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The Potential and Deployment Barriers of Carbon Capture and Storage Technology

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Abstract. Carbon capture and storage (CCS) is a pivotal technology for combating climate change and achieving carbon neutrality, yet its large-scale deployment faces multiple challenges. A systematic analysis of the role, development status, and constraints of CCS technology in global emission reduction reveals an unevenly developed technology chain, presenting systemic bottlenecks such as high energy consumption, elevated costs, insufficient infrastructure, a lack of policy incentives, and low social acceptance. Addressing these barriers necessitates a synergistic approach that integrates technological innovation, policy incentives, and social consensus. Key measures include developing low-energy consumption capture technologies and novel storage solutions to improve economic viability, enhancing commercial feasibility through carbon pricing mechanisms and tax credits, and strengthening storage safety monitoring with transparent data disclosure and community benefit-sharing to alleviate social concerns. The analysis concludes that substantial support from CCS technology for the global carbon neutrality goal is contingent upon holistic advancement across technology, policy, and societal engagement.

Keywords: Carbon capture and storage; carbon neutrality; policy incentives.

1. Introduction

Carbon dioxide (CO_2), as the most important greenhouse gas, has continued to rise in concentration, leading to a series of serious environmental problems, such as global warming, rising sea levels and frequent extreme weather events. To combat climate change, the Paris Agreement proposes to limit global temperature rise to 2℃ and effort to limit it to 1.5℃, which puts higher demands on global carbon emission reduction. Carbon capture and storage (CCS) is a technology that captures CO_2 from the air, transports it and permanently seals it underground [1]. The continuous growth of global carbon emissions and the urgency of carbon neutrality targets (IPCC AR6) have made CCS a core technology for solving the problem of hard-to-abate industries (steel, cement, etc.). The pivotal role of CCS as a transitional technology towards a low or zero emission future has been highlighted by a number of recent publications [2, 3]. And the International Energy Agency's Net Zero Roadmap states that failing to deploy CCS at scale will add an extra 15 per cent to the abatement costs of the 2050 carbon neutrality target. Moreover, meeting climate targets without adopting CCS would mean up to 138% increase in total discounted mitigation costs [4]. As early as the 1980s, countries around the world have begun the research and engineering demonstration of CCS technology, such as the Norwegian Sleipner project, the German Black Pump power plant project, the Icelandic CarbFix project and so on. Among them, the Black Pump Power Plant project in Germany was started on 9 September 2008 by Swedish Waterfall Power in Sprengberg, north-eastern Germany, with an installed capacity of 30MW, which is the world's first coal-fired power plant capable of capturing and sequestering its own CO_2 production [5].

Although the maturity of each link in the CCS technology chain varies, and most of the global projects are in the preliminary stage, focusing on regions such as North America, Europe, and Australia, and its further development is still faced with challenges such as high cost and lack of public awareness, CCS still exhibits significant development potential through continuous technological innovation and policy support. The purpose of this paper is to systematically review the current development status of CCS technology, assess the gap between its technical potential and its practical application, analyse the major systemic and structural challenges it is currently facing, and explore feasible technological breakthroughs and policy support paths, with a view to providing references for the global promotion and commercial application of CCS technology.

2. Global Status of Carbon Capture and Storage Technology

2.1. Status of Carbon Capture and Storage Technology

The CCS technology chain consists of three links: capture, transport and storage, and the development of each link is currently uneven. In the capture chain, post-combustion capture technology has become a mainstream solution by virtue of its compatibility with in-service power plants, but its high energy consumption is a major obstacle to its large-scale diffusion. After a typical coal-fired power plant is retrofitted with a post-combustion capture system, the net power generation efficiency will be reduced by 15-25%, which is equivalent to the consumption of 300-400 kWh of energy per tonne of CO_2 captured [6]. Oxy-fuel combustion technology (capture in combustion), on the other hand, can increase the capture concentration to more than 90%, but is limited to new construction projects due to the high investment in the air separation unit (about 40% of the total system cost) [7]. When considering cost and efficiency, the most economic value at present is pre-combustion capture. This method involves the gasification of fossil fuels to a mixture of H_2 and CO followed by their conversion to CO_2 through a chemical reaction and the separation of H_2 from CO_2 using adsorption technology. This process is based on the classical water gas shift process and is significantly economical. However, this technology is currently mainly applied to the overall coal gasification combined cycle power generation system, and the equipment covers a large area, the initial investment is high, resulting in the actual commissioning of fewer projects based on this technology, so it needs to be further verified in the future by more engineering practice to further validate its feasibility and economic benefits. Direct air capture (DAC) represents the most disruptive approach, with a modular design that allows for flexible deployment in non-point source emission areas, such as Swiss startup Climeworks' Orca plant in Hellsheidi, Iceland, which absorbs 4,000t CO_2 per year, and Global Thermostat's pilot plant in Meccanes, Chile, which removes up to 25 kg of CO_2 from the atmosphere every hour. Global Thermostat's pilot plant in Magallanes, Chile, removes up to 25 kg of CO_2 per hour from the atmosphere, sequesters the CO_2 in basalt rock hundreds of metres underground, and uses geothermal heat to power the plant, making it the world's largest direct airborne carbon capture and sequestration plant. However, the only drawback is that it costs \$150-600/t CO_2 at this stage and is highly dependent on cheap renewable energy sources, making it impossible to achieve large-scale use [8].

