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Research on Multi-technology Coupling and Synergistic Emission Reduction Mechanisms in Carbon Capture and Resource Utilization Processes

Xinyue Tu

School of Guizhou University, Guiyang, China

Abstract

Carbon Capture, Utilisation and Storage (CCUS) are technical routes for carbon neutrality. The five sections of the technical system in the "China Carbon Capture Utilization and Storage Technology Development Roadmap" for 2025 have been extended to include carbon capture, transport, use, storage and combined optimisation. Clusterisation and multi-technology integration have become the main directions for large-scale application. The following are the representative forms of multi-technology coupling discussed in this paper: integrated capture-conversion, cross-industry material and energy coupling, negative emission technology collaboration, and integration with renewable energy. The three kinds of cooperative emission reduction studied are source-sink matching, parameter coordination and system optimisation. Based on the analysis above, multiple-technology coupling can reduce energy consumption, expand the scope of application for carbon dioxide, and improve the economic efficiency of the entire chain. However, due to high costs, a lack of suitable source-sink areas and insufficient policy support, large-scale development has not been achieved. In the future, we will expand the cluster deployment, strengthen standards and policy systems, and move CCUS from an end-of-pipe mode to one based on resource utilisation and value creation.

Keywords

Carbon Capture, Utilization and Storage; Multi-technology Coupling; Synergistic Emission Reduction; Utilization of Carbon Dioxide; Cluster Deployment.

1. Introduction

The world is continuously strengthening its governance of climate change, and carbon capture, utilisation and storage (CCUS) technology has moved from the stage of research and development to engineering application. According to the Sixth Assessment Report of the IPCC, in order to meet the temperature-control goal of the Paris Agreement, carbon capture, utilisation and storage (CCUS) needs to reduce a total of hundreds of billions of tonnes of carbon emissions. China's "1+N" policy system for carbon peaking and carbon neutrality also explicitly lists CCUS as one of the objectives, aiming to promote large-scale technological research and development, demonstration and industrialisation applications [1]. According to the Global CCS Institute, by July 2025, a total of 734 commercial CCS projects around the world were at various stages of development, an increase of 17% from the 624 in 2024. Among them, 77 projects have been put into operation with a combined capture capacity of 64 million tons per year, and an additional 44 million tons per year worth of facilities are under construction. Applications of this technology are no longer limited to natural gas treatment and chemical production; now, the power, steel and cement industries have also been added.

Large-scale application of CCUS is restricted by the performance improvements of individual technologies and by the system of connections among capture, transport, utilisation and

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storage. The old way is a long-winded, high-energy, step-by-step process, so it has not been widely used. Thus, multi-technology integration has been the trend in recent years. It has connected all the links and improved the general efficiency of the system by coordinating the schedule of material flow and energy flow. In January 2026, the State Administration for Market Regulation released 12 national standards for CCUS that took effect in July of the same year and covered key links such as carbon dioxide capture, transport and storage, as well as terminology norms and emission reduction calculations.

At present, there are no systematic studies on the multiple-technology coupling mode and collaborative emission reduction mechanism of CCUS, and related discussions are relatively scattered. The main forms of multi-technology coupling in the carbon capture, utilisation and storage process will be explored in this paper, the mechanism of collaborative emission reduction analysed, and feasible paths for promoting coupling development discussed, thus providing a reference for the large-scale deployment of CCUS and policy formulation.The analytical framework of this article is shown in Figure 1.

