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The Global Development, Challenges, and Prospects of Carbon Capture, Utilization, and Storage Technology

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Abstract:

Against the backdrop of intensifying global climate change and the deepening advancement of carbon neutrality strategies, carbon capture, utilization, and storage (CCUS) technology has emerged as a critical deep decarbonization approach, increasingly capturing the attention of the international community. This paper systematically reviews the current development status of the entire CCUS technology chain, covering the classification and maturity levels of technologies across capture, transportation, utilization, and storage segments. Drawing on international exemplary projects and China's development practices, this analysis examines the multifaceted challenges hindering the large-scale application of CCUS, including economic costs, environmental risks, and policy mechanisms. Although the CCUS technology pathway is gradually becoming clearer and its application scale is expanding, core issues such as high energy consumption and costs, insufficient system integration, and an incomplete institutional framework still need to be overcome. Finally, this paper proposes a technology roadmap centered on reducing energy consumption and improving efficiency, along with policy recommendations involving carbon market mechanisms and cross-regional cooperation. These suggestions provide a theoretical reference and decision-making basis for advancing CCUS commercialization and supporting carbon neutrality goals.

Keywords: carbon capture, utilization, and storage; techno-economic viability; carbon neutrality pathways.

1. Introduction

Global climate change has emerged as a severe challenge to human societal development. Assessment reports from the Intergovernmental Panel on Climate Change (IPCC) unequivocally indicate that the global average surface temperature increased by 1.09°C between 2011 and 2020 compared to the pre-industri-

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al level (1850-1900) [1]. The central objective of the Paris Agreement is to strengthen the global response to this threat by holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C [1]. Achieving this ambitious goal necessitates that the world reaches net-zero carbon dioxide emissions around mid-century, a state known as "carbon neutrality."

The path to deep decarbonization, however, is fraught with challenges, particularly in key sectors such as energy and industry. Research shows that a significant portion of emissions from industrial processes, like calcination in cement production, are inherent to the process itself; approximately 85% of emissions from cement originate here and cannot be eliminated simply by switching to renewable electricity [2]. Similarly, ensuring baseload power supply and sustaining foundational industries like steel and chemicals rely on stable energy and feedstocks, creating critical "hard-to-abate" sectors that pose a major bottleneck on the road to carbon neutrality.

In this context, carbon capture, utilization, and storage (CCUS) technology has arisen as a critical and indispensable solution. CCUS involves capturing CO_2 emissions from sources like coal-fired power plants, steel mills, and cement kilns, or directly from the ambient air, followed by either utilizing the CO_2 as a resource or securely storing it to prevent atmospheric release [3, 4]. This technology not only directly reduces emissions from existing energy and industrial infrastructure, providing a buffer for a smooth energy transition, but also holds the potential to enable "net-negative emissions" in the future, which is vital for balancing economic development with climate goals.

Despite its significant potential, the large-scale commercial deployment of CCUS faces multiple hurdles, including high economic costs, substantial energy penalties, concerns about environmental risks, an incomplete policy and regulatory framework, and lagging infrastructure development. Therefore, driven by carbon neutrality strategies, a systematic review of the current status, challenges, and future prospects of the entire CCUS technology chain is imperative. This paper aims to provide new insights for global climate governance, clarify the developmental trajectory of CCUS technology, and offer a critical theoretical reference and decision-making basis for countries worldwide, particularly for China, which is rapidly advancing its green transition, in formulating effective carbon neutrality strategies.

2. Introduction to Carbon Capture, Utilization, and Storage Technology

CCUS technology is an integrated emissions reduction process designed to mitigate carbon dioxide (CO_2) releases from human activities. It encompasses a full-chain approach beginning with the capture of CO_2 from major point sources, such as fossil-fueled power plants and industrial facilities (e.g., cement, steel, and chemical production), or directly from the ambient air. The captured CO_2 is then compressed and transported via pipelines, ships, or tankers to suitable sites. Subsequently, the technology offers two primary pathways: Utilization involves converting CO_2 into valuable products like synthetic fuels, chemicals, building materials, or using it in enhanced oil recovery (CO_2-EOR), thereby creating economic value. Alternatively, Storage entails the secure injection and permanent isolation of CO_2 into deep geological formations, such as depleted oil and gas reservoirs or saline aquifers. By preventing CO_2 from entering the atmosphere, CCUS serves as a critical technological bridge, enabling deep decarbonization in hard-to-abate sectors and contributing significantly to achieving net-zero emissions targets [4].

