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Research Progress in CO2 Capture and Storage Technology

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Abstract:
With the intensification of global climate change, carbon dioxide (CO_2), as a major greenhouse gas, has become a key focus in achieving sustainable development and carbon neutrality. Carbon Capture and Storage (CCS) technology, an essential method for controlling emissions in industrial and energy sectors, has attracted wide attention. This paper first outlines the primary sources of CO_2 emissions from both daily life and industrial production, highlighting key sectors such as power generation, steel, and cement as major targets for emission control. It then introduces two typical CO_2 capture methods—adsorption and cryogenic separation—explaining their technical principles, advantages, limitations, and applicable scenarios. On the storage side, geological storage technology has matured and has been commercialized in regions such as Northern Europe. Based on this, the paper further explores the future prospects of CCS, emphasizing the need for progress in four areas: technology integration, cost optimization, policy incentives, and market mechanisms. By systematically reviewing current research and practical applications, this paper aims to provide theoretical support and strategic references for CCS development both in China and globally.

Keywords: Carbon Dioxide Capture; Storage Technology; Adsorption Method; Greenhouse Gas Reduction.

1. Introduction

Since the beginning of the 21st century, energy shortages and environmental pollution have become critical challenges to global sustainable development. As the global population continues to grow and industrialization deepens, energy demand keeps increasing. However, the current energy structure remains dominated by fossil fuels such as coal, oil, and natural gas. The combustion of fossil fuels releases large quantities of CO_2, which is widely recognized by the scientific community as the main greenhouse gas responsible for global warming and climate change. Observational data shows that atmospheric CO_2 concentration has risen significantly from approximately 280 ppm before the Industrial Revolution to over 420 ppm by 2023 [1]. This increase has led to a range of major environmental issues, including rising sea levels, frequent extreme weather events, and declining ecosystem stability.

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To balance environmental protection and energy development, the concept of "sustainable development" has become a global consensus. In 2015, the United Nations' 2030 Agenda for Sustainable Development called for urgent action to combat climate change and its impacts [2]. Against this backdrop, carbon peaking and carbon neutrality goals have emerged as core strategies in many countries' transitions toward low-carbon development. Notably, China announced its "dual carbon" goals in 2020—aiming to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [3]—further underscoring the urgency of reducing CO_2 emissions and the strategic importance of CCS.

Among the many greenhouse gas reduction pathways, Carbon Capture and Storage (CCS) is receiving increasing attention for its significant mitigation potential and its relatively low demand for altering existing energy infrastructure. The core process of CCS involves capturing CO_2 from large stationary sources (such as coal-fired power plants, steel mills, and cement factories), transporting it via pipelines or ships to suitable locations, and injecting it into deep geological formations for long-term storage to prevent it from entering the atmosphere [4]. The three key stages of this technology are capture, transport, and storage.

Currently, CO_2 capture technologies fall into three main categories: pre-combustion, post-combustion, and oxy-fuel combustion capture. Of these, post-combustion capture is the most mature and widely used. A typical method involves using chemical solvents (such as monoethanolamide, MEA) that react reversibly with CO_2 in flue gas. However, current capture technologies—especially post-combustion capture—face major challenges, including high energy consumption, high economic cost, and equipment corrosion due to solvent use [5], which hinder their large-scale commercial deployment.

In the storage phase, geological storage is currently the most feasible and promising method. Suitable storage sites include deep saline aquifers, depleted oil and gas fields, and salt caverns. Demonstration projects have shown that, with proper site selection and scientific management, CO_2 can be stored safely and permanently. For instance, Norway's Sleipner project has stored over 20 million tons of CO_2 in the Utsira saline formation of the North Sea since 1996, making it a pioneering example of CCS commercialization [6].

It is also noteworthy that the concept of Carbon Capture, Utilization and Storage (CCUS) has developed rapidly in recent years. CCUS emphasizes not only storage but also the transformation of captured CO_2 into economically valuable products. This includes using CO_2 as a feedstock to synthesize fuels (e.g., methanol), produce building materials (e.g., carbonate minerals), or support microalgae cultivation for biomass resources. CCUS seeks to achieve synergy between emission reduction and resource utilization, offering a better balance between environmental and economic goals.