Early CCS technologies include marine storage, geological storage and surface mineral carbonation, and current storage technologies include geological storage, mineral storage, biological storage and other different types, of which geological storage dominates with mature engineering experience [5]. For example, the Norwegian Sleipner project makes use of the brine-containing strata that exist underground, which are not economically valuable and can precisely store CO_2. Since its operation in 1996, it has safely stored more than 20 million tonnes of CO_2 in the Utsira strata of the North Sea, which has verified the long-term stability of saline aquifer sequestration, and is the world's first commercial carbon capture and sequestration project [9]. Mineralisation storage is also nowadays developing rapidly as an innovative project, and the CarbFix project in Iceland is a good typical example, which achieves 95% CO_2 curing rate within 2 years and dramatically reduces the risk of leakage by injecting CO_2 into a basalt layer to generate carbonate minerals with the help of calcium and magnesium ion reactions [6]. As one of the most common rock types on the Earth's surface, basalt is widely distributed, covering about 5 per cent of the continental area and most of the seabed, and is rich in calcium, magnesium, iron and other elements, and is a highly chemically active rock, with these components capable of reacting with CO_2 and fixing it permanently. At the same time, its naturally loose and porous physical structure facilitates the penetration and contact of carbonic acid solutions, which significantly promotes the carbon fixation reaction. In addition, the bio-sequestration pathway, in which the carbon sequestration capacity of gene-edited microalgae has reached 100t of CO_2/hectare per year, provides new ideas for carbon sequestration in some cities in the coastal region.

2.2. Analysis of Transport Efficiency and Energy Consumption

The persistently high cost of CCS primarily stems from a lack of economies of scale. Taking a typical 600MW coal-fired power plant as an example, deploying a CCS system requires an additional investment of about US$120 million, of which capture equipment accounts for 45% (Mainly includes amine absorption tower and regeneration unit), compression and transport accounts for 25%, sequestration and monitoring accounts for 20%, and system energy loss accounts for 10% [7]. Its main challenges are reflected in the following three aspects, the first is the low equipment utilization rate, affected by the peak demand of the power grid, the average annual operating load factor of the power plant is only 60%-70%, resulting in the idling rate of the carbon capture device exceeding 30%. The second is the scale threshold limitation, when the annual capture volume is lower than 1 million tonnes, the unit cost will rise sharply by 40% (e.g. the cost of China's CRC SITC 120,000 t/year demonstration project is as high as 120 USD/t). Finally, there are regional factor differences, with the United States taking advantage of the low price of shale gas (less than $3/MMBtu), its cost of capturing energy consumption is 30 per cent lower than that of China, while China is affected by the policy of coal-fired tariff control, and the profit margins of enterprises are further narrowed [10].

Policy interventions have demonstrated significant economic leverage in reducing CCS costs. For example, the Petra Nova project in the United States, supported by the 45Q tax credit policy, reduced its net cost to $40/t by selling enhanced oil recovery (EOR) incremental crude oil and carbon credits; in Europe, the Danish government plans to invest €5 billion in carbon capture, utilisation, and sequestration (CCUS) technologies over the next ten years, with the goal of reducing greenhouse gas (GHG) emissions by 2030 by 70% by 2030, and achieve carbon neutrality by 2050 [11]. In contrast, the financial viability of similar projects in China is still highly dependent on direct government subsidies due to the immaturity of the carbon market mechanism [12].