2.1 Carbon Dioxide Capture Technologies

Carbon capture technologies are broadly classified into four categories based on the combustion stage and configuration based on combustion stage and combustion form: pre-combustion capture, post-combustion capture, oxy-fuel combustion, and chemical looping combustion. Pre-combustion capture emphasizes removing CO_2 immediately before fuel ignition. The target material is typically high-pressure synthesis gas with high CO_2 content and minimal impurities, with Integrated Gasification Combined Cycle (IGCC) power plants being a typical application scenario. For example, the IGCC power plant facility at the Nakoso Thermal Power Station in Iwaki, Japan. It operates at a capacity of 250 MW with an efficiency of 48% [5]. Post-combustion capture refers to CO_2 recovery from low-temperature flue gas after dust removal and desulfurization. This technology is considered the most commercially advanced and widely applicable route. An operational example of a retrofitted post-combustion coal-fired power plant is SaskPower's Boundary Dam Power Station in Canada, which houses the world's first integrated and continuously operational post-combustion CCS facility in a coal plant [5]. Oxy-fuel combustion replaces air with pure oxygen for complete fossil fuel combustion, yielding high-concentration CO_2 and water vapor. After condensing and separating the water, nearly pure CO_2 is obtained for sequestration [6]. Chemical looping combustion is a process using metal oxides as oxygen carriers. Metal oxide particles react with fuel in a fluidized bed reactor, producing solid metal particles and CO_2 and water vapor. After condensing and removing the water, nearly pure CO_2 is obtained for storage. The four mainstream capture

technologies exhibit significant differences in maturity, cost, and applicability due to their distinct principles, as summarized in Table 1.

Table 1. Comparison of Primary Carbon Dioxide Capture Technologies [7]

Technology Category	Maturity (TRL)	Applicable Emission Sources	Energy Consumption (Approximate)	Advantages	Disadvantages
Pre-combustion capture	8-9	IGCC, syngas plant	2.3 GJ/tCO_2	High-purity, high-pressure CO_2 stream; compact footprint; potential for H_2 co-production	Complex system with high initial investment; mainly suitable for new-built IGCC plants
Post-combustion capture	9	Coal/gas-fired power plants, industrial flue gas	3.5–3.7 GJ/tCO_2 (Monoethanolamine)	Retrofit-friendly to existing plants; most commercially mature technology	High regeneration energy; sensitive to flue gas impurities (SOx, NOx); solvent corrosion/degradation
Oxy-fuel combustion	7–8	New or retrofitted coal/gas-fired boilers	Air separation: 0.2–0.3 kWh/kg flue gas	High CO_2 concentration (>80%) simplifies separation; high capture rate (>90%)	High energy cost for oxygen production; requires high-temperature resistant materials; significant boiler retrofit needed
Chemical looping combustion	6–7	Fluidized/circulating bed reactors (coal, biomass, gas)	Expected low (no air separation/solvents)	Inherent CO_2 separation; low energy penalty; high-concentration CO_2; inhibits NOx formation	Oxygen carrier sintering/deactivation; challenging solid circulation control; limited large-scale experience

2.2 Carbon Dioxide Utilization Technologies

The CO_2 resource utilization stage is the most direct economic value-generating phase in the CCUS chain. After capture and compression, CO_2 is transported via road tankers, ships, or onshore/subsea pipelines to various endpoints, where it is converted through chemical, biological, and geological pathways into resource products such as chemical feedstocks, fuels, fertilizers, and oil/gas [8]. CO_2 utilization pathways are shown in Table 2. Among these, geological utilization (e.g., CO_2-EOR) represents the most mature technology capable of generating direct economic benefits. Chemical and biological conversion, however, focus on producing high-value-added products and are key to realizing a carbon circular economy in the future.

