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RESEARCH ARTICLE

Current Status and Development Prospects of Carbon Capture, Utilization, and Storage (CCUS) in China: Technical, Policy, and Market Perspectives

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Abstract

Based on in-depth investigation and analysis of the current situation of CCUS development in China, this paper combs and summarizes the technical status and development trends of the carbon capture, transportation, utilization and storage industry (CCUS) at home and abroad in recent years through comprehensive research, and conducts in-depth discussions on the existing technical problems and risks. The analysis shows that in the short term, China's CCUS will still be dominated by CO_2-EOR (Enhanced Oil Recovery) utilization. CO_2 mineralization utilization and chemical utilization will gain new development space with technological breakthroughs. Pure carbon dioxide storage is restricted by policies and costs in the short term, making it difficult to develop rapidly, and will be dominated by demonstration projects in the near future. Future development requires improving relevant laws, regulations and incentive policies, formulating scientific and reasonable systems, regulations and standard systems covering the construction, operation, supervision and termination of CCUS. It is also necessary to improve the source-sink matching of CCUS by forming a complete industrial chain that integrates capture, transportation, utilization, and storage. The construction of carbon dioxide transportation and storage hubs can generate economies of scale and commercial synergy, reduce the unit cost of CCUS projects, and improve the economic efficiency of CCUS projects by using CO_2 miscible flooding to increase oil recovery and producing hydrogen with low emissions. Under China's "dual carbon" strategy, through the implementation of the proposed suggestions, China's CCUS industry can achieve healthy and sustainable development.

Keywords: shale gas preservation, Longmaxi formation, fluid properties, structural control, nonhydrocarbon gases.

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1 Introduction

As of 2022, there were 196 commercial CCUS facilities worldwide, with projects mainly concentrated in North America. Among the 71 new facilities added in 2021, 36 were in the United States. Currently, the operating CCUS facilities can capture and store 42.5 million tons of CO_2 annually. The changing trend of the number of global commercial CCUS projects from 2010 to 2022 is shown in Figure 1 [1–5].

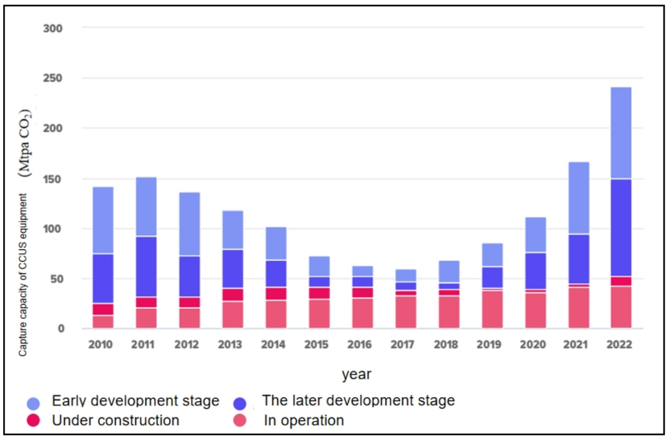

Figure 1. The changing trend of the number of global commercial CCUS projects from 2010 to 2022(GCCSI,2022). [6, 7]

From a chronological perspective, the global development of CCUS technology is accelerating. Before 2000, there were only 5 commercial CCUS projects in operation worldwide; by 2022, this number had further increased to 30. In addition, there are currently 153 global CCUS projects in the construction and early development stages, with a scale exceeding 150 million tons, indicating that the global attention to and recognition of CCUS technology are gradually growing. China explicitly put forward the goals of achieving "carbon peak" by 2030 and "carbon neutrality" by 2060 in September 2020. As a key technology in the pathway towards the "dual carbon" goals, CCUS has received significant attention in China. Therefore, it is of great significance to conduct research and trend analysis on the current status of China's domestic CCUS industry and technology [8–13]. As shown in Figure 2, the number and scale of CCUS projects in major countries worldwide have grown significantly, with some projects planning substantial long-term capacities. The data for Figure 2 comes from the GCCSI database.

