, CO_2 saltwater layer storage has also entered commercial applications.

Other storage technologies such as CO_2 geothermal development, CO_2 enhanced development of coalbed methane and shale gas, CO_2 basalt mineralized storage, and CO_2 hydrate storage are all in the research stage.

Similar to the idea of CO_2 mineralized solid form storage, CO_2 can achieve safe storage of hydrate solid form. The formation of CO_2 hydrates is relatively rapid compared to long-term CO_2 mineralization reactions. Under the high-pressure and low-temperature environment of the shallow saltwater layer in the deep sea, the formation pressure is adjusted by controlling the rate of CO_2 injection and the rate of formation water production to achieve CO_2 hydrate storage. In addition, in the low-temperature environment of shallow natural gas reservoirs, CO_2 and formation water can generate CO_2 hydrates, and CCUS can be implemented to achieve CO_2 hydrate storage. After the formation of CO_2 hydrate in the reservoir, it can serve as an artificial cap rock to prevent the continued upward migration of CO_2, thereby ensuring more secure CO_2 storage and reducing the cost of CO_2 storage monitoring. Research shows that the CO_2 storage capacity of CO_2 hydrate form is three times that of supercritical CO_2 storage capacity under the same pore volume conditions.

2.4 Application of CCUS

The carbon capture process upstream of CCUS is mainly divided into three main technical methods: 1) capture before ignition, and remove carbon gas from the fuel chamber before ignition; 2) After ignition, capture and separate supercritical high speed carbon dioxide from the flue gas generated after ignition; 3) Oxygen-enriched combustion, including combustion processes of air and supercritical carbon dioxide, as well as processes such as air decomposition and air recovery and regeneration. The capture technology in its combustion can also be used for building new factories, while other technologies may also be applied simultaneously to power plants, chemical plants, etc. that are under construction or have already been put into operation [7].

The application of CCUS technology mainly includes physical applications, chemical applications, and biological applications. Physical applications mainly include: applications in the manufacturing of beer and carbonated beverages; Oil displacement solution technology in the third production of oil fields; Low radioactive uptake gas shielded welding during the welding process; In the refrigeration technology of liquid and solid CO_2, used in the refrigeration and preservation process of food, fruits and vegetables; Used as an automatic oxygen reducing and controlled atmosphere preservative for fruits and vegetables, as well as in the field of supercritical CO_2 extraction technology. Chemical applications mainly include the development and application of inorganic and organic fine chemicals, as well as polymer composite materials. For example, using CO_2 based production of urea, modifying and preparing lightweight nano level ultrafine activated carbonates; Using CO_2 catalyst for hydrogenation to produce acetaminophen; Production of various organic synthesis and reaction raw materials using supercritical carbon dioxide as the main raw material; Flame retardant polymers prepared by co polymerization of CO_2 and epoxides, etc; And the use of CO_2 to directly convert into CO, in order to develop corresponding chemicals for hydrogen carbonylation of carbon, etc. [7].

3 Challenges faced by CCUS technology

3.1 Economic challenges

The main problem with CCUS in China is the relatively large investment in demonstration projects. In the current process environment, installing a carbon capture system will result in huge investment and operational maintenance expenses. Taking the installation system of a Shanghai thermal power plant as an example, it will add an additional operating cost of approximately 1.4-6 million yuan/t and directly lead to a significant increase in power generation production costs [7].

The main function of the CCUS project is to reduce carbon emissions, but small and medium-sized enterprises have not achieved emission reduction results after investing a large amount of funds, which seriously interferes with the enthusiasm of small and medium-sized enterprises to implement the CCUS demonstration project. In addition, due to the fact that CO_2 is still mainly transported by tank cars, the transportation cost is relatively high, and the high investment and danger in CO_2 pipeline construction have hindered the popularization of CCUS products [7].

3.2 Technical challenges

Currently, China has carried out experimental demonstration projects for various technical routes throughout the entire CCUS process, but the overall project is still at the research and development and experimental stage, and the scope of the project is too small. Although the number and scale of new projects are increasing, there is still a lack of integrated demonstration projects that integrate the entire process and can be replicated on a larger scale with significant economic benefits. In addition, constrained by the current level of CCUS technology, deployment will increase primary energy consumption by 10-20% or more, resulting in significant efficiency losses, which seriously hinder the promotion and application of CCUS technology. It requires more capital investment to quickly change this situation [7].