Table 2. Primary Pathways for Carbon Dioxide Resource Utilization

Utilization Pathway	Specific Technologies
Geological Utilization	CO_2 Enhanced Oil Recovery(CO_2-EOR), CO_2 Enhanced Coal Bed Methane(CO_2-ECBM), Supercritical CO_2 Fracturing for Shale Gas, CO_2-CH_4 Displacement for Methane Hydrates
Chemical Conversion	Homogeneous Catalysis, Heterogeneous Catalysis
Biological Conversion	Microbial fermentation, artificial photosynthesis/electrosynthesis

2.3 Carbon Dioxide Sequestration Technologies

CO_2 sequestration technologies can be primarily categorized into geological sequestration, mineralization sequestration, and ocean sequestration. Geological sequestration refers to the process of permanently storing gaseous, liquid, or supercritical carbon dioxide within underground geological formations. Mineralization sequestration involves converting CO_2 into stable solid inorganic carbonates, thereby storing carbon on a geological timescale [9]. Ocean sequestration involves injecting CO_2 into deep-sea environments where it dissolves or forms denser CO_2-enriched seawater plumes, effectively isolating it from the atmosphere. Geologic sequestration offers the largest capacity (global >10,000 Gt), capable of meeting the 200-400 Gt demand under the 1.5°C scenario, and is at Tech-

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nology Readiness Level (TRL) 8-9. Globally, 40 projects exceeding 1 Mt CO_2 per yearare operational. Direct coupling with CO_2-enhanced oil recovery (EOR) yields negative costs of $20-60 per ton, leveraging existing oil and gas well networks and seismic data to reduce upfront investment by 30-50% [10]. Researchers generally advocate prioritizing deep geological sequestration, achieving permanent isolation by injecting CO_2 into deep geological formations to rapidly mitigate global warming trends.

3. Global Status of Carbon Capture, Utilization, and Storage Technologies

3.1 Analysis of International Benchmark Projects

The Weyburn-Midale CO_2-EOR & Storage Project in southern Saskatchewan, Canada, has continuously injected CO_2 since 2000. It is the world's longest-running CO_2-EOR project with annual injection exceeding one million tons. As of 2022, it has sequestered approximately 38 Mt CO_2, making it North America's largest onshore CO_2 storage site [11]. The field currently produces an incremental 15,000 barrels of oil per day, with a projected lifetime sequestration capacity of 40 Mt and an extended field life of approximately 25 years. Technologically, the project features a 75-well reverse-nine-point grid employing Simultaneous but Separate Water-Gas Alternation (SSWG) with a Water-Alternating-Gas (WAG) volume ratio of 1:1. Bottomhole pressures range from 14-17 MPa, exceeding the minimum miscibility pressure [12]. All injection wells utilize 13% Cr tubing and CO_2 specialized cementing slurry. Annular pressure is monitored quarterly per Saskatchewan's updated D-14 regulations [13]. Project performance manifests in three dimensions: First, sequestration efficiency: Integrated fluid/pressure ledger analysis indicates 0.30-0.44 t CO_2 sequestered per additional barrel of oil produced, consistent with 90-95% volumetric sweep characteristics of miscible displacement. Second, isolation integrity: 2015 4D seismic data revealed lateral CO_2 plume migration <300 m, with no amplitude anomalies detected within the 200 m thick shale cap [14]. Third, geochemical sequestration: 10-year produced fluid records indicate δ13C-CO_2 decreased from -18‰ to -24‰, with transport simulations estimating approximately 7% of the injected CO_2 converted to dissolved or carbonate phases [15]. The long-term successful operation of the Weyburn project provides valuable experience for global CCUS projects, particularly in CO_2-EOR, regarding technical feasibility, long-term monitoring, and risk management.