2 Current Situation of Domestic CCUS

China's CCUS technology is in a stage of transition from small-scale pilot demonstrations to large-scale demonstration projects. As of September 2021, there were nearly 40 CCUS projects in various stages in China (as shown in Table 1), with a capture capacity of 3 million tons per year. These include 1 100,000-ton onshore saline aquifer CO_2 geological storage demonstration project, 1 600,000-ton commercial CO_2-enhanced oil recovery (EOR) project, and multiple 10,000-ton-level demonstration facilities for industrial and geological utilization of CO_2. In June 2021, China's largest coal-fired power plant (Jinjie

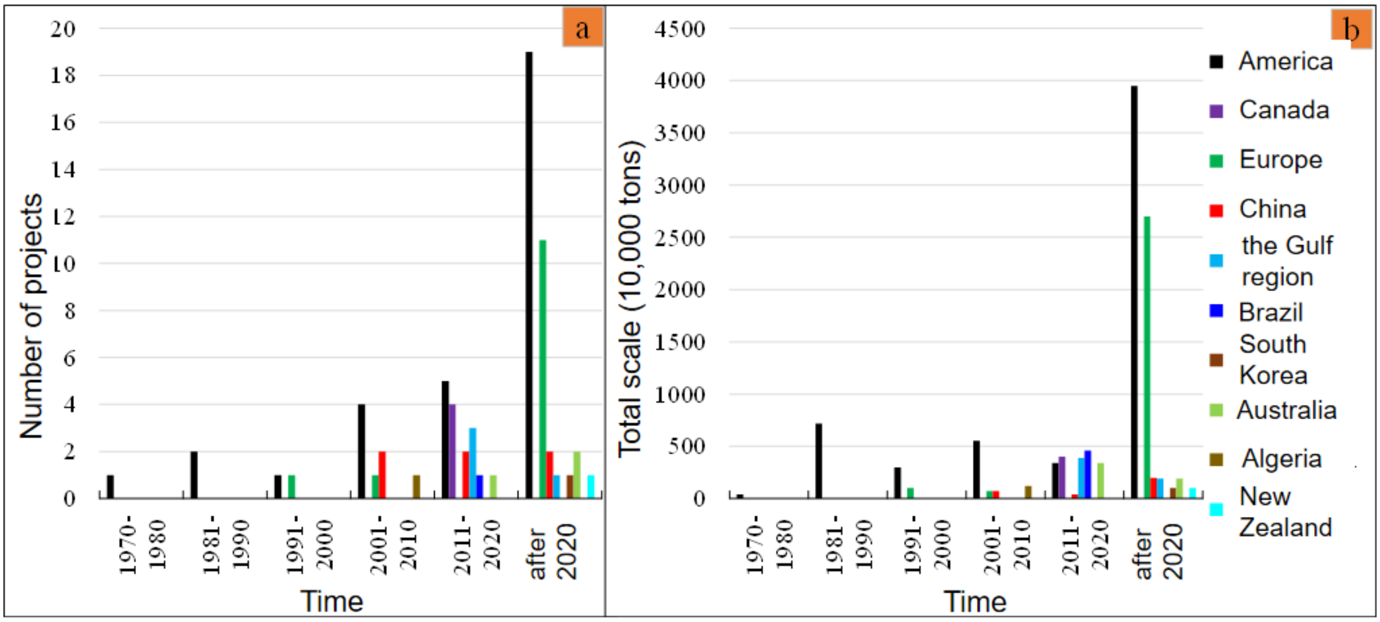

Figure 2. Number and Scale of CCUS Projects in Major Countries Worldwide(as of 2020); Note: The scale of some projects in the figure refers to their long-term planned scale, and the data is sourced from the GCCSI database.

