Carbon Dioxide Capture Technology Applications for Climate Change Mitigation: Policy Requirements, Practical Challenges, and Optimization Pathways

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Abstract. Carbon dioxide (CO2) capture technology constitutes a critical pathway for mitigating global climate change and achieving carbon neutrality, with its primary objective being the reduction of atmospheric CO2 concentrations. Core methodologies encompass chemical absorption, physical adsorption, membrane separation, cryogenic distillation, and biological capture. These technologies facilitate direct emission reductions and, synergistically combined with geological sequestration, enable long-term carbon storage. Notably, direct air capture (DAC), leveraging adsorption-desorption cycles, offers significant advantages: its deployment is geographically unconstrained, facilitating flexible siting, and exhibits strong compatibility with renewable energy integration, thereby enhancing its environmental benefits. Consequently, DAC has garnered substantial academic and industrial interest as a pivotal pathway towards global carbon neutrality, alongside the particularly prominent post-combustion capture. This paper comprehensively reviews the current application landscape of CO2 capture technologies. Optimization strategies are proposed from technological, application, and policy perspectives, aiming to provide theoretical insights for fostering the synergy between technology commercialization and climate governance. Despite the promising prospects, CO2 capture technologies still face notable challenges. Chemically absorbent-based methods, while mature, suffer from high energy consumption during solvent regeneration, limiting their cost-effectiveness. Physical adsorption and membrane separation, though energy-efficient, are constrained by low selectivity and scalability issues in large-scale industrial applications. Cryogenic distillation, effective for high-purity CO2 streams, struggles with excessive energy input for dilute emissions. Biological capture, relying on photosynthetic organisms, is hindered by slow reaction rates and sensitivity to environmental conditions. Direct air capture, despite its flexibility, remains costly due to low atmospheric CO2 concentration, demanding advanced materials like high-capacity adsorbents to improve efficiency. Post-combustion capture, widely applied in power plants and industrial boilers, requires existing facilities, posing technical. Addressing these obstacles necessitates innovation, from material science breakthroughs to process engineering optimizations, coupled with supportive policies to drive technological iteration and market adoption..

Keywords: carbon capture; utilisation and storage; climate change.

1. Introduction

The extensive utilization of fossil fuels has led to a continuous rise in atmospheric carbon dioxide concentrations, triggering severe environmental challenges such as global warming and increased frequency of extreme weather events. The Intergovernmental Panel on Climate Change points out that CCUS technology is currently the only key solution that allows continued fossil fuel use while achieving near-zero emissions. It plays an irreplaceable role in mitigating global climate change.[2,3] The International Energy Agency predicts that by 2050, CCUS will need to handle one-third of global emissions, and by 2060, it will contribute to approximately 14% of emission reductions, making it one of the core means to achieve the goal of net-zero emissions [1,3]. The global population continues to grow, projected to reach about 8.6 billion by 2030, and energy demand is rising accordingly. However, fossil fuels remain the mainstay of current energy consumption, accounting for about 81.5% of global primary energy consumption [3]. The energy industry is facing a dual challenge: it must ensure energy security to cater to the growing demand while reducing carbon emissions to address the climate crisis [1]. For example, China's energy structure, which features "abundant coal, stingy oil and scarce gas", has resulted in high CO_2 emissions. The power sector, accounting for 40%, as well as energy-intensive industries such as steel and cement, have become key focuses for emission reduction, and CCUS technology offers a feasible low-carbon transition path for these incompatible industries [2,4]. After the signing of the Paris Agreement in 2015, 178 global parties committed to limiting global temperature rise to within 2°C, and CCUS technology was incorporated into the emission reduction strategies of different countries. China has set the goals of "reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060". The "14th Five-Year Plan" clearly identifies CCUS as a major demonstration project, promoting technological research and industrialisation through policy guidance and financial support [2,3]. The European Union, the United States and other regions and countries have also accelerated the deployment of CCUS through legislation, such as the EU's CCS Directive and the US's Clean Energy and Security Act [3,4]. CCUS can directly reduce the concentration of greenhouse gases in the atmosphere by capturing $CO_2$from industrial emissions, then storing it underground or reusing it as a resource. For instance, after installing CCUS equipments in thermal power plants and steel mills, CO_2 emissions can be significantly reduced. With large-scale application, it is estimated that by 2050, billions to tens of billions of tons of CO_2 emissions can be reduced globally [1,2]. Data from the IPCC shows that without CCUS technology, the cost of meeting temperature control objects could increase by more than 50% [4]. This paper focuses on the current application status of carbon dioxide capture technologies. From the three perspectives of technology, application and policy, it proposes optimisation strategies to provide theoretical references for the synergy between technology commercialization and climate governance. In terms of technology, CCUS has evolved from traditional combustion chemical absorption and physical absorption to efficient technologies such as oxygen fuel combustion and chemical looping combustion. Through continuous research and development, Total has achieved a CO_2 concentration of 90%-95% in oxygen fuel combustion. However, breakthroughs are still needed in the research and development of low-energy-consumption materials and the integration of the whole process. As for application, the technology has penetrated into fields such as electric power, oil and gas, and coal chemical industry. Total has reduced carbon emissions by 40% in oil and gas development through electric well exploration. The implementation of domestic million-ton-level projects has verified the potential for large-scale application, but the coordination across industries and the balance of economy remain key issues.On the policy front, various countries have built a system integrating "legislation, fiscal and taxation measures, market mechanisms". China guides the development through tax incentives and demonstration projects; the European Union sets quantitative targets with the European Green Deal； the United States provides incentives relying on tax credits. It is necessary to further strengthen the unification of standards and international cooperation, so as to promote CCUS to become a core tool for climate governance.