3.2 Status of Carbon Capture, Utilization, and Storage and Policy Support in China

3.2.1 Development Status

By the end of 2023, over 80 CCUS projects had been commissioned or were under construction nationwide, with a total capture capacity exceeding 8 Mt CO_2 per year. Sixty percent of these projects are coupled with EOR. The 3.2 Mt yr^{-1} project at Qilu Petrochemical-Shengli Oilfield represents Asia's largest single-site CO_2 capture-enhanced oil recovery initiative [16]. Post-combustion amine capture remains dominant in coal-fired power plants (costing approximately $45/t), but five newly started projects employ low-heat-consumption phase-change absorption or oxygen-enriched combustion, reducing energy consumption to 2.3 GJ/t CO_2. Capture costs for high-concentration tail gases in chemical and cement industries have fallen below $25/t [17]. The latest national storage potential assessment indicates that the total effective capacity of onshore saline aquifers and oil/gas reservoirs is approximately 2.4×10^{12} t. The Bohai Bay, Ordos, and Songliao basins account for 60% of this capacity, with a spatial match rate >75% to major emission sources, meeting the conditions for establishing a "million-ton-scale CCUS corridor"[18]. Under current coal and carbon prices (CNY 60/t), the levelized cost of electricity1 (LCOE) for coal-fired power with CCUS increases by approximately 0.18 CNY/kWh. When carbon prices reach ≥CNY 120/t, the LCOE of CCUS-equipped coal plants becomes lower than that of non-abated units, marking a "carbon price inversion" inflection point [19].

3.2.2 Policy Support

CCUS has been continuously included in the national science and technology plans for the 13th and 14th Five-Year Plans. In 2021, the "Science and Technology Innovation 2030-Major Projects" initiative was launched, with central budgetary investments of 3.5 billion CNY supporting seven million-ton-scale demonstration projects [20]. The Guiding Opinions on Establishing a Green Financial System explicitly include CCUS in the green credit and green bond catalogues. Provinces such as Shandong, Guangdong, and Jiangsu provide fiscal subsidies of 30–60 CNY per ton of CO_2 captured and implement off-peak electricity pricing for CCUS operations [20]. The national ETS treats CCUS as a compliance offset project, where 1 t CO_2 sequestered can be exchanged for 1 Chinese Certified Emission Reduction (CCER). In 2023, Guangdong's pilot program allowed 5% of allowances to be offset through CCUS, with an average transaction price of 75 CNY t^{-1}, providing additional cash flow for projects [17]. The Technical Guidelines for Environmental Risk Assessment of

Carbon Dioxide Capture, Utilization, and Storage (Trial), issued in 2022, requires operational monitoring for ≥20 years. The draft Carbon Emission Trading Management Regulations currently under development will, for the first time, establish a national permanent liability transfer mechanism for CCUS [20].

4. Challenges Facing Carbon Capture, Utilization, and Storage Technology

4.1 Economic Cost Issues

Scaling up CCUS projects faces severe economic challenges. High costs permeate the entire chain-capture, transport, and storage-while carbon utilization is crucial for offsetting operational expenses and enhancing project viability. The full-chain economic costs of CCUS are shown in Table 3. First, the initial project investment is substantial. Adding CCUS units can increase the total investment of coal-fired power plants by 40% to 75%. For process industries like cement and steel, the cost increase can be even more pronounced, potentially doubling the total investment and significantly raising financing barriers [21]. During operation, energy penalty is the primary concern. Taking the currently dominant amine absorption technology as an example, its operating costs reduce net power generation efficiency by 8-12%, significantly increasing the LCOE. Furthermore, China currently lacks large-scale CO_2 trunk pipelines. High individual transportation costs (e.g., road tankers) or upfront investments in pipeline construction further erode project economics. Sequestration costs are equally substantial, with subsea storage investments reaching 2-3 times those of onshore solutions. CCUS economics hinge on a dynamic balance between costs and benefits. Current project profitability heavily relies on revenue from geological utilization (e.g., CO_2-enhanced oil recovery), making cash flows highly vulnerable to international oil price fluctuations. While more promising chemical and biological conversion pathways can generate higher value-added, they currently struggle to independently support project economics due to limitations in technological maturity, energy consumption, and market scale. Therefore, overcoming the economic bottlenecks of CCUS requires a dual-track approach: First, continuously reducing costs in capture, transportation, and storage. Second, cultivating and expanding the CO_2 utilization market through policy incentives and market mechanisms, thereby enhancing project resilience and commercial appeal via diversified revenue streams.