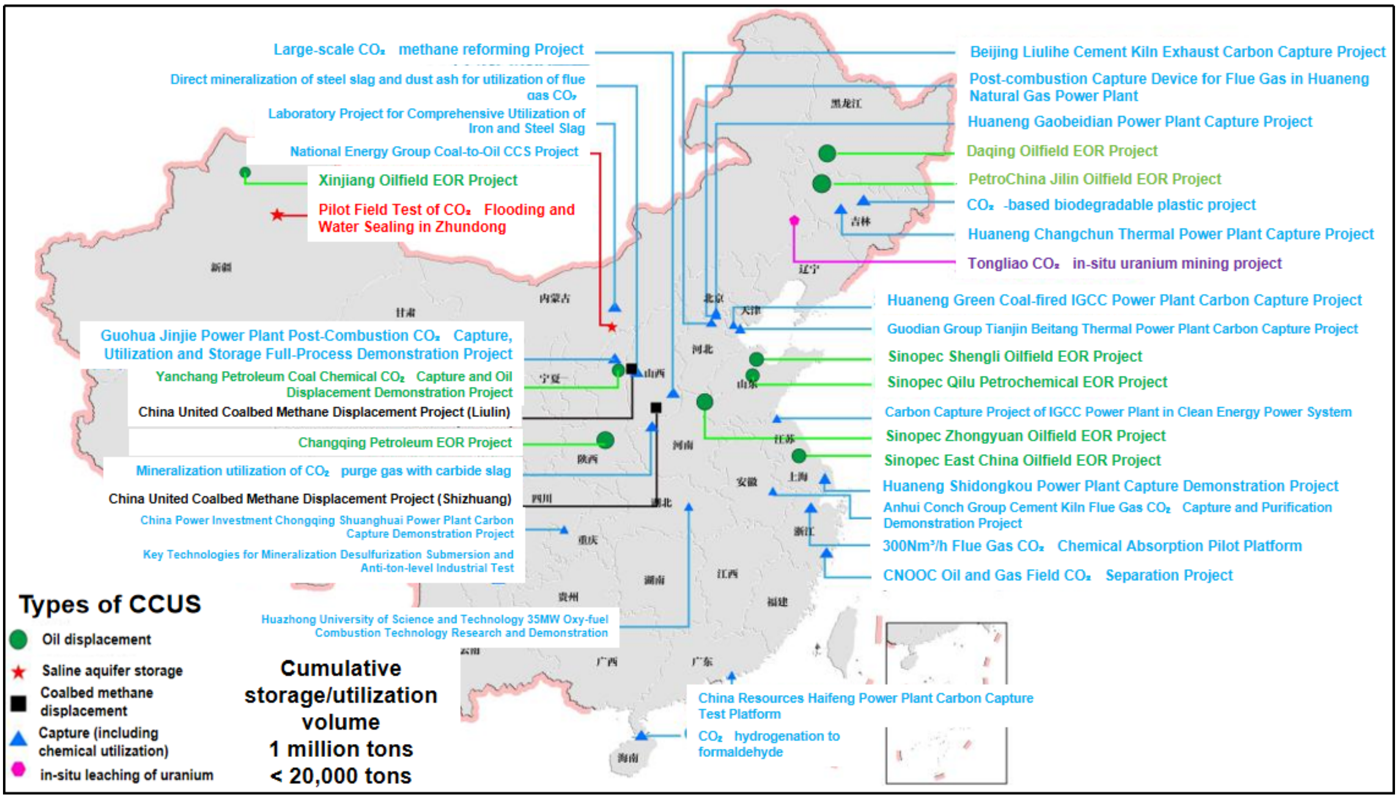

Figure 3. Distribution of CCUS Projects in China.

