Advances and Challenges in Carbon Capture and Storage Technology

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Abstract. Continuously rising CO_2 emissions are exacerbating the climate crisis, making carbon capture and storage (CCS) technology a key pathway for industrial decarbonization and achieving net-zero emissions targets. This review systematically summarizes global CCS technology developments since 2018, covering capture processes (solvent absorption, adsorption, membrane separation), transportation strategies, geological storage mechanisms, and resource utilization pathways. Research indicates that material innovations (e.g., phase-change solvents reducing regeneration energy consumption by 30–50%) and AI monitoring (plume tracking accuracy reaching 92%) have yielded significant results. However, large-scale application still faces three major bottlenecks: excessively high capture energy consumption (>3.5 GJ/tCO_2), economic cost imbalance (costs of 60–120 USD/ tCO_2 far exceed carbon prices), and a public trust deficit (75% of projects in Europe faced opposition). Fragmented policy frameworks and inconsistent technical standards further hinder development. Ultimately, overcoming CCS challenges requires integrating multi-dimensional strategies, developing low-energy materials, standardizing risk assessment models, and strengthening interdepartmental collaboration to achieve sustainable deployment goals by mid-century.

Keywords: Carbon Capture and Storage, Energy Efficiency, Geological Storage, Carbon Pricing Mechanisms

1. Introduction

1.1. Global climate change and the urgency of emissions reduction

Global climate models have confirmed that climate change has significantly increased the frequency and intensity of extreme weather events, particularly extreme precipitation and heatwaves. Satellite observations and ground-based monitoring data consistently show that CO_2 concentrations have continued to rise in recent years. Reports from the National Aeronautics and Space Administration (NASA) and the United Nations (UN) indicate that the annual growth rate far exceeds pre-industrial levels [1]. According to UN reports and model analyses under the Paris Agreement, to limit global warming to 1.5°C, global CO_2 emissions must be reduced by 43% by 2030 and achieve "net-zero" emissions by 2050, necessitating a profound transformation of the global energy system[2]. This target imposes unprecedented urgency on developing global low-carbon technologies, prompting governments in many countries have successively released carbon neutrality roadmaps, committing to achieving carbon neutrality targets by 2050. Among these, carbon capture and storage (CCS) technology, as a key negative emission technology, will play an indispensable role in capturing carbon emissions from industries that are difficult to reduce and removing existing carbon dioxide from the atmosphere to achieve the "net-zero" target. This goal has placed unprecedented urgency on the development of global low-carbon technologies, prompting governments around the world to successively release carbon neutrality roadmaps and commit to achieving carbon neutrality by 2050.

1.2. The importance of CCS technology

CCS has been recognized by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) as one of the key pathways for controlling CO_2 emissions, particularly important for reducing emissions from industrial sources. The core processes of this technology primarily include three stages: carbon capture, carbon transportation, and carbon storage. Carbon capture involves separating CO_2 from industrial emission sources or the atmosphere. Key technologies include post-combustion capture (using chemical solvents to absorb CO_2 from flue gas), pre-combustion capture (separating CO_2 after fuel gasification), and oxy-fuel combustion (using pure oxygen to generate high-concentration CO_2). Carbon transportation involves compressing captured CO_2 into a supercritical fluid and safely transporting it via pipelines, ships, or tankers to storage sites, with continuous leak detection monitoring throughout the process. Carbon storage involves injecting CO_2 into underground geological formations (such as depleted oil and gas fields or deep saline aquifers) and achieving permanent storage through physical containment or mineral solidification, with ongoing monitoring to ensure safety [3].

In high-emission industrial sectors such as coal-fired power generation, steel, cement, and chemicals, CCS can significantly reduce direct CO_2 emissions and is a key technology for achieving "deep decarbonization" in these industries. For the power sector, integrating CCS into coal-fired or gas-fired combined-cycle power plants can achieve emissions reductions while maintaining baseload generation capacity; In the oil and gas sector, CO_2 enhanced oil recovery (EOR) technology can both increase oil and gas recovery rates and achieve partial CO_2 sequestration. CCS technology provides an important emissions reduction supplement for industries that are difficult to fully decarbonize through zero-emission pathways (such as aviation, steel, and chemicals), and is a key enabler for achieving the 2050 "carbon neutrality" target.