Although CCS/CCUS technologies have made significant progress and accumulated valuable engineering experience, large-scale deployment to support deep decarbonization globally still faces many challenges. These include improving capture efficiency, reducing energy consumption and costs, establishing robust monitoring and risk assessment systems for storage safety, improving legal and regulatory frameworks, and designing effective policy incentives to lower investment risks.

Therefore, it is of great theoretical and practical significance to trace the development of CO_2 capture and storage technologies, analyze the status, strengths, and limitations of key technical routes—especially in capture and storage—summarize lessons from representative projects both in China and abroad, and explore obstacles and solutions for large-scale deployment. This paper aims to provide such a review and offer insights into future research directions and potential breakthroughs, with the goal of advancing this technology and supporting global carbon neutrality efforts.

2. Sources of CO_2

Carbon dioxide (CO_2) emissions originate from a wide range of sources, which can be broadly categorized into residential and industrial. Understanding the main emission pathways is critical for formulating effective reduction policies and selecting appropriate capture and storage technologies.

2.1 Residential Sources

Residential CO_2 emissions primarily arise from daily activities such as transportation, household energy use, and waste management. With increasing urbanization, individual carbon footprints contribute significantly to total emissions. According to the International Energy Agency (IEA) 2022 data, the transportation sector accounts for approximately 24% of global CO_2 emissions, including cars, airplanes, ships, and freight vehicles powered by fossil fuels. Household energy use (e.g., heating, boiling water, cooking with natural gas) also contributes a large share. In addition, incineration of household waste and wastewater treatment processes release CO_2 and other greenhouse gases. Although emissions from residential sources are dispersed and smaller in scale, their cumulative impact is significant and persistent.

2.2 Industrial Sources

Compared to residential sources, industrial and energy production activities are the primary sources of CO_2 emissions. According to the IEA, approximately 70% of global CO_2 emissions come from energy conversion and industrial manufacturing [7]. In particular, fossil-fuel-based power generation is a major contributor, with every 1 kWh of electricity typically emitting 0.4–1.0 kg of CO_2. Heavy industries such as steel, cement, and glass manufacturing not only consume large amounts of fuel but also emit additional CO_2 through chemical reactions (e.g., limestone calcination). The petrochemical industry also emits significant CO_2 during processes such as cracking, synthesis, and refining. These industries are characterized by high emission concentrations, stability, and large capture potential, making them top priorities for CCS deployment.

3. Methods of CO_2 Capture and Storage

CCS technology consists of three main stages: capture, transport, and storage. Among them, capture is the technical core, accounting for more than 70% of the total cost. Based on different separation mechanisms and application scenarios, capture technologies can be classified into various pathways, including adsorption and cryogenic separation.

3.1 Page Numbers

Adsorption is a technique that separates CO_2 using the surface properties of solid materials. It works by leveraging either physical or chemical interactions between the adsorbent and CO_2. Physical adsorption, which depends on weak van der Waals forces, is suitable for low-temperature, high-pressure environments and uses materials like activated carbon and zeolites. Chemical adsorption, by contrast, relies on functional groups (e.g., amines) that react with CO_2 to form carbonate or ammonium salts, and works under ambient conditions. Common materials include metal-organic frameworks (MOFs) and functionalized silica. Adsorption offers advantages such as simple equipment, high selectivity, and environmental safety, making it suitable for small-scale or intermittent sources. However, its limitations include low adsorption capacity, high material costs, sensitivity to water vapor, and high regeneration energy requirements [8]. Current research focuses on developing new materials with high surface area, water resistance, and low cost, such as amine-functionalized MOFs and covalent organic frameworks (COFs) [9], while also promoting the modularization and automation of adsorption systems for industrial application.