Power Plant) CCUS project was officially put into operation, with a scale of 150,000 tons. In 2022, Sinopec announced the completion and commissioning of China's first million-ton-level CCUS project - the Qilu Petrochemical-Shengli Oilfield CCUS project. This project captures CO_2 from Qilu Petrochemical and transports it to Shengli Oilfield for oil displacement and storage. It is expected that over the next 15 years, a total of 10.68 million tons of carbon dioxide will be injected, which can increase oil production by 2.965 million tons [14–18]. As shown in Figure 3, the distribution of CCUS projects in China highlights the concentration in certain industries and regions, reflecting the strategic planning of CCUS development.

Most of the CCUS demonstration projects that have been put into operation or are under construction in China are small-scale capture and oil displacement demonstrations in the petroleum, coal chemical, and power industries, lacking large-scale full-process industrial demonstrations with a combination of multiple technologies.

3 Analysis of Development Bottlenecks and Trends of Domestic CCUS

With the proposal of the "dual carbon" goals, the importance and urgency of developing CCUS technology have become increasingly prominent, and some domestic enterprises have begun to attach importance to the development of CCUS technology. CCUS is a systematic industry, and its industrial chain consists of multiple links such as carbon dioxide capture, compression, transportation, utilization or storage. These links are interlocking and require a high degree of integration and coordinated development among all links [19, 20].

3.1 Capture

Carbon dioxide capture relies on specific carbon sources, and the capture processes and technologies are complex. Their large-scale promotion and application are still constrained by "double highs" (high energy consumption and high cost). Capture technologies can be broadly classified into absorption, adsorption, and membrane technologies, with significant differences in maturity among them [21]. At present, pre-combustion physical absorption has entered the commercial application stage, post-combustion chemical adsorption is still in the pilot scale stage, post-combustion membrane separation technology is in the pilot scale stage, and most other capture technologies are in the industrial demonstration stage. Post-combustion capture technology is the most mature capture technology in China and can be used for capture retrofits in

Table 1. Statistics of Typical CCUS Projects (as of September 2021).

Affiliated enterprises	Project Name	Affiliated enterprises	Project Name
Sinopec	Sinopec Shengli Oilfield CCUS Demonstration Project	National Energy Group	National Energy Group Coal-to-Oil CCUS Project
	Sinopec Zhongyuan Oilfield EOR Project		Demonstration Project of Full-Process CO_2 Capture and Storage after Combustion in Guohua Jinjie Power Plant
	Sinopec Qilu Petrochemical EOR Project	China Guodian Corporation	Carbon Capture Project of Guodian Group Tianjin Beitang Thermal Power Plant
	Sinopec Shengli Power Plant CCUS Project	CPI (China Power Investment Corporation)	Carbon Capture Demonstration Project of China Power Investment Corporation Chongqing Shuanghuai Power Plant
	Sinopec East China Oilfield EOR Project	Huazhong University of Science and Technology	Huazhong University of Science and Technology 35MW Oxy-fuel Combustion Technology Research and Demonstration
PetroChina	PetroChina Jilin Oilfield EOR Project	China Resources Group	Carbon Capture Test Platform of China Resources Haifeng Power Plant
	Changqing Petroleum EOR Project	Jinyu Group	Carbon Capture Project for Exhaust Gas from Beijing Liulihe Cement Kiln
	Daqing Oilfield EOR Project	Conch Group	Demonstration Project of CO_2 Capture and Purification from Cement Kiln Flue Gas of Anhui Conch Group
	Pilot Field Test of CO_2 Flooding and Water Sealing in Zhundong	China United Coalbed Methane Corporation Limited (CUCBM)	CUCBM CO_2-Enhanced Coalbed Methane Project (Shizhuang)
CNOOC	CNOOC Lishui 36-1 Gas Field CO_2 Separation Project		CUCBM CO_2-Enhanced Coalbed Methane Project (Liulin)
	CNOOC Offshore CO_2 Storage Project	Tongliao Uranium Industry	Tongliao CO_2 In-situ Leaching Uranium Mining Project
Xinjiang Dunhua Petroleum	Kelamayi Dunhua Petroleum - Xinjiang Oilfield CO_2-EOR Project	Zhejiang University	300 Nm^3/h Flue Gas CO_2 Chemical Absorption Pilot Platform
Yanchang Petroleum	Yanchang Petroleum Coal Chemical CO_2 Capture and Oil Displacement Demonstration Project	Inner Mongolia Baorong Environmental Protection New Materials Co., Ltd.	Laboratory Project for Comprehensive Utilization of Steel Slag
Huaneng Group	Huaneng Green Coal-fired IGCC Power Plant Carbon Capture Project	Zhongyuan Oilfield, Sichuan University, etc.	Key Technologies and 10,000-ton Industrial Test of Mineralized Desulfurization Slag
	Post-combustion capture device for flue gas in Huaneng natural gas power plant	Boda Oriental New Chemical Industry	CO_2-based Biodegradable Plastic Project
	Huaneng Gaobeidian Power Plant Capture Project	Lu'an Group	Large-scale CO_2-methane reforming
	Huaneng Changchun Thermal Power Plant Capture Project	/	Direct mineralization and utilization of flue gas CO_2 by steel slag and dust ash
	Carbon Capture Project of IGCC Power Plant for Clean Energy Power System	/	Mineralization and utilization of CO_2 by carbide slag
	Huaneng Shidongkou Power Plant Capture Demonstration Project		