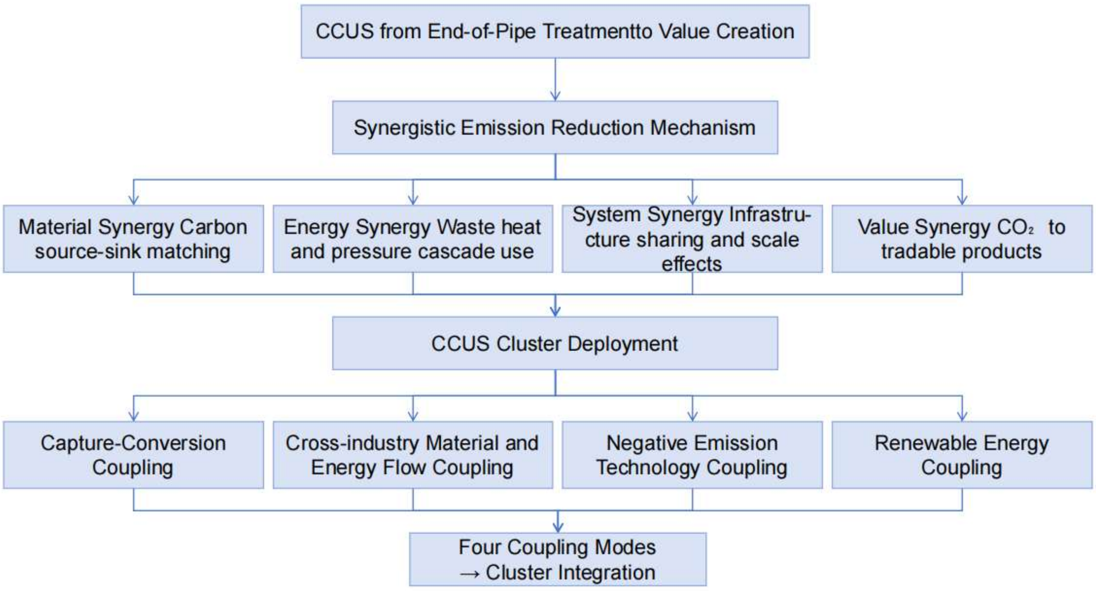

Figure 1. Schematic diagram of multi-technology coupling and collaborative emission reduction mechanism for carbon capture, utilization and storage

2. Integrated Capture-Conversion Technology Coupling

Integrated capture and conversion are now trending directions for the field of carbon capture, utilisation and storage. The steps of the old way are as follows: first, carbon dioxide is absorbed, then heated to be released, and finally sent to a conversion device. The comparison between the traditional stepwise process and the integrated process is shown in Figure 2. This process has high energy consumption and a complex system, so it is not suitable for large-scale deployment. The combined technology for adsorption and catalysis is in the same system and does not require an intermediate desorption step.

The "Integrated Carbon Dioxide Capture-Conversion Synthesis Methane Technology" co-developed by the Shanghai Institute of Advanced Research of the Chinese Academy of Sciences and Baosteel Energy Saving Company is a typical case. In June 2026, this technology was selected as one of the scientific and technological achievements of the China Petroleum and Chemical Industry Association (CPCIA). The expert group believed that this technology had established a complete process route, a nickel-based adsorption-catalysis dual-functional material had been developed, the coupling mechanism of capture and conversion had been

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clarified, and material preparation had achieved ton-scale amplification. The proposal of the dual-tower circulation process has solved the problems of continuous flue gas capture, in-situ carbon dioxide conversion, and large-scale operation. The first domestic pilot demonstration unit has been built. This scheme avoids the traditional step-by-step process and directly converts adsorbed carbon dioxide in-situ; it is a relatively short-process, low-energy-consumption technical route [2].

