The Current Status and Future Prospects of Carbon Capture, Carbon Transportation, And Carbon Utilization Technologies in Chinese Coal-Fired Power Plants Within the Context of Dual Carbon Goals

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Abstract. Carbon dioxide capture, utilization, and storage (CCUS) constitute vital measures for achieving net emissions reduction in China. Against the backdrop of the “dual carbon” initiative in China, this paper meticulously examines and analyzes the key technological principles, merits and demerits, and bottlenecks associated with CCUS carbon capture in the country’s thermal power plants at the current stage. It combines the prevailing industrial application status and the future development trajectory of pertinent technologies with considerations of industrial economic benefits and business models. Building upon this analysis, the paper summarizes the application status of CCUS technology in China’s thermal power plant industry and presents future prospects. On the technological front, the three capture methods grapple with the challenge of high costs. Therefore, there is a need to intensify efforts in developing low-cost and efficient carbon capture materials, as well as researching and practically applying low-cost oxygen generation technology. Economically, CCUS technology currently faces high costs, low returns, and certain commercial barriers, placing China in a demonstrative business model stage. To overcome these challenges and realize the economic benefits of CCUS technology, government incentives and technological innovation are imperative. These measures aim to reduce the overall cost of CCUS technology, stimulate the scale development, and foster commercialization, ultimately contributing to the achievement of China’s carbon emission reduction targets.

Keywords: CCUS technology; thermal power plant; carbon capture; carbon economy.

1. Introduction

Amidst the rapid economic growth of human society, the surge in greenhouse gas emissions has led to global warming and an increased frequency of extreme disasters. Currently, China holds the highest carbon emissions globally, and the nation is earnestly working towards reaching the peak of carbon emissions by 2030 and achieving carbon neutrality by 2060—a significant commitment known as the “double carbon” goal. As per the World Energy Yearbook 2023, coal power stands as the predominant force ensuring the security and supply of electricity in China, contributing to 56.0% of electricity generation [1]. Unfortunately, this reliance on coal power results in substantial carbon emissions. Meanwhile, alternative energy sources encounter challenges such as extended return cycles and technical barriers, leaving them in a state of stagnation [2]. Confronted with the imperative of deep decarbonization, China’s Annual Report on Carbon Capture, Utilization, and Storage (2023) highlights the difficulty of phasing out fossil energy at the current stage. Instead, the report emphasizes the necessity of relying on Carbon Capture, Utilization, and Storage technology (CCUS) to accomplish this goal [3]. Presently, CCUS projects face general cost challenges, and there is a need to break through key industry technologies while also maturing the business model. Effectively promoting the low-cost, commercialization, and industrial clustering of CCUS technology has emerged as a focal point of research in recent years.

In the realm of Carbon Capture, Utilization, and Storage (CCUS) technology for thermal power plants, both domestic and international scholars have devised diverse carbon capture and compression technologies based on distinct principles. These technologies have been explored in terms of their large-scale economic implications, though there is a noticeable dearth of studies amalgamating various CCUS technologies with considerations of large-scale economies.

This paper focuses on the CCUS technology and business model pertinent to thermal power plants. It initiates its exploration from the engineering prerequisites of CCUS for thermal power plants. Building upon the existing landscape of CCUS capture and compression technology in thermal power plants, the paper aims to comprehensively synthesize the crucial aspects of carbon capture technology and associated costs for these power plants. Furthermore, it seeks to identify pertinent technical bottlenecks, delineate developmental trajectories, and conduct an in-depth analysis of the business model and economic feasibility of CCUS projects within the context of the dual-carbon background. The paper not only anticipates the developmental prospects of CCUS projects but also endeavors to foster the expansion and commercialization of CCUS technology in China.

2. Thermal Power Plant Capture Technology

Carbon dioxide (CO_2) capture technologies employed in thermal power plants can be categorized into three distinct groups based on the combustion process and mode: pre-combustion capture, post-combustion capture, and oxygen-enriched combustion.