most domestic thermal power plants. However, post-combustion capture technology (amine solvent capture) has issues of high energy consumption and high cost in the absorption and desorption processes due to the inherent characteristics of the technology itself. Efforts to reduce energy consumption in the capture link are crucial to lowering the overall process cost, but breakthroughs in capture technology require substantial capital investment and a long period of time.

There are also significant differences in carbon capture technologies, processes and costs across different industries. In the short-term (before reaching the carbon peak by 2030), carrying out early CCUS demonstration projects targeting the coal-fired power industry is the focus. In the medium and long-term (after reaching the carbon peak by 2030), with the adjustment of energy supply and utilization structure, the absolute amount of carbon emissions in the power industry will decrease to a certain extent. Due to the inherent attributes of their own processes, hard-to-abate industries such as steel, cement and chemical engineering will be the key industries for the medium- and long-term layout of CCUS technologies. In the chemical industry, the process links emitting CO_2 are relatively concentrated, and the concentration of emitted CO_2 is relatively high. CO_2 only needs to go through dehydration and compression, which can greatly save the cost and energy consumption of the capture link. Therefore, the chemical industry is an ideal early industry for CO_2 capture deployment, which helps reduce the overall process investment and promote technological development, progress and industrial cluster construction. Compared with the chemical industry, cement and steel industries have lower CO_2 concentrations, and their capture costs and energy consumption are lower than those of the chemical industry but higher than those of the coal-fired power industry, making them suitable as the second echelon for carbon capture.

3.2 Transportation

CO_2 transportation refers to the technology required to transport captured CO_2 from the source to appropriate locations for storage or utilization. It serves as an intermediate link between gas sources and storage/utilization processes, and a reasonable transportation technology can ensure the economy, safety, and stability of CCUS projects [22]. Among China's existing CO_2 transportation technologies, tank truck transportation and ship transportation have reached the stage of commercial application, mainly used for CO_2 transportation with a scale of less than 100,000 tons per year. Pipeline transportation is still in the pilot scale stage; Jilin Oilfield and Qilu Petrochemical use onshore pipeline to transport CO_2. The cost of subsea pipeline transportation is 40% to 70% higher than that of onshore pipeline. At present, the technology for subsea pipeline transportation of CO_2 lacks experience and is still in the research stage in China. When the transportation volume exceeds 1 million tons per year, pipeline transportation is the optimal choice for CO_2 delivery. Compared with the other two methods, pipeline transportation has the lowest cost, the most convenient operation, and the highest transportation safety. It is suitable for long-distance and large-volume CO_2 transportation and will become the main trend in the future.