Table 3. Full-chain economic costs of CCUS [21]

Stage	Current Cost Challenges	Cost Composition
Capture	120-200 yuan/ton	Capital Expenditure: Increases total power plant investment by 40-75%, with heavy industrial projects seeing nearly 100% increase Operating Costs: Amine absorption process reduces net power generation efficiency by 8-12%
Transportation	Approx. 1.0 yuan/ton/km (tank truck)	Lack of pipeline network, reliant on high-cost tanker trucks New pipeline construction faces substantial upfront investment (routing, environmental impact assessment, safety assessment)
Utilization	High energy consumption in conversion technology, and expensive catalyst costs	Geological utilization (CO_2-EOR): Generates direct revenue, with each ton of CO_2 increasing oil production by 0.08-0.15 barrels, valued at approximately 30-70 yuan Chemical conversion: Produces synthetic fuels, methanol, plastics, etc. High product value, but market capacity remains to be developed Mineralization utilization: Produces construction materials with lower value but enables permanent sequestration
Sequestration	Onshore: ¥35-106/ton Subsea: 2-3 times onshore costs	Onshore costs primarily consist of per-well drilling and completion expenses Offshore projects involve costly marine platforms and infrastructure

4.2 Environmental and Safety Risks

The environmental impacts and risks of CCUS technology manifest in two dimensions: First, agent dispersion or CO_2 leakage may occur during capture, transport, and storage. While high-concentration CO_2 is non-toxic, it may threaten human safety and ecological stability due to complex terrain, groundwater chemical changes, and pro-

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longed exposure. Second, while CCUS aids in reducing greenhouse gases, its operation requires additional energy, chemicals, and infrastructure investments. This introduces new pollution sources such as solid waste from absorbent degradation and additional energy consumption emissions, creating uncertainty regarding overall environmental benefits [22].

4.3 Policy and Mechanism Barriers

Carbon possesses dual attributes as both an environmental resource and a financial asset, which creates complex challenges in the practical operation of the entire CCUS chain. At the environmental policy level, the reduction in total flue gas volume after CO_2 capture leads to an increase in the concentration of uncaptured pollutants, such as NO_x and SO_x. This may cause the concentration-based emissions of these pollutants to exceed regulatory limits, potentially subjecting enterprises to penalties despite an overall reduction in total greenhouse gas emissions.

At the payment mechanism level, third-party carbon capture and transportation service providers may act as environmental stewards, charging processing fees if they treat greenhouse gases as pollutants. If they treat them as commodities, they must purchase them from emitting enterprises and resell them to oilfield clients, realizing value through enhanced oil recovery and carbon reduction trading. Service providers must shoulder the full financial and technological investment across all stages-carbon purchase, capture, storage, transportation, and sales-in a single transaction. This high barrier directly inhibits the expansion and commercialization of the carbon capture market [20].

The large-scale promotion of CCUS technology requires government policy support and comprehensive oversight throughout the entire process. Establishing supporting laws and regulations to build a scientific regulatory framework involving government, enterprises, and society is essential to ensure the healthy and orderly development of the CCUS industry [21].

5. Technology Pathway for Carbon Capture, Utilization, and Storage

5.1 Carbon Capture, Utilization, and Storage Technology Roadmap

To achieve carbon neutrality goals, CCUS technology development must adhere to the core principles of reducing energy consumption, improving efficiency, and controlling costs. A phased roadmap for overcoming technical bottlenecks across the entire chain is proposed in Table 4.

Table 4. CCUS Technology Development Roadmap

Technology Segment	Near-Term Goals (2025-2030)	Long-Term Goals (2030-2040)
Capture	Develop novel solvents & membranes for low-concentration sources [23] Regeneration energy 2.0-2.2 GJ/tCO_2; Cost 200-250 CNY/tCO_2	Achieve energy consumption ≤ 1.5 GJ/tCO_2 and cost ≤ 150 CNY/tCO_2 [24] Demonstrate integrated capture-conversion technologies
Transportation	Pilot regional CO_2 pipeline networks Establish national standards and safety regulations	Establish a national CO_2 trunk pipeline network Develop multimodal transport (ship, truck) to reduce costs
Utilization	Breakthroughs in high-value conversion (e.g., methanol, olefins) & biological sequestration [25] Promote pilot projects for chemical-biological coupling	Achieve large-scale production of liquid fuels/chemicals Establish commercial pathways for carbon-negative products
Sequestration	Optimize underground space use & assess storage safety [24] Conduct demonstration projects for onshore/offshore storage	Establish large-scale (10M-ton level) storage bases Achieve sequestration cost ≤ 50 CNY/tCO_2 with modular technology

5.2 Policy Recommendations

The large-scale development of CCUS requires dual-track drivers of technology and policy. Based on international experience and China's national conditions, the following tiered and systematic policy recommendation framework is proposed.