1.3. Scope and objectives of the review

As CCS technology continues to advance in laboratories and demonstration projects, the number of studies on CCS economic models, life cycle assessment (LCA), and policy incentives has significantly increased since 2018, covering regions such as North America, the European Union, and China. These studies have explored various aspects, including CO_2 capture materials, system optimization, storage monitoring, cost assessment, and policy formulation. However, there are significant differences in research priorities among countries, particularly regarding carbon pricing mechanisms, regulatory frameworks, and public acceptance.

This review aims to integrate core literature since 2018, systematically review the latest research progress on various CO_2 capture technologies, analyze the current status of engineering practices and risk management for CO_2 transportation and geological storage pathways, and explore the impact of policy and economic incentive mechanisms on the large-scale promotion of CCS technology, with the aim of providing a comprehensive reference for future research.

2. Progress in key stages of the CCS technology chain

2.1. Capture technologies

As the starting point of the CCS process and its primary cost driver, innovation in capture technologies is critical for reducing the overall system energy consumption and economic barriers. This section will first review the optimization achievements and inherent limitations of conventional capture methods, followed by a focused analysis of emerging technological development pathways with significant energy-saving potential.

2.1.1. Traditional capture methods

Traditional capture methods in CCS technology primarily include three mature processes: post-combustion capture, pre-combustion capture, and oxy-fuel combustion.

Post-combustion capture uses chemical solvents (such as amine solutions) to separate CO_2 from industrial flue gas (CO_2 concentration 4%-15%), suitable for retrofitting existing power plants and heavy industrial facilities. However, this technology suffers from significant drawbacks: solvent regeneration energy consumption accounts for 60%-70% of capture costs [4], leading to a significant reduction in system energy efficiency.

Pre-combustion capture generates high-concentration CO_2 (15%-40%) through fuel gasification and water-gas shift reactions, combined with physical adsorption methods (such as pressure swing adsorption) for efficient separation. This technology is suitable for integrated gasification combined cycle (IGCC) systems and can co-produce clean hydrogen. However, its main limitation lies in its reliance on new gasification facilities and high initial investment costs [5].

Oxy-fuel combustion uses high-purity oxygen (>95%) to replace air for combustion, producing flue gas primarily composed of CO_2 (concentration 80%-98%). After condensation and dehydration, it can be directly stored, significantly simplifying the capture process. However, the high energy consumption of air separation units (ASUs) for oxygen production accounts for 30%–40% of operational costs, and high-temperature corrosion-resistant equipment is required [6].

Overall, the aforementioned traditional methods are based on mature chemical engineering technologies but face core obstacles such as high capture energy consumption (reducing power plant efficiency by 20–30%) and economic constraints (capture costs of approximately $40-80 per ton of CO_2), severely limiting their large-scale application. To overcome these limitations, next-generation technologies (such as chemical looping combustion, novel membrane separation, and low-energy solvents) are currently under active development.

2.1.2. Emerging technologies

Electro-swing Carbon Capture (ESC) is based on electrochemical oxidation-reduction reactions, utilizing electroactive adsorbents such as quinone-based polymers. CO_2 adsorption is driven by applying a voltage, and high-purity CO_2 is released in the reverse direction after power is disconnected. It can be directly coupled with renewable energy electricity (such as wind power or photovoltaic power), completely avoiding the high-temperature steam regeneration requirements of traditional amine-based methods, with theoretical energy consumption as low as 1 GJ/t-CO_2. However, the main challenges facing this technology include the long-term cycling stability of electrode materials not yet meeting the requirements for large-scale application, and the integration costs of large-scale electrochemical systems still needing further optimization.

Phase-change solvents such as dimethylcyclosiloxane mixture (DMX) and blended systems of 2-amino-2-methyl-1-propanol (AMP)/diethylethanolamine (DEEA) trigger phase separation after absorbing CO_2. In the DMX system, only the CO_2-rich phase enters the regeneration unit, significantly reducing regeneration energy consumption and solvent loss. However, their stability under complex flue gas compositions still needs to be validated [7].

Chemical Looping Combustion (CLC) uses metal oxides as oxygen carriers to achieve CO_2 separation within the fuel reactor, offering advantages of low energy consumption and high purity. This technology has demonstrated high efficiency and near-zero emissions potential in experimental systems, but it still faces challenges such as oxygen carrier costs and reactor wear.

