Dean&Francis
ISSN 2959-6157

Current Status and Future Prospects of Carbon Capture and Storage Technology

Mingyu Gao

Department of Groundwater Science and Engineering, Chang'an University, Xian, China
2023905959@chd.edu.com

Abstract:

Carbon Capture and Storage (CCS) is widely recognized as a pivotal technological solution for mitigating climate change and achieving global carbon neutrality goals. This article provides a systematic review of the entire CCS technological chain, elucidating its core principles and system components, which encompass three primary capture methods—pre-combustion, post-combustion, and oxy-fuel combustion—alongside the critical processes of transportation and geological storage. Through detailed examination of pioneering international projects, including China's Shenhua Ordos and Norway's Sleipner initiatives, this study analyzes the practical implementation pathways, operational experiences, and verifies the technical feasibility of large-scale CCS deployment. Furthermore, the review delves into the significant challenges currently impeding wider adoption, such as high economic costs, substantial energy consumption (the "energy penalty"), and long-term storage safety concerns. Finally, the article evaluates future development trends, highlighting the role of technological innovation, international policy support, and the evolving paradigm towards Carbon Capture, Utilization, and Storage (CCUS). This comprehensive review aims to serve as a valuable reference for understanding the potential, limitations, and future directions of CCS technology in the global effort to reduce carbon emissions.

Keywords: carbon capture and sequestration; climate change; carbon neutral.

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1. Introduction

Global energy-related carbon dioxide emissions are at a record high of 37.4 billion tons, an increase of 410 million tons or 1.1% compared to 2022 [1]. If land-use changes (such as deforestation) are included in the calculation, total global emissions are estimated to be 40.9 billion tons, the same level as in 2022. While the adoption of clean energy has partly slowed the growth of emissions, dependence on fossil fuels and extreme weather events (such as drought-induced shortages in hydropower generation) have continued to boost emissions. Without technologies like solar photovoltaics, wind power, and electric vehicles, emissions growth from 2019 to 2023 would have been three times higher than current levels. Global warming is one of the most severe environmental challenges facing the world today, and carbon dioxide is the most influential greenhouse gas contributing to this warming. Carbon dioxide (CO_2) emissions are the main factor causing climate change, posing significant risks to humanity and the planet through global warming, extreme weather events, and rising sea levels. The Intergovernmental Panel on Climate Change (IPCC) report states that CO_2 emissions must be reduced by 45% in 2030, compared to 2010 levels in order to limit global temperature rise to a certain threshold and achieve net-zero emissions by 2050 [2]. The Paris Agreement also proposed this objective, advocating for stabilizing atmospheric carbon dioxide concentrations below a certain threshold to limit global temperature rise this decade to well below that level. Achieving this target necessitates reducing atmospheric carbon dioxide levels. Carbon Capture and Storage (CCS) technology is recognized as one of the effective ways to reduce carbon dioxide emissions and achieve net-zero goals [3].

Given that CCS technology plays a critical role in achieving global carbon neutrality, this article aims to systematically review and summarize the CCS technology system and its current development status. First, this article will explain the core principles and processes of CCS technology, including the three main stages of capture, transportation, and storage. Second, it will analyze typical domestic and international project examples to evaluate their technical pathways and application effectiveness. Finally, it will explore the major challenges facing CCS technology (such as economic costs and energy consumption issues) and its future development trends. This article aims to provide a clear understanding of CCS technology's potential for emissions reduction, application bottlenecks, and development directions, as well as to offer a reference framework for China's relevant technology research and policy formulation.

2. The CCS Technological Chain

CCS technology is an integrated systems engineering project designed to separate carbon dioxide from industrial emission sources, compress and transport carbon dioxide, and eventually store it in underground geological formations or utilise it. The entire process primarily involves three core stages: capture, transport, and storage.

2.1 Carbon Dioxide Capture

The capture process aims to separate high-concentration CO_2 from flue gases emitted by industrial sources such as power stations, cement plants, and steelworks. Based on timing and operating principles, it is divided into three primary categories.