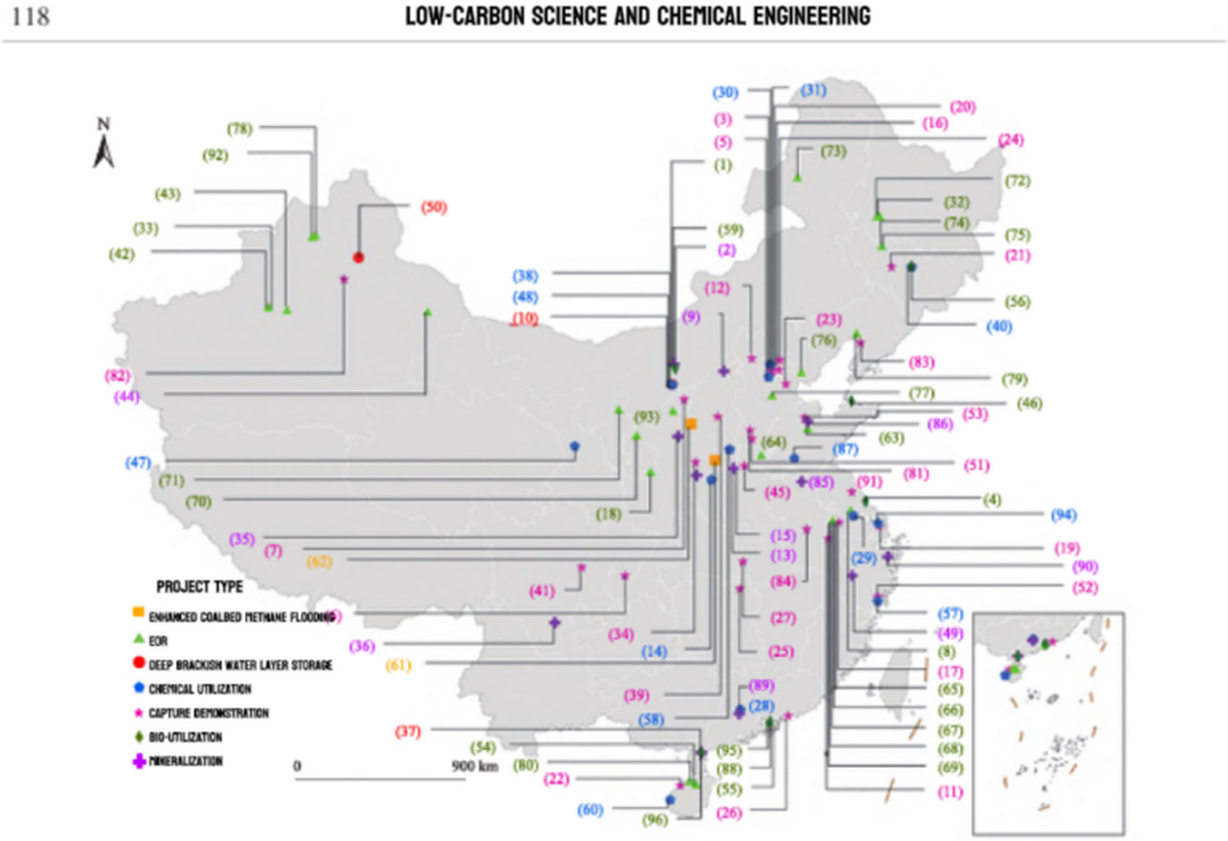

Fig.1 Distributions ofCCUS demonstration projeets in China

The core content of this image presents the distribution of China's CCUS (Carbon Capture, Utilization, and Storage) demonstration projects. In the form of classified labels, it shows the main application directions of these projects, with the quantity of each type indicated by the numbers in parentheses, covering the following core fields: first, utilization projects, which include those related to enhanced oil recovery and coalbed methane as well as Carbon dioxide resource utilization directions such as biological utilization, chemical utilization, and mineralization; second, storage projects, which highlight saline aquifer storage projects to demonstrate the application layout of geological storage technology; and third, capture projects, which list capture demonstration projects to reflect the technological demonstration progress in the carbon capture link. Additionally, the image illustrates the connection between space and scale, with the mention of "900 km" presumably related to CCUS project-associated infrastructure, referring to either the length or the spatial span of the project coverage area, which implies that some projects possess a certain spatial scale and cross-regional synergy characteristics.

2. The current application status of carbon dioxide capture technologies for climate change

2.1 Carbon dioxide capture technology

Global CCUS technology has gradually moved from laboratory research to industrial demonstration. By the end of 2023, there were about 400 CCUS projects worldwide that are operational, under construction or planned. Among them, the United States accounts for more than one-third, covering industries such as power, cement and chemicals [3]. For example, the US Petra Nova project is one of the world’s largest carbon capture projects in coal-fired power plants, with an annual capture capacity of 1.4 million tons of CO_2, mainly used for oil displacement [5]. The European Union has funded 26 CCUS projects through its "Innovation Fund", with a total investment of over 3.3 billion euros. It focuses on promoting decarbonisation in industrial clusters and plans to capture 50 million tons of CO_2 annually