2.1. Pre-combustion Capture

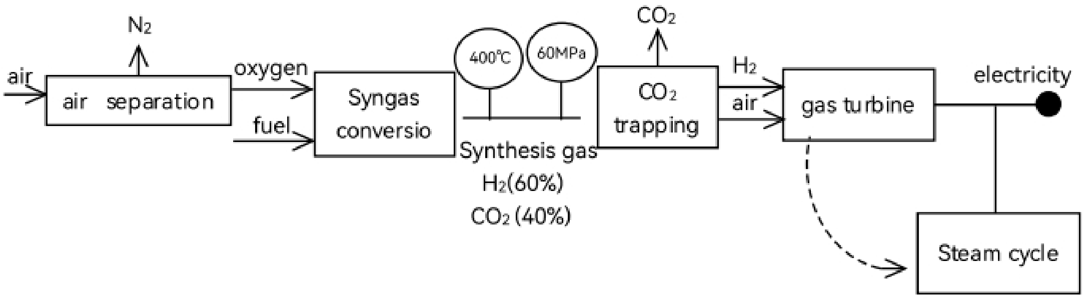

Fig. 1 Pre-combustion capture schematic (Photo credit: Original)

Pre-combustion capture involves isolating carbon elements before fossil fuels are burned [1]. Key methods for this process include solution absorption, solid absorption, membrane separation, and low-temperature fractionation, as shown in figure 1.

In pre-combustion capture, raw materials like coal and biomass fuels undergo gasification with oxygen or air. This process leads to a reaction in the combustion section, generating CO_2, CO, H_2, N_2, and sulfide. The mixture gas is under high pressure, facilitating the separation of CO_2. Post-reaction, CO_2 undergoes treatment via absorption, adsorption, or membrane separation technologies before being compressed and transported to the subsequent stage. The remaining gases, like N2, are either released or recycled (e.g., CO, H_2).

Solution absorption involves using solutions to extract CO_2 from the mixture. This method employs various absorption principles: physical solution absorption, chemical solution absorption, and a combination of both. Physical absorption relies on altering CO_2 solubility in solutions (such as methanol, N-methylpyrrolidone, polyethylene glycol dimethyl ether, etc.) based on pressure changes to separate CO_2. Lower temperatures and higher pressures enhance the solvent's efficacy in CO_2 absorption, while desorption regeneration occurs at higher temperatures.

Solid Absorption Method: This technique involves separating CO_2 from the mixture using a solid adsorbent, categorized into physical and chemical adsorption based on different principles. Physical adsorption primarily follows a regeneration cycle process involving adsorption at higher pressure, followed by depressurization with washing or evacuation. Adsorption materials with variable pressure or variable pressure/temperature characteristics include activated carbon, molecular sieve, hydrotalcite, and cage hydrate. Chemisorption utilizes chemical reactions with substances like amines, silicates, and carbonates for CO_2 adsorption, with desorption and regeneration occurring at high temperatures. Key features include high adsorption selectivity and resilience to ambient steam or water. Some adsorbents can operate at medium to high temperatures (200~600 °C), eliminating the need to cool the conversion gas, thereby reducing overall capture costs.

Membrane Separation Method: In this approach, membrane separation utilizes the pressure difference on both sides of the membrane as the driving force, achieving selective separation based on the distinct permeability of each component in the membrane [3], as shown in figure 2.

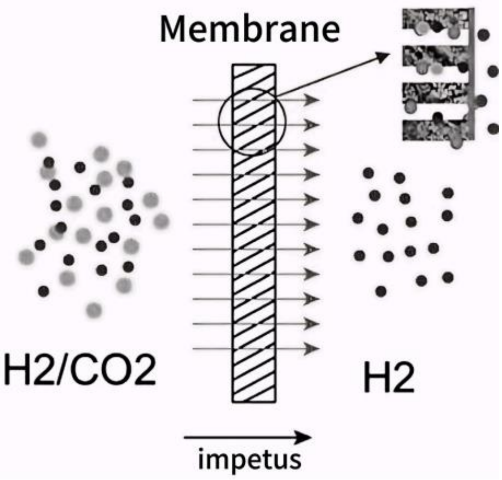

Fig. 2 Membrane separation method (Photo credit: Original)

The low-temperature separation method relies on the distinct melting and boiling points of mixed gases to achieve gas separation. The CO_2 obtained through this method boasts high purity and can be directly utilized. However, the widespread adoption of this technology is impeded by significant drawbacks such as substantial energy consumption and elevated equipment costs during the separation and compression processes [4].