3.3 Utilization and Storage

How to properly dispose of the captured carbon dioxide is an important link in improving the healthy development of the industrial chain, which is generally divided into two major approaches: utilization and storage.

CO_2-enhanced oil recovery (CO_2-EOR) can improve oil recovery efficiency and generate economic benefits as well as energy security benefits. Its economic performance is mainly affected by oil prices, CO_2 purchase costs and oil replacement rates [23, 24]. CO_2-EOR projects in China have been successively carried out in domestic oilfields. Among them, the oil replacement rate (gas consumption per ton of oil) of Jilin Oilfield is about 4.67:1 (4.67 tons of carbon dioxide injected can produce 1 ton of oil), that of Shengli Oilfield is about 2:1, and that of Xinjiang Oilfield is about 2.56–3.57:1. A preliminary calculation shows that, based on a CO_2 purchase cost of 300 yuan/ton, an injection cost of 80 yuan/ton, and an oil replacement rate of 3:1, the CO_2 cost required for producing each ton of crude oil is 1,140 yuan/ton. The analysis herein is intended to be comprehensive and technically rigorous.

The CO_2 mineralization utilization route is the fastest-developing technical route in China's CCUS technology apart from geological utilization. Benefiting from the relatively mature markets for downstream products of mineralization utilization, such as building materials and chemical fertilizers, as the cost of the mineralization utilization process further decreases, the mineralization utilization route is expected to become the second route that can generate economic benefits [25].

The technological development level of CO_2 chemical utilization at home and abroad is basically synchronized, and significant progress has been made, with a large number of new technologies such as electrocatalysis and photocatalysis emerging [26]. However, although a small number of industrial-scale pilot plants for this route have been put into operation, there are still some technical bottlenecks in industrial-scale plant integration, product purity, and preparation costs that have not yet been broken through.

The development level of biological utilization at home and abroad is basically synchronized, mainly focusing on microalgae fixation and gas fertilizer utilization. However, constrained by costs, especially issues related to energy consumption in algae separation and the cost of gas fertilizer preparation, China has advanced relatively slowly in the biological utilization of carbon dioxide. Although a 100,000-ton-level microalgae carbon sequestration project was proposed as early as 2021, it still remains in the project demonstration stage [27].

There are still many problems in the geological storage of carbon dioxide. In China, the ownership of storage sites is unclear, there is a lack of standards or specifications for storage site selection, and there is a deficiency in the regulatory framework for safety monitoring and leakage emergency response after storage, with relatively insufficient technologies and experience.

Assessments of carbon dioxide storage potential vary greatly and require detailed geological data as support. Storage also faces many other uncertainties, such as the risk of carbon leakage to the local environment, the risk of earthquake-induced leakage, public acceptance issues, and investment uncertainties. These involve various aspects including regulatory authorities, society, and the environment, with long processes, cumbersome links, great difficulty in connecting upstream and downstream related fields, and extremely high uncertainty [28]. Both geological utilization and geological storage of carbon dioxide involve complex engineering site selection, suitability assessment of storage sites, storage potential evaluation, risk assessment, injection, monitoring, and other professional technical needs with high technical difficulty. There are also issues such as unclear competent authorities for the use of storage sites, and they generally need to be constructed, managed, and operated by enterprises with relevant qualifications [29, 30].

Overall, in the short-term, CO_2-EOR utilization will still be the main focus, while CO_2 mineralization utilization and chemical utilization will gain new development space with technological breakthroughs. Pure carbon dioxide storage is constrained by policies and costs in the short-term, making it difficult to achieve rapid development. In the near future, it will be dominated by demonstration projects. With the increasing pressure of the country's carbon reduction and emission reduction efforts and technological breakthroughs in the field of geological safe storage, geological storage will develop steadily in the future.