Pre-combustion capture involves converting fossil fuels into synthesis gas (syngas), primarily composed of CO and H_2 through gasification or reforming reactions prior to combustion. The CO from syngas is then converted into CO_2 and H_2 through water-gas shift, and then separated to produce high-concentration CO_2 [4, 5]. This method captures CO_2 at high concentrations and pressures, making separation easier, but the system is complex and is primarily used in integrated coal gasification combined cycle (IGCC) systems.

Oxy-fuel combustion capture uses high-purity oxygen (O_2) rather than air to combust fuel, producing flue gas primarily composed of CO_2 and H_2O. After cooling and dehydration, this flue gas yields highly concentrated CO_2 (up to 95% concentration) [4, 5]. This method avoids nitrogen dilution but is expensive due to oxygen production costs.

Post-combustion capture involves directly separating CO_2 from flue gas after combustion. This represents the most readily integrated solution with existing power plants. Common methods include chemical absorption (e.g., using amine solvents), physical adsorption, and membrane separation. While this technology is the most widely applicable, it faces challenges due to low CO_2 partial pressure in flue gas and relatively high capture energy consumption.

2.2 Carbon Dioxide Transportation

Captured CO_2 must be compressed to a supercritical state (to reduce its volume) and transported to the storage site. Primary transport methods include pipeline transport, ship transport, and tanker transport.

Pipeline transport is the most economical and reliable method for large-scale, long-distance transport, making it the first choice for land-based CCS projects. Ship transport is suitable for longer distances, medium-scale operations, or the storage site is offshore, offering high flexibility facilities. Road tanker transport is only viable for small-scale, short-distance operations, is extremely costly, and is typically used for demonstration projects or early-stage applications [4].

2.3 Carbon Dioxide Storage

Storage is essential for ensuring the long-term isolation of CO_2 from the atmosphere. Primary sequestration methods include geological storage, ocean storage, and mineral sequestration.

Geological storage involves injecting supercritical CO_2

ISSN 2959-6157

into sealed geological formations at depths exceeding 800 metres, using caprock to form a seal. This is the most prevalent and technically mature approach currently, with storage sites mainly comprising depleted oil and gas fields and mineral carbonation. Depleted oil and gas fields have clear geological structures and can utilise CO_2 for enhanced oil recovery (CO_2-EOR), yielding economic benefits. Deep saline aquifers, with their widespread distribution and substantial sequestration potential, represent a key future direction for storage [4].

Oceanic sequestration involves injecting CO_2 into the deep sea or venting it through pipes on the seabed, where high pressure and low temperatures cause it to dissolve or form solid hydrates. This method remains in the research phase due to substantial controversy surrounding its potential impacts on marine ecosystems.

Mineral sequestration utilises the reaction between CO_2 and natural silicate minerals (such as olivine and serpentine) to form stable carbonate minerals, achieving permanent storage. The technology is not mature, with slow reaction rates and high costs, but it offers the highest level of safety.

3. Global Application Examples of CCS Technology

3.1 The Shenhua Ordos CCS Project

The Shenhua Group's Ordos CCS Demonstration Project is the first project to achieve full-process carbon dioxide capture and storage at a scale of 100,000 tonnes per annum globally. This project captures carbon dioxide generated during coal direct liquefaction and injects it into saline aquifers within the Ordos Basin for permanent storage. Injection began in January 2011 and concluded in April 2015, with the actual injection period extending one year beyond the original schedule. The Ordos Basin, where the project is located, presents more complex geological conditions. Its successful implementation of CO_2 storage verifies the feasibility of sequestration under diverse geological structures. Regarding capture technology, the choice and optimisation approach differ due to variations in CO_2 concentration and composition within the gas source. For example, the relatively low concentration of carbon dioxide in power plant flue gas makes capture more challenging. In contrast, the coal-to-liquids project features exhaust gas with a higher CO_2 concentration, facilitating capture. Regarding sequestration, the project employs ultra-low permeability reservoir technology, providing valuable experience for regions with similar geological conditions in China. Regarding injection solutions, saline aquifer carbon dioxide geological sequestration projects typically employ fewer injection wells but deliver substantial volumes, predominantly using horizontal wells [6]. Several carbon capture research projects are currently under development, such as Sinopec Qilu Petrochemical's CCS initiative. China continues to intensify its research efforts in carbon capture, utilisation, and storage (CCUS) technologies, striving to enhance carbon capture capacity, reduce carbon emissions, and improve the ecological environment.