by 2030 [3]. In terms of technical links, post-combustion chemical absorption is the most widely used capture technology, such as the US Kemper project. Oxygen fuel combustion technology has proven feasible in Total’s Lacq project in France [1,5]. The pipeline is the main means of transportation. The United States has built more than 7,200 kilometres of CO_2 pipelines, with an annual transportation capacity of about 80 million tons [5]. Geological storage is the main form of storage. Norway’s Snøhvit project in the North Sea injects CO_2 into subsea saline aquifers, with an annual storage capacity of 1 million tons [3].

2.2 Carbon dioxide capture application

Carbon dioxide is widely used in many fields. The power industry is one of the core application areas for carbon dioxide capture technologies, with a particular focus on coal-fired power plants. This is because the power industry relies on fossil fuels such as coal and is one of the main sources of global carbon emissions. In China, coal-fired power generation accounts for a high proportion, with huge emissions from individual plants. Moreover, power plant emission sources are concentrated and the flue gas composition is relatively stable, which facilitates the application and promotion of large-scale capture technologies, making it an important breakthrough for achieving large-scale emission reductions in the short term. Next is the oil and gas industry. $CO_{2\text{-}v}$enhanced oil recovery is the most mature application method. The United States processes approximately 60 million tons of CO_2 annually through this technology, increasing oil recovery rates by about 10% to 15% [5]. Total has collaborated with Norway’s Statoil to develop carbon storage operations in the North Sea, achieving large-scale storage using depleted gas fields [1]. Ultimately, in the industrial sector, hard-to-abate industries such as steel and cement are gradually adopting CCUS. For example, Germany’s Schwarze Pumpe power plant uses oxygen fuel combustion technology to capture approximately 300,000 tons of CO_2 annually [5]. Canada’s Boundary Dam project uses CO_2 emitted from coal-fired power for oilfield enhanced recovery, achieving a "win-win" of emission reduction and increased production [3].