3.2 Cryogenic Separation

Cryogenic separation is a technology based on phase changes of CO_2 under high pressure. The method compresses and cools a gas mixture so that CO_2 condenses or sublimates, thereby separating it from gases like N_2, O_2, or CH_4. Techniques include condensation separation and membrane-assisted cryogenic separation. The condensation method adjusts pressure and temperature to liquefy CO_2 near its critical point for recovery, suitable for gas streams with high CO_2 concentrations (e.g., cement kiln exhaust, natural gas processing). Membrane-assisted methods use selective membranes (e.g., polyimide, ceramic composites) for preliminary separation before compression, improving purity and efficiency. Cryogenic separation offers high separation purity (>99%), continuous industrial-scale operation, and applicability to large emission sources. However, it also involves high initial investment, significant energy consumption for compression and cooling, complex system design, and demanding process control. The technology has been successfully applied in several natural gas fields in Northern Europe, including Norway's Sleipner project, which has captured and geologically stored CO_2 continuously for over 20 years [10].

4. Future Outlook for CO_2 Capture and Storage

Despite notable progress, global CCS deployment still faces multiple challenges, including technical efficiency, cost, policy frameworks, and public acceptance. Future development is expected to evolve along several key dimensions:

4.1 Technological Innovation and Integrated Pathways

Improving system efficiency and broadening application scenarios will require integrating multiple capture technologies (e.g., adsorption + membrane, chemical absorption + cryogenic compression). In addition, CCUS—emphasizing resource utilization—has become a new research focus. CO_2 can be converted into methanol, methane, polymer monomers, or used for concrete curing and algae cultivation. Artificial intelligence and big data are also being applied in CCS systems to optimize processes, predict risks, and monitor leaks. Especially in geological monitoring, sensor networks and geophysical models enable real-time tracking of CO_2 behavior, increasing confidence among regulators and the public.

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4.2 Cost Optimization and Scale Deployment

High cost remains a major barrier. Traditional solvent-based capture methods are energy-intensive and corrosive, resulting in high unit costs. To reduce costs, innovations are needed in materials, processes, and scaling. Developing low-energy, durable adsorbents and membranes can reduce costs significantly. Process design should move toward integrated, modular systems to facilitate deployment and cross-industry adaptability. Additionally, CCS industrial cluster models—in which multiple enterprises share capture systems, pipelines, and storage facilities—are emerging to dilute costs through economies of scale.

4.3 Policy Support and Market Mechanisms

Policy is a crucial driver of CCS. Western countries have incorporated CCS into national emissions reduction strategies and provided funding for its development. In China, the 14th Five-Year Plan explicitly supports CCUS development, with pilot projects launched in Shandong, Inner Mongolia, and other regions. Moving forward, carbon taxes, emissions trading, and green finance must be strengthened to incentivize CCS deployment. Clear standards, safety regulations, and environmental assessments will also help build public trust and improve acceptance.

5. Conclusion

Carbon capture and storage (CCS) technology is an essential tool for achieving the “dual carbon” goals and mitigating global warming. It has moved from theoretical research to practical and commercial applications. This paper has analyzed the main sources of CO_2 emissions, identifying industrial sectors (such as power, steel, and cement) as priorities for CCS deployment. In terms of capture technologies, adsorption is promising for small-scale applications due to its simplicity and customization potential, while cryogenic separation is more suitable for high-volume industrial settings due to its efficiency and purity. Geological storage has matured, with projects like Norway’s Sleipner offering valuable experience. Looking forward, CCS must advance in four key areas:1. New materials and integrated pathways to enhance capture efficiency and adaptability. 2. Optimized system design to reduce energy use and costs. 3. Policy incentives and financial support to drive market adoption. 4. Improved standards and monitoring to ensure safety and public confidence.

In summary, CCS is not only vital for near-term emission reductions but also a foundational technology for achieving a long-term zero-carbon future. With coordinated progress across technology, policy, and market systems, CCS is poised to play an increasingly crucial role in global green transformation.

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