In comparison to other capture methods, particularly post-combustion, pre-combustion capture offers advantages like low energy consumption, rapid absorption rates, and a substantial capture capacity. Nevertheless, the application of its capture device is limited. Among the four methods, the membrane separation method shows promise but is currently confined to laboratory stages, with relatively high capture costs. On the other hand, the solution absorption method, though in its early stages of application, incurs costs ranging from \$35 to \$50 per ton due to process-related expenses, significantly exceeding the international standard of \$15 per ton. Consequently, the development of new, cost-effective, and efficient absorbents, or enhancements to the stability of membranes, coupled with solutions for the scalability of separated membrane materials, is crucial to realizing large-scale applications [2], ultimately yielding economic benefits.

2.2. Oxygen-enriched Combustion

The oxygen-enriched combustion technology involves the utilization of a gas with a high concentration of oxygen to displace air, thereby altering the combustion process. This modification leads to the production of CO_2 that is more readily separable and captureable. Typically, this technology is divided into two main types: atmospheric oxygen-enriched combustion (AOC) and pressurized oxygen-enriched combustion (POC). POC builds upon AOC by effectively recuperating the enthalpy of water in the flue gas through elevating the combustion system pressure to 10 to 15 bar. This approach enhances the efficiency of carbon capture [5]. Additionally, oxygen-enriched combustion technology can be further categorized into four groups based on different oxygen-enriched configurations: oxygen gun injection combustion, micro-oxygen-enriched combustion, air oxygen combustion, and pure oxygen combustion, as shown figure 3.

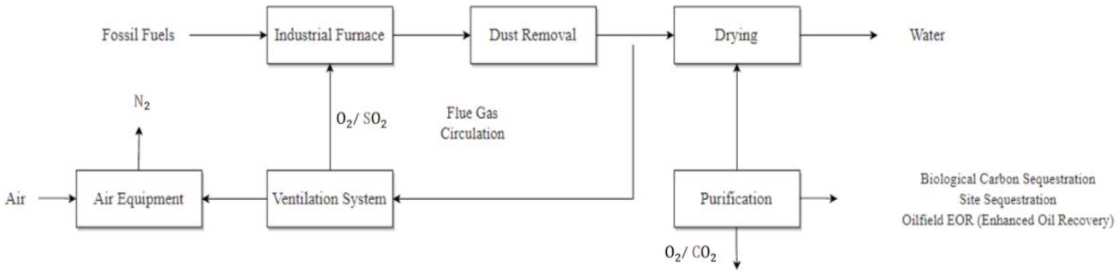

Fig. 3 Process flow diagram of oxygen-enriched combustion technology (Photo credit: Original)

As shown in table 1, oxygen-enriched combustion offers advantages in terms of lower difficulty and cost for equipment transformation. The primary gases produced through this combustion method include H_2O and CO_2, resulting in reduced NO_x emissions, which are environmentally friendly and capable of enhancing boiler operational efficiency. However, there is a tendency for increased enrichment of SO_2 and SO_3. Despite this, capture and separation remain relatively simple. It stands out as the most promising and energy-efficient method among the three methods, with an efficiency loss of only 4% [5]. The integration of oxygen-rich combustion technology into large coal-fired power plant boilers not only boosts combustion efficiency but also lowers the ignition temperature of primary air pulverized coal. Consequently, this reduces fuel consumption, contributing to significant savings in boiler fuel consumption. A case study involving the application of oxygen-enriched combustion technology in the 2×300 MW coal-fired generator set boiler at Guoelectric Chongqing Hengtai Power Generation Co., LTD demonstrated remarkable outcomes. Post the implementation of this technology, the generator set exhibited a substantial reduction in fuel consumption (by over 80%) and significantly curtailed the depth of the unit’s peak load (by less than 30%). These results showcased outstanding achievements in energy conservation and emission reduction [6].

Table 1. Classification of enriched oxygen combustion technologies

Category	Description	Application Scenarios
Oxygen Gun Combustion	Utilizes an oxygen gun to directly inject O_2 into the combustion chamber	High-intensity smelting in the steel industry
Micro-Oxygen Combustion	O_2 is mixed with air outside the furnace in a certain proportion before combustion	Kilns and furnaces with operating pressures below 20 kPa
Air-Oxygen Combustion	Simultaneous injection of O_2 and air, mixed through a burner before combustion	High-standard combustion systems
Pure Oxygen Combustion	Utilizes O_2 directly instead of air for combustion	Glass industry