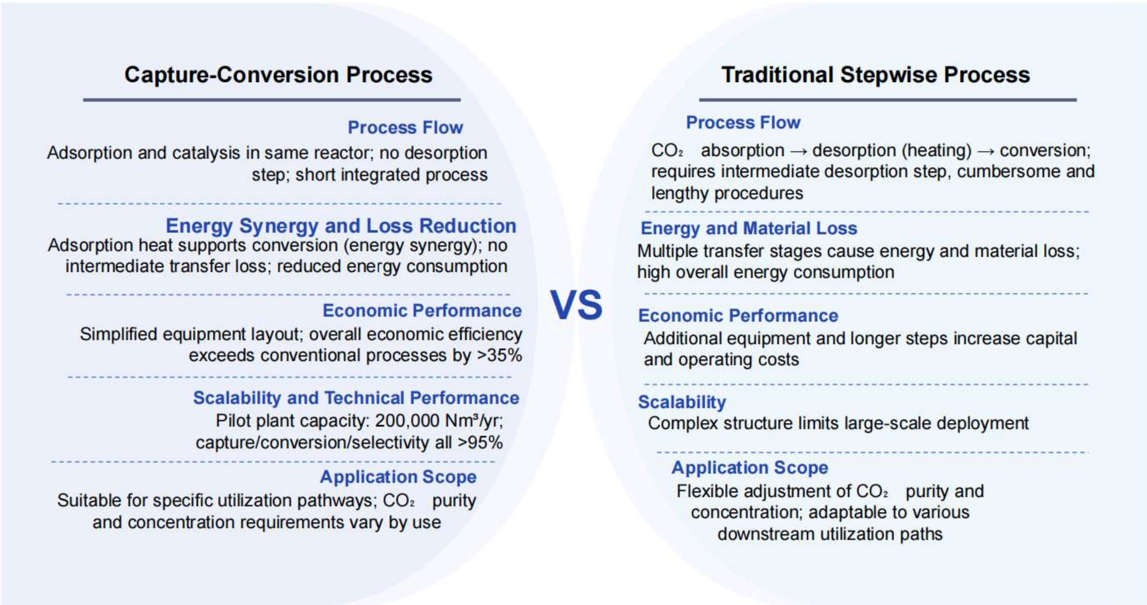

Figure 2. Comparison between traditional stepwise process and capture-conversion integrated process

The core of the combined process is a dual-functional material that is both adsorptive and catalytic, thus performing capture and conversion in the same reactor and avoiding energy loss and material loss at intermediate stages. A shorter period will reduce capital and expenses for the equipment. Based on the above calculation, the overall economic efficiency of the integrated process exceeds that of the old separate processes by more than 35%. The design of the pilot demonstration unit is a flue gas treatment capacity of 200,000 m^3/year, and its capture rate, conversion rate and methane selectivity are all above 95%. In terms of emission reduction, the heat released during adsorption can be used to supply energy for the conversion step, achieving energy synergy; and the adsorbed carbon dioxide has high activity and can thus be utilised in the following reactions [3]. Both materials and processes have been improved to build an all-encompassing chain for this technology, from reaction mechanism to demonstration application.

The combined scheme is not feasible in all cases. Methanol synthesis, protein production and mineralized building materials are different types of utilisation paths that require different concentrations and purities of carbon dioxide, and thus have varying process parameter requirements. The three extensions will be material development, process intensification and system integration.

3. Cross-industry Coupling of Material Flow and Energy Flow

A typical type of cross-industry material and energy flow connection in the field of carbon capture, utilisation and storage is being explored. Match carbon sources, hydrogen sources,

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oxygen sources, and other factors from various industries at a large scale to achieve coordinated emission reduction across all these industries.

The CCUS industrial demonstration project of HBIS Group is a typical case. In January 2026, two technologies were fully commissioned at the Tangsteel New Area: "high-temperature blast furnace gas carbon capture coupled with microbial carbon sequestration for protein production" and "steel slag flue gas carbonisation resource utilisation". This is the first time that carbon capture and utilization in China has established an all-encompassing chain from industry. The trademark licence for the "CarbXRock" in the project has also been obtained. The high-performance pressure swing adsorption material in this carbon capture process is used, and waste heat and waste pressure resources are also utilised. Capture efficiency of blast furnace gas is relatively high, and the concentration of captured CO_2 exceeds 95%. The CO_2 are then used for microbial fermentation, and the resulting microbial protein content is as high as 70 per cent; it can be used directly as a protein feed. In terms of solid waste utilization, the project has broken through the technology of synergistic solidification of low-concentration flue gas CO_2 and steel slag, and the carbon sequestration capacity of the produced building materials reaches 20% with a compressive strength of more than 30 megapascals. In short, this project will convert carbon sources and solid waste in steel production into resources for value-added applications, rather than dealing with them as waste. The carbon capture and resource conversion process of the HBIS Group project is shown in Figure 3.