2.2. CO_2 transportation

The safe and efficient transportation of CO_2 is a critical component of its journey from capture sources to storage or utilization sites, primarily relying on two methods: pipelines and ships. Pipeline transportation involves conveying CO_2 in a supercritical state (approximately 31°C, 7.38 MPa) through high-pressure pipeline systems to storage or utilization sites [8]. Ship transportation is a flexible method that uses cryogenic storage tankers to liquefy CO_2 (-50°C, 0.7 MPa) and transport it in modular form via sea or river transport, suitable for long-distance or cross-border projects [9]. Transportation costs and influencing factors are the focus of this section.

2.2.1. Transportation cost model

The transportation cost model is constructed based on dense-phase fluid dynamics and logistics optimization theory, with core variables including distance, flow rate, terrain, and CO_2 purity. The pipeline transportation cost function is typically expressed as:

$$C_p = a \times L + b \times Q^{-0.7} \tag{1}$$

where L is distance (km), Q is flowing rate (million tones/year), and coefficients a and b are influenced by terrain and materials.

The shipping cost function is expressed as:

$$C_s = c \times L \times Q^{-1} + d \tag{2}$$

where c and d are ship operation coefficients. Pipeline transportation has a significant economic advantage in short-distance scenarios (typically $L < 300$ km), with a unit cost of approximately 2–5 \$/ton of CO_2 [10]. Conversely, shipping is more cost-effective for cross-sea or ultra-long-distance ($L > 1{,}500$ km) transportation, with a unit cost of approximately 15–30 \$/ton CO_2 [11].

2.2.2. Factors influencing transportation costs

CO_2 purity is critical for corrosion prevention, as impurities (such as O_2 and H_2O) increase corrosion and energy consumption risks terrain elevation significantly impacts construction costs, with each 100-meter elevation difference potentially increasing construction costs by 7–10%. Additionally, cross-border approval cycles and regulatory complexity significantly influence investment decisions and timelines.

2.2.3. Application cases

Pipeline Transportation Case (Cortez Pipeline, United States): This pipeline spans 800 km with an annual transportation capacity of 14.5 million tons, utilizing supercritical conditions (pressure 10–15 MPa) for transport, with a unit cost of approximately $3.2/ton. However, the construction costs for the mountainous sections exceeded the budget by 40%, highlighting the significant impact of terrain factors [12].

Marine Transportation Case (Northern Lights Project, Norway): This project is designed to transport liquid CO_2 (–50 °C) by ship to a storage site in the North Sea, with estimated shipping costs of $18 per ton. Compared to the land-based pipeline alternative ($32 per ton), this demonstrates the economic advantages of shipping in specific scenarios [13].

2.2.4. Model limitations

Although the aforementioned transportation cost models provide an important framework for evaluating the economic viability of pipeline and ship-based solutions, existing models still have certain limitations that must be considered in decision-making. On one hand, the models may underestimate the accelerated corrosion effects of impurities in CO_2 (such as H_2S and water vapor) on pipeline materials and the resulting additional maintenance costs. On the other hand, the market volatility of carbon pricing mechanisms (such as the European Union Emissions Trading System (EU ETS)) poses challenges to the accuracy of long-term transportation cost predictions.

2.3. Geological storage monitoring technologies

Geological carbon storage represents a crucial phase in the secure and permanent sequestration of captured CO_2 beneath the Earth's surface. Its long-term safety and stability fundamentally rely on advanced monitoring technologies capable of detecting potential leaks or formation shifts. Current mainstream storage site types and emerging monitoring technologies are now pivotal research priorities.

2.3.1. Mainstream storage reservoirs

Geological storage primarily relies on two types of mainstream reservoirs. Depleted oil and gas reservoirs offer lower storage costs due to their ability to utilize existing drilling infrastructure and abundant geological data (e.g., the successful experience of the North Sea Sleipner project) [14]. Deep saline aquifers possess significantly greater global storage potential, but their heterogeneous pore structures significantly increase the difficulty of predicting CO_2 migration pathways underground, leading to higher uncertainty and risk [15].

2.3.2. Advanced monitoring technologies

To ensure the long-term safety and integrity of geological storage, advanced monitoring technologies are undergoing rapid development, with the application of artificial intelligence (AI) being particularly prominent. Convolutional neural network (CNN)-based plume migration monitoring technology analyzes and processes time-series microseismic data to automatically identify and precisely track the dynamic migration paths of underground CO_2 plumes, with current model recognition accuracy exceeding 92%. By integrating high-precision surface deformation data obtained from satellite interferometric synthetic aperture radar (InSAR) with real-time wellhead pressure sensor information, a high-resolution three-dimensional leakage risk mapping technology has also been preliminarily deployed in multiple projects [16].