5.2.1 Macro Strategy and Regulatory Framework

Explicitly incorporate CCUS into the national and local "1+N" policy framework for carbon neutrality, establishing its indispensable role in decarbonization pathways for hard-to-abate sectors such as power generation, steel, cement, and chemicals [26]. Promptly enact the "Regulations on the Management of Carbon Dioxide Capture, Utilization, and Storage" to clarify project approval procedures, regulatory responsibilities of relevant departments, long-term monitoring requirements, and post-storage liability transfer mechanisms, thereby providing legal safeguards for the industry's healthy development.

5.2.2 Economic Incentives and Market Mechanisms

Establish a national CCUS special fund to provide proportional subsidies for capital expenditures of the first batch of million-ton flagship projects and offer operational cost-based incentives for capture volumes during the initial operational phase. Expand green finance support by encouraging local governments to issue special bonds for CCUS infrastructure development. Accelerate the refinement of CCUS methodologies within the national carbon market and explore establishing regional or sector-specific Carbon Capture Credits (CRC) trading mechanisms to create diversified revenue streams for projects.

5.2.3 Infrastructure and Cluster Development

Develop nationally coordinated CCUS industrial clusters prioritizing the Beijing-Tianjin-Hebei region, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and energy-rich western regions. Construct supporting CO_2 transport pipelines and storage infrastructure to achieve economies of scale and cost sharing. Establish a national underground space resource database for precise assessment and public disclosure of storage potential, reducing pre-project site selection costs and uncertainties.

5.2.4 International Cooperation and Capacity Building

Actively leverage cooperation platforms such as the Belt and Road Initiative to promote the export of China's CCUS technologies, equipment, and standards. Participate in building international CCUS cooperation platforms to advance mutual recognition of monitoring standards, carbon accounting methodologies, and carbon credits. This deepened collaboration, encompassing joint research, demonstration projects, and capacity building, will facilitate the establishment of a globally consistent regulatory framework. Such efforts are crucial for reducing deployment costs and accelerating the global transition to carbon neutrality.

6. Conclusion and Outlook

6.1 Conclusion

This review systematically examines the full technology chain of CCUS, its global application status, challenges, and future prospects. First, the CCUS technology chain has matured significantly. Post-combustion capture, CO_2-EOR and deep geological storage represent the most commercially advanced pathways, while emerging technologies like chemical looping combustion and chemical conversion demonstrate substantial potential. Second, globally, pioneering projects like Canada's Weyburn-Midale have validated the long-term safety and feasibility of the technology. China has seen rapid development, with a growing number of projects and capture capacity reaching a preliminary scale. Additionally, the alignment between sources and sinks is favorable, laying the foundation for cluster-based development. Finally, high economic costs, uncertain environmental risks, and inadequate policy mechanisms remain the core bottlenecks constraining large-scale commercial deployment. CCUS technology development should focus on the following directions: Technologically, continue advancing key technologies for low-energy capture, high-value CO_2 conversion, and secure storage. Systemically, optimize cross-regional pipeline network planning and design, region-specific technical pathways. Institutionally, establish carbon pricing models reflecting long-term emission reduction value and a full life-cycle assessment framework. Collaboratively, promote international data sharing and mutual recognition of standards.

6.2 Outlook

This paper systematically reviews the current status, challenges, and prospects of the entire CCUS technology chain, providing a comprehensive reference framework for research and policy development in this field. However, this study also has certain limitations, primarily because the data and conclusions cited originate from a large number of different independent literature sources. Significant variations in technical boundaries, assumptions, calculation methods, and data years across studies make rigorous cross-comparisons and integrated analysis of presented economic data (e.g., costs), technical parameters (e.g., energy consumption), and potential assessments (e.g., storage capacity) challenging. This may partially affect the precision and generalizability of certain conclusions. Future research urgently requires the establishment of unified, transparent technical-economic evaluation standards and methodologies to enable more scientific and comparable assessments of different technology pathways

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and projects. Ultimately, driven by the dual engines of technological innovation and policy innovation, CCUS will inevitably play an indispensable key role in the global journey toward carbon neutrality, providing core support for building a clean, secure, and efficient energy future.

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