3. Barriers to Carbon Capture and Storage Deployment

3.1. Technical Issues

Current CCS technology has several obvious limitations. It essentially represents a strategy that trades energy consumption for emission reduction benefits. During the capture process, power generation facilities retrofitted with CCS need to consume a large amount of additional energy for CO_2 capture and compression, resulting in a significant reduction in overall power generation efficiency. It is estimated that the energy conversion efficiency of a domestic coal-fired power plant retrofitted with CCS may drop from 48% to 36%, a reduction of up to one quarter.

There are also a number of problems in the transport process. Currently, the most important means of transporting CO_2 is by pipeline and ship, and for pipeline transport, pipelines are generally constructed underground, and any excessive leakage will lead to land acidification and a series of chain reactions. In the case of storage, the risk of leakage is not only a technical issue, but also involves intergenerational responsibility. The In Salah project in Algeria has forced the European Union to revise the sequestration siting criteria by requiring a 10-kilometer no-build zone outside the fault zone due to injection pressure-induced ground microseismicity (magnitude 3.3) [6]. There is still a great deal of uncertainty about the future of CCS technology, which can currently be considered as a staged means of reducing emissions. The technology currently has limited maturity, especially lack of practical verification of large-scale integration projects, and its commercial promotion and application potential has not yet been fully confirmed.

3.2. Economic Issues

The main problem that currently prevents the large-scale application of CCS technology is that its cost is too expensive. The current CCS has not yet formed a mature market mechanism, mainly due to the fact that the adoption of CCS technology will lead to a significant increase in the power generation cost of the power plant. Roughly calculated, the current domestic coal-fired power plant after the adoption of CCS technology, its power generation cost will increase by 2-3 times (in 2005, the domestic coal power generation cost is about 0.23-0.28 yuan/(kW/h)), based on which the adoption of CCS technology will make the power generation cost rise to 0.4-0.8 yuan/(kW/h) [13].

The capture process constitutes the most costly component of CCS technology, which accounts for about 70-80% of the overall project cost, and the cost of CO_2 capture using current capture technology is about US$40-60/t, while the acceptable capture cost is only US$20/t [14]. CCS-equipped plants have higher capital expenditure (CAPEX) and operational expenditure (OPEX) than comparable plants that do not use this technology, making it uneconomical to use CCS technology in comparison.

In the transport chain, many researchers believe that the transport of CO_2 is very similar to that of oil and gas and the cost of its transport varies depending on the environment in which the CO_2 is captured, and the capture of CO_2 from low-concentration emission sources (e.g. flue gases from coal-fired power plants) consumes a large amount of energy and chemicals, which leads to a dramatic increase in its cost [13].

In the case of storage, CO_2 is injected and stored underground for thousands of years, and it must be ensured that it will not leak, which requires stringent requirements for the survey, selection and modelling of geological formations, as well as for the long-term monitoring technology after storage. A comprehensive evaluation system of the potential risks associated with long-term CO_2 storage, including pollution of groundwater, damage to local ecology, and impacts of CO_2 leakage and transfer on public health and the environment, as well as on climate change, has not yet been established to promote the implementation of monitoring and management of CO_2 storage sites [15].

3.3. Policy and Institutional Issues

Given the critical role of CCS technology in achieving climate change objectives, without effective policy support and market incentives, it will be difficult to develop it to the scale required to address climate change. In May 2015, some of the major oil and gas companies wrote to the The United Nations Framework Convention on Climate Change (UNFCCC) secretariat asking for “clear, stable, long-term, ambitious policy frameworks”, stating that a price on carbon “should be a key elements of these frameworks” [16]. The move will incentivise a low-carbon transition by promoting energy efficiency improvements, switching fossil fuels from coal to gas, and investing in CO_2 capture and storage systems, renewable energy, smart buildings and grids, and new transport business models. The failure of the carbon market mechanism is particularly prominent in China, where the price of allowances in the national carbon market has long been below $10/t, while the cost of a power plant using CCS technology is over $60/tonne, a difference of up to six times. More critically, CCUS projects are not included in the Carbon Emission Allowance (CEA) offset mechanism, resulting in their carbon emission reductions not being realized [11]. Although the US 45Q tax credit provides $85/t subsidy, it is limited to geological sequestration scenarios, which excludes bio-utilisation (e.g. microalgae sequestration) and inhibits technological innovation [10]. Mismatched policies and unsuitable systems will be a significant impediment for the promotion and development of CCS technologies.