2.3 The Synergy between Technology Application and Climate Change Governance

There is a deep synergistic relationship between CCUS technology and climate change governance. CCUS is the only technology capable of achieving large-scale emission reductions in the use of fossil fuels, supporting the low-carbon transition of incompatible industries. By 2050, it will need to handle one-third of global CO_2 emissions [1, 3]. Climate change governance promotes the research, development and application of CCUS through policy guidance such as China’s 《Plan for Scientific and Technological Support for Carbon Peak and Carbon Neutrality》. As well as economic incentives like the US 45Q tax credits and market mechanisms such as the EU carbon trading system [3]. A positive feedback loop exists between the two: technological maturity helps reduce governance costs, with capture costs, for instance, dropping from 600 yuan per ton to 140–400 yuan per ton. Meanwhile, upgraded governance goals drive technological innovation, as seen in China’s plan to develop million-ton-level CCUS clusters [2, 4, 5]. International cooperation, as embodied by the OGCI (Oil and Gas Climate Initiative), further strengthens this synergy, jointly contributing to the achievement of global climate goals [1, 3].

3. Policy demands for the application of carbon dioxide capture technology

3.1 Requirements for Policy Framework Construction

First, improve the legal and regulatory system. The United Nations needs to clarify the legal status of CCUS projects and formulate special regulations covering the entire process of capture, transportation, and storage. For example, it should standardise the site approval for CO_2 geological storage, long-term monitoring responsibilities, and mechanisms for pursuing liability for environmental risks [3,5]. Second, unify technical standards and accounting systems. Establish technical standards for capture efficiency, energy consumption, and purity, and unify methods for quantifying and verifying emission reductions to ensure that the emission reduction effects of projects are measurable and traceable [3,5]. Third, establish an industrial chain coordination mechanism. Introduce policies for cross-industry cooperation to promote linkage between emission sources such as power plants and refineries with oil fields and storage sites. Plan regional CCUS industrial clusters and share infrastructure like pipelines [2,4].

3.2 Demand for Economic Incentive Policies

First, there are fiscal and tax incentives. The government can expand the scope of tax reductions and exemptions, offer depreciation benefits for investments in capture equipment, and provide fixed subsidies for emission reductions based on tons of CO_2. For reference, China’s "three-year exemption and three-year halving" income tax policy can be taken as an example. Additional rewards can also be given to low-energy-consumption technologies such as oxygen fuel combustion [3]. Next is investment and financing support. Capture projects can be included in the scope of green bonds and special loans support, and a national-level CCUS fund can be established to reduce enterprises ’ financing costs. Exploring financial instruments such as carbon futures can enhance the stability of project returns [3,4]. Finally, there is the market incentive mechanism. The CO_2 emission reductions captured can be included in carbon market transactions, allowing enterprises to use them to offset carbon emission quotas. Priority market access can be granted to products made from recycled CO_2 like biodegradable plastics[3,5].

4. Practical challenges in the application of carbon dioxide capture technology

4.1 Technical bottleneck

Initially, a primary challenge lies in the effective capture of low-concentration emission sources. The process of capturing dilute CO_2 streams from industrial flue gases, such as those emitted by coal-fired power plants and steel mills, is particularly energy-intensive and economically burdensome. Current capture systems, including amine-based absorption, exhibit low efficiency when applied to flue gases with CO_2 concentrations below 15%, leading to disproportionately high energy penalties and operational expenses, typically ranging from 300 to 600 yuan per ton of CO_2 captured [2,5]. Moreover, the performance of existing absorbents remains unsatisfactory in terms of stability, regeneration energy, and adsorption capacity under realistic conditions, further constraining their large-scale applicability. Another significant barrier is the insufficient technological maturity of several advanced capture methods. Promising alternatives such as chemical looping combustion (CLC) and membrane separation techniques have shown potential in laboratory and small-scale pilot studies. However, they still face substantial challenges in scalability, long-term stability, and system integration. These technologies have not yet been widely demonstrated at commercial scale, resulting in a lack of operational data and performance guarantees under real-world conditions [1,5]. Similarly, oxy-fuel combustion—another leading candidate—requires high-purity oxygen, whose production via cryogenic air separation is extremely energy-intensive. This significant auxiliary power consumption greatly diminishes the net efficiency of the power plant and hinders the economic viability and broad adoption of the technology. Finally, there remains a critical lack of seamless technical integration between the capture, transportation, and storage stages of carbon management. For instance, the purity level of CO_2 captured from conventional systems often fails to meet the stringent standards required for enhanced oil recovery (EOR) or geological storage, necessitating additional and costly purification steps. Furthermore, the transportation of CO_2 via pipelines presents non-trivial challenges related to material corrosion and fracture control. Breakthroughs in corrosion-resistant materials, monitoring technologies, and safety standards are urgently needed to enable reliable and integrated carbon infrastructure.