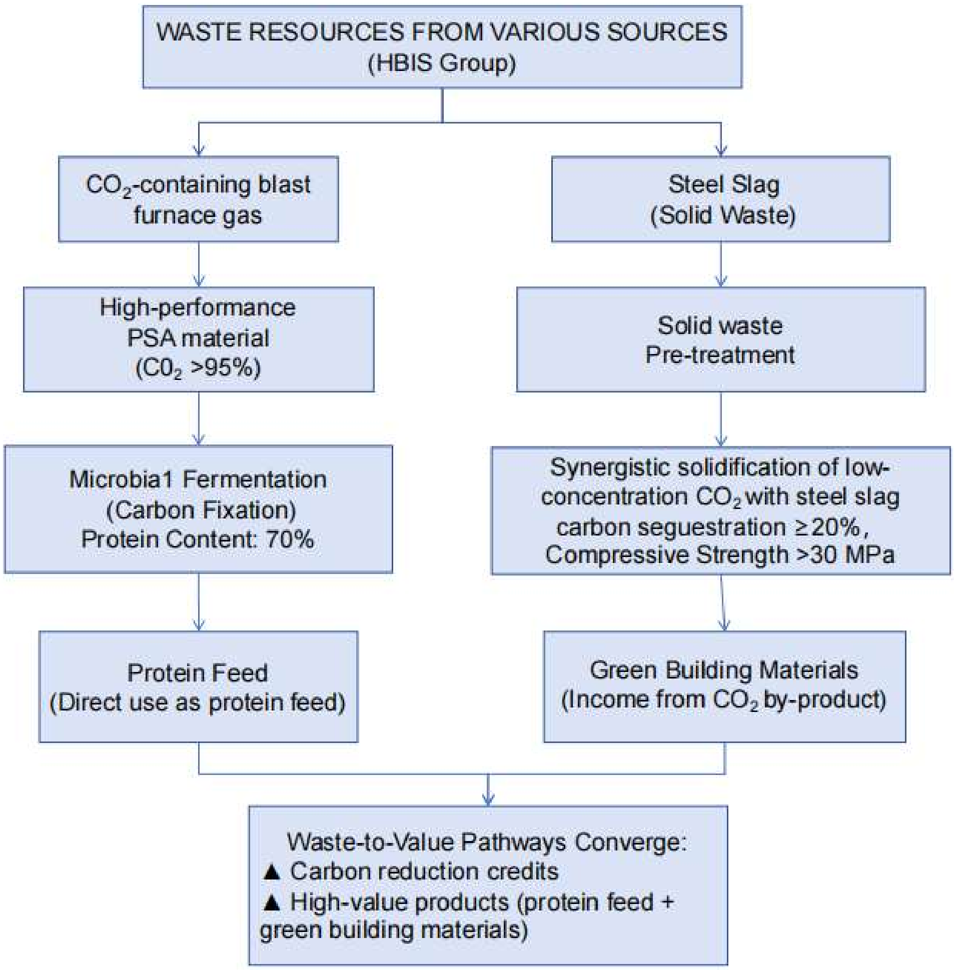

Figure 3. Schematic diagram of the resource conversion pathway via cross-industry coupling of material and energy flows

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The synergistic emission reduction effect of this project can be divided into the following three parts. Matching carbon sources and carbon sinks to connect distributed emission sources with CO_2 absorption or storage areas and reducing transportation costs [4]. Hierarchical use of energy: Pressure swing adsorption materials can be combined with waste heat and waste pressure resources for higher energy-efficiency operation. The by-product of CO_2 emissions will no longer be treated as waste but will be used to produce high-value-added products, such as protein feed and green building materials, and thus generate income through carbon reduction.

If this technical route is promoted around the world for the steel industry, the amount of annual CO2 reduction is expected to be tens of millions of tons [5]. HBIS Group has signed several agreements for CCUS industrial demonstration projects with BHP Billiton in the past, signed the "Carbon Search Plan" with Tencent, and jointly built a chain from basic research to industrial demonstration in collaboration with scientific research institutions such as the Institute of Process Engineering at the Chinese Academy of Sciences and Beijing University of Science and Technology. These cross-border collaborations indicate that a coupling of material and energy flows needs to be realised, and technological breakthroughs as well as synergy between upstream and downstream of the industrial chain are required.