In addition, technical innovation can be used to clarify the geological factors (reservoir heterogeneity, etc.) that affect the migration of CO_2 after storage in geological data, reduce the risk of carbon storage through the commissioning of CCUS sites, and develop emergency plans [7].

3.3 Environmental challenges

CCUS traps liquid CO_2 at high concentrations and pressures, with a density smaller than that of oil and water. After being sealed in underground reservoirs, it will continue to migrate upward. Under geological movements such as earthquakes and the corrosive effects of CO_2 dissolved in water on the formation, it will intensify the migration of CO_2. When CO_2 leaks and escapes to the surface, it will have an impact on the ecological environment [7].

Therefore, achieving safety full permanent carbon storage is a necessary prerequisite for carrying out CCUS projects. However, the geological factors of each CCUS project are different, and the environmental assessment standard system is difficult to quantify. Based on existing CCUS projects, establishing CCUS environmental assessment technical guidelines has guided and referenced significance for future deployment of CCUS [7].

3.4 Policy challenges

At present, although the country has corresponding rules and regulations for reference throughout the entire process of the CCUS demonstration project, there are no targeted special work regulations, which also makes the enthusiasm of enterprises in implementing the CCUS demonstration project not high. In terms of current policy situation, the Chinese government still holds a positive attitude towards the development of CCUS, but mostly uses macro policy guidance and incentives, rather than specific financial and tax support for CCUS development projects. There are also no corresponding policy provisions for the selection, construction, operation management, geological utilization of demonstration projects, as well as environmental risk assessment and monitoring before and after the closure of storage sites [7].

4 Mature experience of CCUS technology in developed countries from an international perspective

4.1 UK

UK: Plan specific decarbonization strategies in multiple fields, with a focus on supporting research on advantageous low-carbon technologies
The UK has become the first country in the world to formulate emission reduction policies through regulations and has proposed detailed emission reduction strategies in key areas [1].

The UK set a target of reducing emissions by 80% by 2050 in the 2008 Climate Change Act, which was revised in June 2019 to achieve net zero greenhouse gas emissions. In April 2021, the UK announced again that it would reduce greenhouse gas emissions by 78% by 2035 (compared with 1990 levels), The overall idea of promoting net zero greenhouse gas emissions in China has been clearly proposed. The emission reduction targets of oil, industry, transportation, infrastructure, construction and other industries are the main basis for countries around the world to achieve the net zero emission level. The British government has given special carbon targets in various fields and proposed targeted regulations in various fields.

The UK highly values its most distinctive low-carbon technology development [8].

The UK has deployed a series of research actions in key technical fields such as greenhouse gas removal, CCUS, renewable energy, construction, and industrial emission reduction [9]. In March 2021, the UK launched a £ 1 billion net zero innovation portfolio plan to develop key low-carbon technologies, focusing on priority areas such as offshore wind power, advanced modular reactors, energy storage and flexibility, hydrogen energy, biomass energy, industrial fuel conversion, advanced CCUS, household housing, direct air capture, greenhouse gas removal, and disruptive technologies [9].

4.2 US

The United States: Using the environment as the foundation of foreign and economic policies to promote the development of clean energy [10].

In 2021, President Biden of the United States said he would return to the Paris Agreement, defining a new strategy to achieve a carbon free energy policy in 2035 and a carbon neutrality policy in 2050. At the same time, he will also make it clear through executive orders that environmental crisis resolution will be placed at the core of the U.S. government's foreign policy and economic development policy, and will establish the White House National Environmental Strategy Office, the U.S. Global Environmental Strategy Task Force Establish the clean fuel strategy and auto industry policy of the US federal government, cancel subsidies for US fossil fuels and other measures to promote carbon neutrality development in the US. In addition, some state governments in the United States have also formulated stricter carbon neutrality measures than the government, which is also a feature of the United States [10].

The Biden administration is committed to promoting the common growth of clean resources and innovative technologies, achieving a global clean energy economy of 100% by 2050. We have successively formulated major regulations related to the development of clean energy, such as the US Energy Innovation Act, the Building a Modern and Sustainable Infrastructure and a Fair Clean Energy Future Plan, the Clean Energy Revolution and Environmental Justice Plan, the Energy Storage Challenge Roadmap, and the Clean Future Act. We will continue to invest more than $200 billion in transportation Reinvestment in key industries such as construction and clean energy to further promote clean energy innovation and effectively support China's clean energy economic development [10].