3.2 The Sleipner Project

The Norwegian Sleipner facility is the first commercial CCS project in the world, and also the first demonstration project to store carbon dioxide on a large scale in subsea geological formations. The project is located in the Sleipner West gas field in the Norwegian North Sea, in water depths of approximately 82 metres, and is operated by the Norwegian state-owned petroleum company (now Equinor). The project commenced operations in 1996, and is the world's first initiative to permanently store industrially emitted carbon dioxide underground. The primary driver for Norwegian companies undertaking this project was Norway's imposition of substantial carbon taxes on natural gas exports, which prompted businesses to develop emission reduction technologies.

In the Sleipner project, post-combustion capture methods are employed to capture carbon dioxide. Flue gas generated during natural gas processing contains low concentrations of carbon dioxide (approximately 3%–15%), which is chemically absorbed using liquid amine-based solvents such as monoethanolamine (MEA). The carbon dioxide is reacted with the solvent to form carbonates, which are subsequently heated or depressurised to release pure carbon dioxide for separation. During subsequent transport, the carbon dioxide is compressed to a supercritical state (temperature 37°C, pressure 8 MPa) and piped through an approximately 2.3-kilometre inclined shaft to the injection point for underground injection. The final sequestration phase project employs geological storage, injecting carbon dioxide into the Utsira brine aquifer approximately 800–1000 metres below the seabed. This formation consists of high-porosity sandstone (porosity 36–40%), overlain by a 200–300-metre-thick caprock of Nordland shale [7]. The carbon dioxide exists as a supercritical fluid with a density lower than water, enabling upward migration to the top of the formation where it is permanently sequestered by the shale caprock. The Sleipner project also employs comprehensive monitoring, including seismic and gravity monitoring. Seismic monitoring involves repeated three-dimensional towed seismic surveys to image the development of the injected CO_2 plume. By comparing seismic data from different years, the distribution and migration of CO_2 within the storage reservoir are analysed [8]. Gravity monitoring employs permanently installed reference stations on the seabed to measure gravitational changes, thereby estimating CO_2 mass variations and dissolution rates.

The project sequesters approximately one million tonnes of carbon dioxide annually. Since 2011, over 13 million tonnes have been stored, with projections indicating the project could sequester approximately 20 million tonnes over a 200-year operational lifespan [9]. Compared to post-combustion capture technologies commonly employed in other projects, this initiative utilises amine-based solvent capture. During desorption, flash separation and distillation enable highly efficient CO_2 desorption, achieving rates exceeding 95% [9]. As the world's first commercial CCS project, Sleipner's successful operation demonstrated the viability of scaling CCS technology from laboratory to industrial scale. It also proved the feasibility and safety of seabed saline aquifer storage, providing a model for global CCS deployment. The project's experience has been adopted into the CCS development roadmaps of the European Union and the International Energy Agency (IEA), accelerating global cooperation on carbon reduction technologies.

The successful implementation of these projects demonstrates the feasibility of scaling CCS technology from theoretical concepts to large-scale application, providing invaluable engineering experience for global emissions reduction. Nevertheless, achieving the worldwide deployment of CCS technology required to meet climate targets remains subject to a series of significant economic, technical, and societal challenges.