2.3.3. Application cases

In Salah Project, Algeria: The research team deployed a distributed acoustic sensing (DAS) fiber optic network and combined it with a CNN model for real-time data analysis, successfully achieving continuous monitoring of caprock stress evolution during CO_2 injection and effectively warning of potential fault activation risks 14 days in advance [17].

Aquistore Project, Canada: This project innovatively combined drone-mounted multispectral imaging technology with in-well fluid sampling to construct a dynamic leakage probability assessment model. This integrated monitoring method not only enhanced risk warning capabilities but also significantly reduced overall monitoring costs by 37% [18].

2.3.4. Technical challenges

Geochemical complexity remains the core challenge for deep saline aquifer storage. CO_2-mineral reactions (such as calcite precipitation) leading to pore blockage have not yet been adequately quantified by AI monitoring models [19]. Current digital twin integration predictions for century-long storage periods still have errors exceeding 30%. Future breakthroughs require the deep integration of digital twin technology with in-situ sensor networks to achieve more precise geological-chemical coupling process simulation and long-term predictions.

3. Challenges and recommendations for the development of CCS technology

Although carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) technologies hold great promise, their large-scale deployment still faces multiple challenges at the technical, economic, and social levels. This section will systematically review these core obstacles and propose corresponding optimization recommendations based on existing research.

3.1. Technical barriers

In the capture process, the energy consumption of traditional amine-based solvent regeneration is extremely high (3.5–4.2 GJ/t-CO_2), accounting for 60–70% of operational costs, while high-temperature environments exacerbate equipment corrosion (at a rate of approximately 0.5 mm/year). Although novel materials such as metal-organic frameworks (MOFs) demonstrate high adsorption potential (up to 12 mmol/g, far exceeding zeolite's 1.2 mmol/g), their large-scale production costs are prohibitively high (approximately $120/kg, far exceeding traditional adsorbents' <$15/kg), and they are highly sensitive to humidity, with efficiency degradation reaching up to 40% under actual operating conditions. For example, the U.S. NET Power plant employs innovative supercritical CO_2 cycle technology to reduce capture energy consumption to 1.8 GJ/t-CO_2, but its reliance on specialty alloy materials extends the investment payback period to over 12 years [20]. Therefore, overcoming material cost and energy consumption barriers is the top priority for advancing capture technology commercialization.

In the storage phase, deep saline aquifer storage faces complex geochemical reaction challenges, such as secondary mineral precipitation (e.g., calcite >35%) caused by CO_2-brine-rock interactions, resulting in annual pore blockage rates of 2–5%, directly affecting storage capacity and safety. More critically, existing AI-based monitoring models (e.g., using CNN to process microseismic data) still exhibit prediction errors exceeding 30% for century-long storage periods [21]. Notably, the European Union (EU) Advanced In-Situ Monitoring of Sealing (AIMS) project developed iron-based nanoparticle tracers and X-ray computed tomography to quantitatively assess mineral blockage dynamics in real time, improving prediction accuracy to 88%. While this advancement holds promise, its long-term reliability requires further validation. In summary, there is an urgent need to integrate digital twin technology with in-situ sensor networks to construct more accurate geochemical coupling models to address the challenges of long-term storage safety prediction.

3.2. Economic challenges

Technological development is severely constrained by insufficient economic incentive mechanisms, creating a vicious cycle. Currently, only 21% of global industrial emissions are covered by carbon pricing mechanisms, and carbon prices vary significantly across regions (EU ETS $90/t vs. China carbon market $8/t), weakening investment incentives for CCUS. In CO_2 resource utilization, only approximately 15% of enhanced oil recovery (EOR) projects achieve true "net sequestration," while the remaining 85% ultimately re-release CO_2 due to the combustion of extracted crude oil. Financial institutions often classify CCUS technologies as high-risk in their risk models (e.g., "Technology Readiness Level 3"). Technologies with long payback periods (>15 years), such as algal bio-capture, lack effective risk mitigation instruments. The liability sharing and green bond financing model of Norway's Northern Lights project is a case of innovative model worth emulating. Therefore, establishing an effective carbon pricing mechanism, developing innovative financing tools (such as green bonds and risk guarantees), and clarifying the allocation of responsibilities between governments and enterprises are key to overcoming economic bottlenecks.