3.4. Social Acceptance Issues

Social acceptance is an important factor influencing the application of CCS around the world. There is currently no universal model that can explain social acceptance of new technologies, but based on current research a framework has been proposed that includes a range of different factors that can influence social acceptance. These factors include acceptance and attitude, knowledge, experience, trust, fairness, affect, perceived costs, risk and benefits, outcome efficacy and problem perception [17]. Each of these factors plays a different role in the level of social acceptance. The Boundary Dam CCS project in Saskatchewan, Canada, created 200 jobs, but the aboriginal people in the sequestered area initiated a lawsuit because they were not included in the revenue sharing, which eventually forced the government to commit to the land compensation (5% of the project revenue) [6]. Therefore, it is necessary to go to explain the importance of CCS technology to the society in an appropriate and neutral way. Currently, the society has a low level of awareness of CCS technology, and there are general misunderstandings and concerns, and information asymmetry and insufficient publicity are the main reasons for the lack of public awareness.

4. Pathways for Advancing Carbon Capture and Storage

4.1. Technological Innovation

Focus on the development of low-energy and low-cost next-generation capture technologies (such as new adsorption materials and membrane separation technologies), and actively lay out cutting-edge DAC and biosequestration. Accelerate the demonstration and commercialisation of mineralised storage technologies, utilise their advantages of permanent carbon sequestration and safety, investigate system integration technologies for large-scale CCS projects, and optimize the energy efficiency of the whole process from capture, transportation to storage.

4.2. Policy and Market Incentives

Formulate a clear catalogue and development plan for the CCUS industry and incorporate it into the national carbon neutral strategy system. Draw on international experience (e.g. US Section 45Q) to establish differentiated tax credit or subsidy policies to directly hedge the high upfront costs of projects. Accelerate the incorporation of emission reductions generated by CCUS projects into the offset mechanism of the national carbon CEA, so that their environmental benefits can be transformed into economic gains. Explore the establishment of a policy to subsidize the difference in price of carbon contracts.

4.3. Regulatory Framework and Risk Management

Conduct a nationwide detailed survey and assessment of geological storage potential and establish a database of storage sites. Formulate strict national standards and regulations on site selection, operation, closure and post-monitoring of storage sites. Develop and mandatorily apply low-cost, real-time, long-term leakage monitoring and early warning technologies for storage areas. Clarify the long-term responsibility of the storage project and the risk disposal mechanism, and solve the problem of "intergenerational responsibility".

4.4. Public Engagement and Social License

Promote the openness and transparency of CCS information, and regularly publish project monitoring data and safety reports. Design community benefit-sharing mechanisms (e.g. energy funds, local investments) to ensure that the communities where the projects are located can benefit from the projects. Carry out multi-channel public education and communication to explain the technology principles, risks and global emission reduction contributions in a neutral and easy-to-understand way, so as to eliminate the "neighbourhood effect".

5. Conclusion and Outlook

5.1. Conclusion

This paper has systematically reviewed the critical role and development status of Carbon Capture and Storage (CCS) technology in global carbon dioxide emission reduction. It has detailed the technical characteristics and bottlenecks inherent in the capture, transport, and storage processes, analyzing the principal challenges across technological, economic, policy, and social dimensions. The analysis concludes that while CCS technology holds significant emission reduction potential, its large-scale application remains constrained by systemic issues including high energy consumption, substantial costs, inadequate infrastructure, imperfect policy mechanisms, and low social acceptance. As a major carbon-emitting country, China must explore a CCS development path tailored to its national context, considering its unique energy structure and storage conditions. Promoting the transition of CCS from demonstration to commercial application necessitates multi-dimensional collaboration.

5.2. Outlook

The main contribution of this review is that it comprehensively organizes and analyzes the CCS technology chain and integrates various factors such as technical feasibility, economy and social acceptance, providing a systematic framework for understanding the complexity of the CCS system and its promotion path. However, due to the limited scope of available public data and cases, this paper is still insufficient in the assessment of regional storage potential, policy simulation and empirical analysis of social awareness. Future research could integrate geographic information system (GIS) and economic modelling to conduct more detailed research on storage potential and pipeline network layout, and strengthen the empirical exploration of public perception and community participation mechanisms in the Chinese context, in order to enhance the scientific and social feasibility of CCS decision-making.

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