4. The Economic Viability and Technical Challenges of CCS Technology

4.1 Energy Consumption and Efficiency Issues

The operation of CCS systems itself consumes substantial energy. During the capture phase, particularly in post-combustion chemical absorption methods, solvent regeneration demands significant thermal energy, while compressing CO_2 to a supercritical state requires considerable electrical power. This directly results in power plants expending more fuel on their own carbon capture rather than generating electricity for external supply, reducing net power generation efficiency by approximately 13% to 44% [2]. Secondly, CO_2 transportation and post-monitoring storage further increase energy demands and may produce CO_2 emissions. Fundamentally, while CCS reduces CO_2 emissions, it may simultaneously diminish overall productivity or efficiency. Consequently, CCS systems must be powered by low-carbon energy sources; otherwise, their net emission reduction benefits will be significantly diminished.

4.2 Economic Challenge

The high cost of CCS projects is the most significant barrier to their development. Firstly, substantial capital expenditure and operational costs are required. A power plant equipped with a CCS system necessitates additional expensive equipment for capture, compression, transport, and injection compared to a conventional plant. According to the IPCC report, its energy costs are 10% to 40% higher [2]. This requires substantial initial investment, while ongoing operational costs are further increased by consumable replacements (such as amine solvents), equipment maintenance, and electricity consumption. Secondly, the full lifecycle cost is a significant concern. The operational lifespan of CCS equipment (approximately 40 years) is shorter than that of many power plant structures. This implies that CCS facilities may require replacement or major refurbishment during the plant's operational lifetime, substantially increasing the total lifecycle cost [10]. Finally, financing models and policy dependence remain critical. The economic viability of CCS projects currently hinges heavily on policy support such as carbon pricing, government subsidies, and tax incentives. For example, the Norwegian Sleipner project was directly driven by carbon taxation. Without stable and sufficiently high carbon market prices or policy incentives, CCS projects struggle to achieve commercial profitability.

4.3 Long-term Storage Security and Monitoring

To ensure CO_2 is permanently and securely sequestered while gaining public trust is pivotal to securing societal acceptance for CCS technology. Although the IPCC indicates that over 99% retention rates within 100 years are achievable with meticulous site selection and management, potential leakage risks persist, potentially occurring through faults, fractures, or abandoned wellbores [2]. Such leaks would not only negate emission reduction efforts but could also pose hazards to local ecosystems and human health. Monitoring, reporting and verification (MRV) requirements necessitate establishing long-term, efficient and cost-controlled monitoring systems (such as seismic and gravity monitoring employed in the Sleipner project) to verify storage integrity and develop corresponding remediation measures and accountability mechanisms. The establishment and operation of such systems entail substantial costs. Since CCS involves underground injection, its complexity and potential risks are often poorly understood by the public, readily triggering Not In My Backyard effects. Lack of community support and transparency may lead to project delays or outright rejection. Consequently, effective public communication and science education are important.

5. The Development Trend and Policy Support of CCS Technology

5.1 International Policies and Cooperation Agreements

The international community's emphasis on CCS technology is reflected in multiple climate agreements. The Paris Agreement established global temperature rise control targets, prompting nations to incorporate CCS into their Nationally Determined Contributions (NDCs) and long-term low-carbon strategies [10]. The IPCC particularly emphasises that CCS must shoulder approximately 32% of the emissions reduction burden to achieve the 1.5°C temperature control target, establishing its irreplaceable status [2]. In practice, the United States currently operates 15 large-scale CCS facilities, capturing around 0.4% of the nation‘s annual emissions, with over 121 projects in the development pipeline [3]. The Chinese government is also actively advancing CCS technology demonstrations, with 11 projects currently operational to support its 2030 carbon peak and 2060 carbon neutrality targets[3]. In terms of policy instruments, the United States has significantly enhanced CCS economic viability by expanding the Section 45Q tax credit and providing direct funding (such as the 2023 investment of one billion US dollars to support two million-tonne-scale carbon removal projects). China, meanwhile, leverages preferential electricity prices, tax relief, and dedicated research programmes to drive technological implementation. The European Union also provides funding and market incentives for CCS projects through innovation funds and its Emissions Trading System (ETS). Collectively, these international initiatives are propelling CCS technology from pilot schemes towards large-scale deployment.