3.3. Social issues

The promotion of CCUS also faces obstacles in terms of institutional environment and public awareness. At the policy and regulatory level, there are at least nine different geological storage risk assessment frameworks globally (e.g., the United States Environmental Protection Agency (EPA) Class VI and EU Carbon Storage Directive (CSD) regulations), leading to lengthy and costly duplicate certification processes for cross-border projects. Additionally, technology transfer barriers are significant, with CCUS-related patent conversion rates in developing countries at approximately 8% (far below the 42% in developed countries), partly due to export restrictions on critical materials under agreements like the Wassenaar Arrangement. Second, public acceptance remains a significant hurdle, with up to 75% of CCS projects in Europe facing community opposition. The primary reasons are twofold: first, ineffective risk communication, as the public often overestimates the probability of leaks by 100 times; second, unequal distribution of benefits, as projects often fail to adequately safeguard local community interests (e.g., the Dutch Porthos project did not explicitly commit to local employment quotas) [22]. The successful experience of the Canadian Quest project is worth learning from. By establishing a "Community Co-governance Committee" and publicly disclosing real-time monitoring data on storage, transparency and community participation were significantly enhanced, with public acceptance rates rising sharply from 34% to 79%. Enhancing public trust requires transparent communication mechanisms, effective risk education, and ensuring that communities benefit fairly from the project.

3.4. Development recommendations

Based on the aforementioned challenge analysis, the core research directions for promoting the large-scale development of CCUS technology can focus on the following three technical areas:

Capture Material and Process Innovation: Prioritize the development of low-cost, high-stability, and low-energy-consumption next-generation capture materials (such as optimized MOFs, new membrane materials, and bio-based adsorbents) and processes (such as phase-change solvents, electrochemical capture, and chemical looping combustion), with a focus on addressing engineering scaling challenges and adaptability in complex gas environments.

Intelligent Storage Monitoring and Prediction: Deeply integrate artificial intelligence (AI), digital twin technology, and dense in-situ sensor networks to build a high-precision, multi-scale geological storage dynamic simulation and real-time risk warning platform, significantly improving the reliability of predictions for long-term storage effects (particularly deep saline aquifer geochemical reactions).

System integration and negative emission pathways: Advance the integration and optimization, cost reduction, and commercial viability verification of negative emission technologies such as biomass energy carbon capture and storage (BECCS) and direct air capture (DACCS), and exploring their synergistic pathways with renewable energy, hydrogen energy, and other systems.

4. Conclusion and outlook

4.1. Conclusion

This review systematically summarizes the research progress of CCS technologies since 2018. In terms of capture technologies, traditional methods (absorption, adsorption, membrane separation) continue to be optimized, while emerging technologies such as electrochemical capture, phase-change solvents, and chemical looping combustion show significant potential for reducing energy consumption. Economic models for the transportation phase are gradually being refined, with clearer definitions of the applicable scenarios and cost structures for pipeline and ship transportation. Geological storage, as a critical phase, primarily utilizes depleted oil and gas reservoirs and deep saline aquifers. Advanced monitoring technologies enabled by artificial intelligence (such as CNN plume tracking and InSAR leakage risk mapping) are significantly enhancing the safety oversight capabilities of storage operations. Additionally, the resource utilization pathways for CO_2 in enhanced oil recovery, fuel synthesis, and mineral solidification are continuously expanding.

However, the large-scale deployment of CCUS technology still faces significant challenges: Technologically, the high energy consumption and material costs of the capture process, as well as the long-term stability and precise prediction challenges of the storage process, require urgent breakthroughs; Economically, the absence of carbon pricing, financing difficulties, and the uncertainty of the “net storage” effects of resource utilization pathways constitute major obstacles; socially, fragmented policies and regulations, technical transfer barriers, and a lack of public trust severely constrain project implementation. These challenges are intertwined, highlighting the need for a multi-dimensional approach involving technological breakthroughs, economic incentives, policy coordination, and social participation to drive CCUS development.

4.2. Outlook

Although this review aims to systematically summarize the research progress and challenges of CCS technology since 2018, it still has certain limitations. The paper cites a large amount of technical performance data (such as energy consumption and costs), but due to differences in boundary conditions, evaluation methods, and assumptions across studies, rigorous quantitative comparisons are challenging. It is recommended that future research establish a more unified standard evaluation framework (such as standardized Life Cycle Assessment or Techno-Economic Analysis models) to objectively compare the advantages and disadvantages of different technologies.

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