However, the combustion of carbon-based fuels within recirculated flue gas and pure oxygen streams, rather than in air, poses substantial challenges in oxygen separation and production, thereby increasing costs. The complexities in supplying pure oxygen, notably considering the high expense associated with oxygen separation technology (where low-temperature distillation remains the only proven method for large-scale high-purity oxygen production), constrain the commercial viability of carbon-based fuel technologies. Currently, there are no full-scale oxygen-rich combustion projects within the 1000 MW to 2000 MW scale, although several sub-scale commercial demonstration plants are gradually emerging worldwide. For instance, CS Energy and Vattenfall have proposed 25 MW and 250 MW oxygen-rich coal-fired units, respectively [7]. Regarding the domestic application of oxygen-rich combustion technology, its adoption remains limited due to constrained equipment investments, oxygen production costs, and various other factors. Consequently, it has found only a small number of applications in burner transformations within the thermal power industry. These applications primarily focus on leveraging oxygen-rich micro-oil ignition steady combustion technology to economize fuel consumption and enhance the flexibility of coal-fired thermal power units.

2.3. Post-Combustion Capture

Post-combustion capture serves as a method for capturing CO_2 emitted in the flue gas from combustion processes. This approach exhibits strong compatibility with existing coal-fired power stations, allowing for a direct retrofit of the tail flue in existing power plants. With relatively modest fixed investment requirements and an independent, flexible capture system, it stands out as the primary application technology for carbon capture in China's coal-fired power plants [4].

Various methods for CO_2 capture after combustion exist, including chemical solution absorption, solid adsorption, membrane separation, and more. The chemical solution absorption method involves selecting alkaline solutions such as amine solutions to absorb and generate salt. Subsequent changes in pressure and temperature facilitate the analysis of CO_2. This method is particularly suitable for flue gas with low partial pressure of CO_2 and is presently the most mature and commercially viable absorption method. The transformation process does not disrupt existing procedures, but the solvent regeneration process incurs a high energy consumption ranging from 20% to 30%, alongside potential equipment corrosion issues.

In recent years, advancements in water-less systems and new ionic liquids have shown substantial potential in addressing the aforementioned challenges. Currently, commonly used liquid absorbers encompass organic amines, ammonia water, and ionic liquids. The advantages and disadvantages of each absorber are detailed in Table 2.

Table 2. Comparison of advantages and disadvantages of various liquid absorbents

Absorbent Type	Advantages	Disadvantages
Organic Amines	Commercially proven; high capture efficiency	Severe equipment corrosion; susceptible to thermal degradation; susceptible to oxidation from gases like SO_2, NO_x
Ammonia Solution	High absorption rate; can capture other acidic gases and produce by-products	NH_3 is volatile leading to reduced absorption efficiency
Ionic Solutions	High selectivity; minimal equipment corrosion; good thermal stability; broader range of operating temperatures and pressures	High cost; high viscosity leading to reduced mass transfer efficiency

The solid adsorption method employs van der Waals forces or chemical bonding to adsorb CO_2, and the subsequent analysis is achieved by manipulating temperature and pressure. Although some materials have entered the Chinese stage in this context, challenges persist, including high production costs, low selectivity, and the occurrence of cycle inactivation phenomena. These issues require resolution for the solid adsorption method to reach its full potential.

As outlined in Table 3, there is currently no solid adsorbent that can simultaneously satisfy the requirements of high CO_2 selectivity, large adsorption capacity, rapid adsorption/desorption kinetics, easy regeneration, low raw material costs, high recovery stability, and chemical and thermal stability in the presence of other components in flue gas (such as SO_x, H_2O, HCl, NO_x, and Hg). Consequently, the focus of future research is directed towards the development of solid adsorbents with characteristics such as low regenerative energy requirements, high adsorption/desorption rates, good stability, and economic feasibility [8]. Addressing these aspects will be crucial for advancing the effectiveness and viability of the solid adsorption method in CO_2 capture processes.

Table 3. Advantages and disadvantages of various solid absorbents

Adsorbent Type	Advantages	Disadvantages
Biochar	Widely available raw materials, low cost, abundant porosity, and environmentally friendly	Weak CO_2 adsorption capacity, low CO_2 capacity and selectivity at low pressures, challenging large-scale synthesis
Zeolite	Large specific surface area, strong CO_2 adsorption capacity	Low adsorption temperature, highly challenging to capture CO_2 in humid environments
Metal-Organic Frameworks (MOFs)	High specific surface area, high porosity, and adjustable structures	Low CO_2 adsorption capacity at room temperature, high cost, complex synthesis process
Calcium-based Matrix	Low raw material cost, high effective adsorption temperature, large CO_2 adsorption capacity	Prone to sintering during cyclic regeneration, poor cyclic stability.