4.2 Policy Outlook

Firstly, the government needs to strengthen support for technological research and development. It should set up special funds to tackle key problems in low-energy-consumption capture materials, such as high-efficiency adsorbents and integrated technologies, and promote the large-scale development of demonstration projects with a capacity of at least one million tons or more[3,4]. Secondly, improve standards and incentive mechanisms. Formulate mandatory standards for capture efficiency and energy consumption, and include emission reductions in carbon market transactions. Expand tax incentives such as immediate refund of value-added tax[3,5]. Thirdly, promoting cross-industry collaboration. Planning regional CCUS industrial clusters, coordinating the layout of emission sources and storage sites, and building shared transportation pipelines [2,4].

4.3 Research Limitations and Future Directions

From a technical perspective, several core technologies critical to the feasibility of carbon capture, utilization, and storage (CCUS) remain underdeveloped. Specifically, the effective capture of CO_2 from industrial flue gases with low concentrations (typically below 15%) continues to pose substantial challenges due to high energy penalties and low absorption efficiency with current solvents. Concurrently, ensuring the long-term safety and integrity of pipelines for large-scale CO_2 transportation introduces complex technical hurdles, including corrosion control, fracture prevention, and reliable leakage monitoring. These technologies have not yet undergone extensive validation in real-world, large-scale engineering demonstrations, resulting in significant uncertainties regarding their reliability and scalability in integrated commercial projects [5]. Economically, the high cost of CCUS deployment presents a major barrier to its commercial adoption. Current operational expenses, particularly for carbon capture, often range between 300 to 600 yuan per ton of CO_2, which leads to a pronounced cost-price inversion when compared to prevailing carbon market prices. This economic mismatch means that most CCUS projects remain financially unviable without substantial government subsidies or policy support. Consequently, the absence of a self-sustaining market mechanism weakens investor confidence and fails to generate adequate market-driven impetus for broad implementation. In terms of data availability, there is a notable insufficiency in long-term monitoring data related to the safety and stability of geological CO_2 storage. Critical questions regarding potential leakage pathways, geomechanical responses, and the long-term behavior of sequestered CO_2 remain partially unanswered due to the limited duration and scale of existing storage projects. Moreover, the evaluation system for quantifying long-term emission reduction effects and environmental impacts is still incomplete, hindering accurate risk assessment and societal acceptance of CCUS technologies .

5. Conclusion and prospect

5.1 Main Conclusion

As a core means to address climate change and advance carbon neutrality, carbon dioxide capture technology involves various dimensions such as technological innovation, engineering practice, and policy support. From the perspective of the technical system, current methods mainly include combustion capture, pre-combustion capture, and oxygen fuel combustion capture. Next -generation technologies, such as those based on new adsorbents and membrane separation, are accelerating their research and development. Transformative technologies like third generation chemical looping combustion have also entered the exploration stage, aiming to reduce energy consumption and costs. With regard to application fields, this technology is widely used in high-carbon-emission industries such as power, oil and gas, coal chemical, and steel. The power industry focuses on flue gas capture in coal-fired power plants, achieving emission reductions through large-scale projects; the oil and gas industry uses captured carbon dioxide for enhanced oil recovery, balancing emission reduction and increased production; industries like chemical and steel recover high-concentration carbon emissions during production, and some projects even realise carbon resource conversion and utilisation, such as producing methanol and building materials. Currently, the technology still faces key bottlenecks: The efficiency of core materials and processes needs to be improved, the cost of the entire industry chain remains high, cross-regional infrastructure coordination is insufficient, and policy details and standard systems need to be refined. In the future, with technological iteration, the emergence of scale effects, and continuous policy efforts, carbon dioxide capture technology will play a more critical role in the global carbon neutrality process, promoting in-depth transformation of high-carbon industries and the development of a low-carbon economy.

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