4.3 Japan and South Korea

After China, Japan and South Korea have proposed carbon neutral targets by 2050.

Japan: In December 2020, the "2050 Green Growth Strategy" was released, targeting 14 industries such as energy, transportation, manufacturing, and construction. It proposed development goals and key tasks to achieve carbon neutrality by 2050, promote the development of industrial electrification and the transformation of the circular economy, promote deep decarbonization in the power sector, and accelerate the development of carbon cycling and resource utilization. In June 2021, the "2050 Carbon Neutral Green Growth Strategy" was updated to incorporate the offshore wind power industry into the new generation renewable energy industry. The ammonia fuel and hydrogen energy industries have been merged and a new generation of the thermal energy industry has been added [1].

South Korea: In December 2020, the "2050 Carbon Neutralization Strategy" was released, proposing the "3+1" measures of low-carbon economic structure, building a low-carbon industrial ecosystem, building a fair and equitable low-carbon society, and strengthening the construction of carbon neutrality systems, aiming to achieve carbon neutrality by 2050. The "Green New Deal" plan will invest 73.4 trillion won to support the development of green infrastructure, new and renewable energy, green transportation, green industry, and CCUS and other green technologies. At the same time, the "Carbon Neutralization Section" [1].

The Technology Innovation Promotion Strategy identifies 10 key core green technologies to achieve carbon neutrality, including hydrogen energy, solar and wind energy, bioenergy, CCUS, steel and cement, petrochemical industry, industrial process improvement, transportation energy efficiency, building energy efficiency, and digitization.

5 Conclusion

Pre-combustion captures, such as ethanol, synthetic ammonia, and natural gas processing industries, as well as post-combustion capture, are currently the key research and application directions for carbon capture. Currently, the carbon capture efficiency is less than 90%, and the carbon capture cost accounts for 60% to 85% of the total cost of CCUS projects. The focus of carbon capture research and development is to improve carbon capture efficiency and reduce carbon capture costs.

CO_2 utilization technology is currently in the industrial demonstration stage. Breaking through the bottleneck of high-temperature and high-pressure environments and finding suitable catalysts to improve carbon utilization efficiency are the key research directions in the next stage of CO_2 utilization technology.

Currently, oil and gas fields and saltwater layers are still the mainstream storage media for CO_2. The focus of CO_2 storage research in the next stage should be on improving CO_2 to improve oil and gas recovery, increasing the potential for CO_2 storage in oil and gas fields and saltwater layers, enhancing research on CO_2 geothermal development, CO_2 enhanced development of coalbed methane and shale gas, CO_2 basalt mineralization and storage, and CO_2 hydrate storage.

On the whole, CCUS has great potential for emission reduction and may achieve zero or even negative emissions. It promotes the development of other relevant industries through a series of CO_2 utilization methods. As a promising new technology in development, the industrial utilization of CO_2 also has great prospects. However, due to the constraints of the economy, technology, environment, and policies, some problems are difficult to solve in a short time. Considering China's national conditions, the time for large-scale development of CCUS projects is not yet ripe. In terms of economy, achieving the profitability of CCUS projects is an important constraint factor in promoting CCUS; In terms of technology, focus on innovation, develop low-cost and low-power carbon capture technologies, clarify the uncertainty of geological conditions in carbon storage sites, improve oil and gas recovery in CO_2 development, monitor CO_2 storage migration, and promote the leapfrog development and sustainable operation of CCUS. In terms of policies, the introduction of subsidy policies for CCUS projects, the establishment of a carbon trading market, the increase of carbon taxes, and the gradual improvement of special laws, regulations, and standard systems for CCUS all contribute to accelerating the deployment of CCUS; In terms of environment, establish technical guidelines for CCUS environmental assessment to ensure the safe operation of CCUS projects.

It is recommended that the government formulates a CCUS development plan, explore fiscal policies conducive to the development of CCUS, and encourage enterprises to carry out integrated demonstration projects throughout the process; Increase research investment in relevant applied technologies and supporting technologies at the scientific research level; On the one hand, the enterprise level deepens cooperation and exchanges with developed countries in Europe and the United States to obtain international financial support. On the other hand, it conducts research and sorting on advanced demonstration projects abroad, timely summarizes and improves domestic demonstration projects, accumulates engineering experience and technical data throughout the entire industrial chain, and lays a solid foundation for the construction of China's CCUS technical standards system.

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