The membrane separation method leverages the variance in the rate of gas molecules passing through a membrane to achieve separation. Currently, many of these methods remain at the laboratory stage. To advance this technology, future efforts could focus on developing mixed matrix membranes that combine high permeability and high selectivity. This can be achieved through techniques such as doping, surface treatment, and functionalization. Additionally, exploring cost-effective raw materials and optimizing the membrane material preparation process can contribute to reducing manufacturing costs, facilitating the widespread application of membrane materials in CO_2 separation and capture [9]. In essence, the key direction for the future of post-combustion capture technology lies in the development of materials that are not only highly effective in absorption but also cost-efficient. This involves a multidisciplinary approach, encompassing advancements in membrane design, material synthesis, and manufacturing processes to address the economic feasibility of large-scale CO_2 capture and separation.

3. Economic Analysis of CCUS Technology in Thermal Power Plants

3.1. Cost Analysis

Table 4. CCUS cost technologies for each stage from 2025 to 2060

		Year					
		2025	2030	2035	2040	2050	2060
Capture Cost (Yuan/ton)	Pre-Combustion	100-180	90-130	70-80	50-70	30-50	30-40
	Oxygen-Enriched Combustion	300-480	160-390	130-320	110-230	90-150	80-130
	Post-Combustion	230-410	190-280	160-220	100-280	80-150	70-120
Transportation Cost (Yuan/ton)	Tanker Transport	0.9-1.4	0.8-1.3	0.7-1.2	0.6-1.1	0.5-1.1	0.5-1
	Pipeline Transport	0.8	0.7	0.6	0.5	0.45	0.4
Storage Cost (Yuan/ton)			50-60	40-50	35-40	30-35	25-30

Note: The costs encompass both fixed expenses and operational costs.

The breakdown in Table 4 underscores that the predominant share (around 70% to 80%) of CCUS operating costs originates from capture and compression processes. Notably, higher concentrations of CO_2 production (exceeding 90% by volume) generally translate to diminished costs associated with capture and compression. Thus, elevating CO_2 production concentrations emerges as an effective strategy to curtail the overall expenses in CCUS operations. Nevertheless, it is crucial to note that the analysis and data available for evaluating the transportation costs of CCUS technology are limited. The primary factors influencing transportation costs encompass project construction and operation timelines, CO_2 transportation distance, pipeline dimensions, as well as inlet and outlet pressures in the pipeline system. Furthermore, the cost of sequestration forms a significant component of the overall CCUS technology cost. Introducing innovations such as replacing the conventional oil displacement method with sealing and loading techniques can have a discernible impact on enhancing the economic viability of CCUS applications. This shift in approach can potentially contribute to optimizing the cost-effectiveness of CCUS technologies, thus fostering their broader adoption and implementation.

3.2. Benefit Analysis

Table 5. Analysis of CCUS technology benefits

Economic and social potential performance	Formation mechanisms	Examples
Avoiding the substantial stranded costs of infrastructure	The current infrastructure associated with China’s major emission sources faces a limited operational lifespan. CCUS technology not only prevents premature decommissioning of existing facilities but also mitigates the need for additional investment in constructing other low-carbon infrastructure. This, in turn, significantly reduces the economic costs associated with achieving carbon neutrality	The estimated magnitude of stranded assets in China’s coal power sector could range from 3.08 to 7.2 trillion yuan
Positive social impact	Mitigating the impacts of climate change, boosting industrial output and employment opportunities, ensuring energy security, enhancing comprehensive ecological management capabilities, and addressing bottlenecks in regional development	By the year 2050, the extensive implementation of CCUS technology is anticipated to generate a cumulative workforce ranging from 4×10^6 to 1.2×10^7 jobs
The benefits brought about by carbon trading	The carbon market and CCUS synergistically complement each other. The official establishment of China’s unified carbon market not only opens up commercialization prospects for the industrialization of CCUS but also presents strategic opportunities. Concurrently, carbon pricing within the carbon market stands out as a crucial instrument supporting CCUS development, propelling the creation of a positive feedback loop characterized by heightened investment and financing, coupled with sustained reductions in costs. This interplay not only fosters a conducive environment for CCUS growth but also signifies a strategic alignment between market mechanisms and technological advancements, paving the way for a sustainable and economically viable approach to carbon reduction.	In 2022, the total trading volume of Carbon Emission Allowances (CEA) in the national carbon market reached 50.8895 million tons, with a total transaction value of 2.814 billion yuan.