4 Suggestions for the Development of Domestic CCUS Industry

Based on the experience of CCUS project commercialization and industrial chain construction at home and abroad, suggestions on the development trend of domestic CCUS industry are put forward from four aspects:

(1) Strengthen national support and improve relevant laws, regulations, and incentive policies. Formulate scientific and reasonable systems, regulations, and standard systems covering the construction, operation, supervision, and termination of CCUS to ensure the healthy development of the CCUS industry; Introduce a pricing mechanism for carbon dioxide emission reduction through measures such as carbon taxes, tax credits, carbon emission trading, CCS obligations, emission performance standards, or government procurement standards, thereby incentivizing investment in capture facilities and transferring some of the benefits to transportation and storage providers.

(2) Form a complete CCUS industrial chain covering capture, transportation, utilization, and storage. Launch full-process and large-scale demonstration projects aimed at commercialization to accelerate the formation of business models, providing practical support for the industry in formulating technical standards, project monitoring, and risk assessment methods; Promote central or local governments to conduct research on the planning of carbon dioxide infrastructure transportation networks, and advance the improvement of CCUS source-sink matching.

(3) Carry out large-scale and clustered construction. By planning and building carbon dioxide transportation and storage hubs, economies of scale and commercial synergy effects can be generated,

which will reduce the unit cost of CCUS projects, lower investment risks, and at the same time promote better source-sink matching.

(4) Actively develop new technologies and explore CCUS commercialization methods. In the near-term, improving crude oil recovery through CO_2 miscible flooding and producing hydrogen with low emissions can enhance the economic viability of CCUS projects; in the long-term, developing new CO_2 utilization technologies will drive the development of the CCUS industry.

5 Conclusion

(1) In the short term, China's CCUS development will continue to be dominated by CO_2-enhanced oil recovery (EOR) applications. At the same time, CO_2 mineralization and chemical utilization are expected to gain new growth opportunities with technological breakthroughs. Pure geological storage of CO_2 remains constrained by policy and cost factors, making large-scale deployment challenging in the near future and limiting it primarily to demonstration projects. In the medium- to long-term, as technologies advance and supporting policies improve, mineralization-based utilization will gradually expand, while novel CO_2 conversion and utilization technologies will become the key drivers for the sustainable growth of the CCUS industry. Additionally, in the near term, combining CO_2-EOR with low-emission hydrogen production can enhance economic viability, while future breakthroughs in CO_2 transformation technologies will further strengthen the industry's development potential.

(2) Strengthening national support and improving the legal and regulatory framework are essential for ensuring the healthy development of CCUS. This includes establishing comprehensive standards covering project construction, operation, monitoring, and decommissioning. Furthermore, implementing effective carbon pricing mechanisms and supporting incentive policies—such as carbon taxes, tax credits, emissions trading schemes, mandatory quotas, and government procurement—will increase industry participation. These measures should also allocate part of the benefits to transportation and storage links to promote integrated development across the entire CCUS value chain.

(3) Current CCUS development in China faces multiple technical and structural challenges, including persistently high capture costs and energy consumption, insufficient infrastructure for CO_2 transportation and storage, and the lack of a mature, fully integrated industrial chain and business model. These barriers have limited most projects to small-scale demonstrations with few full-chain implementations, impeding progress toward large-scale emission reduction. To overcome these obstacles, China should accelerate the construction of a comprehensive CCUS industrial chain, implement large-scale integrated demonstration projects to accumulate operational experience, and establish robust standards for technical regulation, risk management, and performance evaluation. Building centralized CO_2 transportation and storage hubs will enable economies of scale, reduce unit costs, and optimize source-sink matching. Additionally, near-term strategies such as improving oil recovery through CO_2-EOR and integrating CCUS with low-carbon hydrogen production can enhance profitability, while long-term breakthroughs in mineralization and advanced utilization technologies will be critical to sustaining CCUS growth.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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