5.2 Direction of Technological Innovation

CCS technology is advancing rapidly towards lower energy consumption, reduced costs, and diversified applications. In the capture stage, the development of novel membrane materials, phase-change solvents, and adsorbents has significantly decreased energy consumption and operational costs. For example, membrane separation methods are progressively replacing traditional amine absorption processes due to their compact equipment and low energy requirements. In the storage phase, advances in intelligent monitoring and risk prediction technologies have enhanced the safety of geological storage and public confidence. Concurrently, CCUS technology has expanded pathways for carbon dioxide resource utilisation, including synthesis into methanol, plastics, and carbonated beverages. It also enables biofuel production via microalgae carbon fixation or application in enhanced oil recovery (EOR), generating economic benefits while achieving sequestration. The IEA projects that by 2030, the unit cost of CCS emissions reductions could fall to US$35–60 per tonne, rendering it competitive within carbon pricing markets [11]. Furthermore, CCS systems coupled with renewable energy sources—such as green electricity and green hydrogen—are emerging as a key area of exploration. This integration holds promise for fundamentally resolving the energy penalty associated with CCS, thereby enabling near-zero emission cycles.

5.3 The Expansion of Resource Utilization

CCUS represents a technology evolution based on CCS that prioritises utilisation, focusing not only on carbon sequestration but also on its circularity and economic value. Carbon dioxide can serve as a chemical feedstock in synthesis reactions, such as producing methanol, urea, and biodegradable plastics. It can also be applied as a gas fertiliser in agriculture to enhance crop yields, or employed in EOR during hydrocarbon extraction, simultaneously achieving carbon storage and improved recovery rates. Resource utilisation significantly improves the economics of CCS projects, providing a pathway to commercial viability. In the future, as carbon product markets expand and conversion technologies mature, CCUS holds promise as a new growth driver for the low-carbon economy. It will form an integrated capture-utilisation-storage closed-loop system, propelling high-carbon industries towards a green circular transition.

6. Conclusion and Outlook

6.1 Conclusion

This article has systematically reviewed the Carbon Capture and Storage (CCS) technology framework, detailing its fundamental principles and the integrated processes of capture, transport, and storage. The analysis confirms CCS as a critical technological pathway for achieving deep decarbonization, particularly within hard-to-abate sectors such as power generation, cement, and steel manufacturing. Its indispensability stems from its unique ability to directly mitigate industrial emissions where other alternatives are limited. The examination of full-chain demonstration projects, including the Shenhua Ordos project in China and Norway's landmark Sleipner facility, provides robust evidence of the technical feasibility of large-scale CO_2 capture and secure geological storage. These projects have yielded invaluable operational data and engineering benchmarks. However, the current state of CCS deployment faces significant headwinds. Major barriers persist, including high capital and operational expenditures, substantial energy penalties—especially during the capture stage—and enduring concerns regarding long-term storage integrity and public acceptance. Therefore, overcoming these challenges is a prerequisite for the technology's widespread adoption.

6.2 Outlook

This article provides a systematic overview of the CCS technology framework, offering a comprehensive theoretical reference for CCS technological advancement. However, there are still limitations, such as the absence of quantitative comparisons between different technical pathways and a lack of in-depth analysis of regional policy environment variations. Future research may focus on areas such as life-cycle assessment (LCA), geographic information system-supported potential storage analysis, and economic modelling of CCUS product chains. Concurrently, comparative international studies and interdisciplinary collaboration should be strengthened, with particular emphasis on synergistic innovation mechanisms linking policy, market, and technology. Only through continuous technological iteration, effective policy incentives, and broad public engagement can CCS technology genuinely underpin the achievement of global climate objectives.

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