As depicted in Table 5, CCUS technology demonstrates its capacity to mitigate the stranded costs associated with a significant portion of China’s infrastructure. Through the overhaul of energy and industrial infrastructure, it markedly diminishes the carbon footprint of existing facilities, averting the costly early decommissioning necessitated by carbon constraints. Given China’s status as the world’s largest producer of coal power, steel, and cement, the imperative to address emissions from short-lived infrastructure becomes paramount. CCUS application not only forestalls premature facility decommissioning but also curtails the supplementary investments required for alternative low-carbon infrastructure, thereby substantially reducing the economic burden of achieving carbon neutrality.

Moreover, the societal advantages of CCUS technology encompass reductions in climate change-related losses, enhancements in industrial output value and job opportunities, assurance of energy security, and augmentation of capabilities for ecological and environmental governance. Research conducted by the Oil and Gas Industry Climate Initiative projects that, by 2050, the deployment of CCUS technology could generate millions to tens of millions of jobs. Crucially, the symbiotic relationship between the benefits of carbon trading and CCUS technology unfolds as a catalyst for commercial opportunities in industrial development. This synergy propels the establishment of a virtuous cycle, fostering increased investment and financing while perpetuating a trend of cost reduction. In essence, CCUS technology not only plays a pivotal role in meeting carbon reduction objectives but also exerts a profound and positive influence on China’s economic and societal landscape.

3.3. Business Model

Table 6. Existing CCUS business models in China

Business model	Specificities	Source of revenue	Advantages and disadvantages
Outsourcing model	Carbon dioxide capture only, no utilization and storage, limited to capture and sale only	Gain on sale of carbon dioxide Carbon trading revenue Clean feed-in tariff subsidy revenue	The economic returns are higher, and lower subsidies for sequestration are not available
Integration model	Participate in all CCUS sessions	Revenue from oil drive utilization Carbon trading revenue Clean Feed-in Tariff Subsidy Income Utilization of sequestration subsidy income	Strong profitability with certain thresholds and strong policy dependence
Joint venture model	Participation in the market as a common enterprise	Revenue from oil drive utilization Carbon trading revenue Clean Feed-in Tariff Subsidy Income Utilization of sequestration subsidy income	Certain commercial barriers to cost and benefit sharing

From Table 6, it can be seen that the revenues under each business model are different, and the integration model is the main business model now, but the costs of carbon capture, transportation, storage and other processes under each business model are relatively high, and government incentives and technological innovation are needed to reduce the costs. CCUS technology is still in the development stage, and there are many problems such as immature technology and low efficiency, etc. In addition, many companies face the problem of insufficient revenues, and the government has not yet defined the subsidy policy. China’s business model is still in the early demonstrative stage, and the government has not yet had a clear subsidy policy, many companies are faced with the problem of insufficient revenue, it is still necessary to explore new ways of carbon utilization, to find out new points of profit, to speed up the development of industrial clustering, and to promote the process of commercialization of CCUS in China.

4. Conclusion

In the realm of technology, all three carbon capture methods grapple with the challenge of addressing high costs. Each method—pre-combustion capture, oxygen-enriched combustion, and post-combustion capture—possesses distinct advantages and faces specific challenges. Pre-combustion capture boasts a sizable capture capacity and rapid absorption rate but contends with the issue of low material stability. Oxygen-enriched combustion technology is relatively mature; however, the difficulty in separating oxygen remains a noteworthy obstacle. Post-combustion capture, widely applied in coal-fired power stations, confronts challenges related to equipment corrosion and material preparation.

On the economic front, CCUS technology presents a high threshold, modest income, and certain commercial barriers. China currently operates within an exemplary business model, necessitating government incentives and technological innovation to alleviate the overall cost of CCUS technology and realize its economic benefits.

Building upon these insights, we propose the following outlook. First and foremost, in terms of technology, there is a need to intensify efforts in developing low-cost and efficient carbon capture materials. Concurrently, research and practical applications of low-cost oxygen generation technology should be prioritized. Secondly, within the business model, continuous innovation is essential. Identifying new profit points can drive the scalability and commercialization of CCUS technology, contributing to the attainment of China’s carbon emission reduction goals. This dual focus on technological advancement and innovative business strategies is pivotal for the successful integration and widespread adoption of CCUS technologies.

Authors Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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