4. Coupling of Negative Emission Technologies with Biomass Energy Synergy

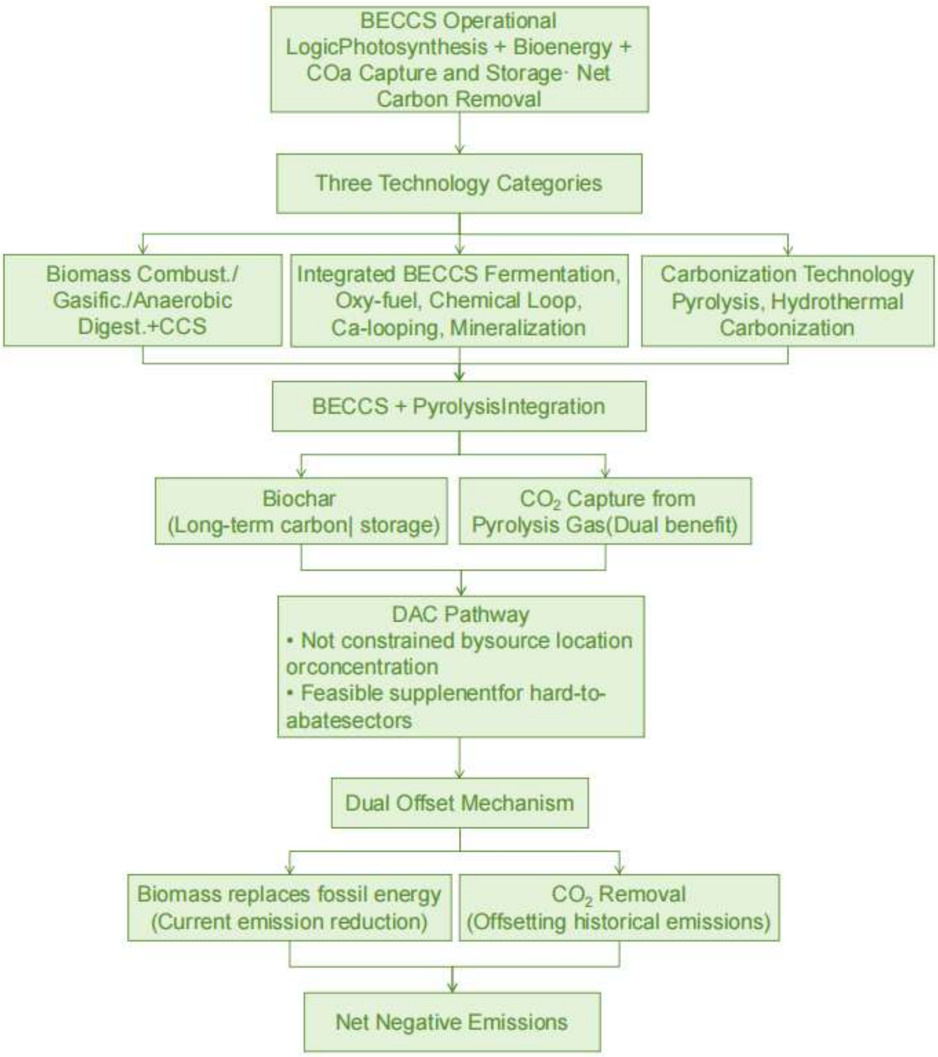

Figure 4. Operational logic of BECCS and negative emission technology pathways

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The first two chapters present the problems of capturing and using carbon dioxide from industry. However, only by reducing emissions will the goal of carbon neutrality be reached in the long run; thus, negative-emission technologies are needed to offset the remaining emissions. The Sixth Assessment Report of the IPCC put direct air capture and biomass carbon capture and storage on the list of front-line technologies for reducing the amount of carbon dioxide in the atmosphere. Together, the two kinds of technology and CCUS form a high-level synergy model. The operational logic and technical path of BECCS are shown in Figure 4.

Operating logic of biomass carbon capture and storage (BECCS): During the growth stage of biomass, CO_2 in the atmosphere is absorbed by photosynthesis and converted into energy. After use, the CO_2 that is released in the process of utilisation is captured and stored to achieve net carbon removal [6]. The research group on the Resources and Environment Subject of the Department of Energy and Power Engineering at Tsinghua University has divided BECCS-related technologies into three categories: biomass combustion, gasification and anaerobic digestion coupled with CCS, integrated BECCS technology (which includes fermentation carbon sequestration, oxygen-rich combustion, chemical chain, calcium cycle and alkali heat treatment and mineralization), and carbonisation technology (pyrolysis and hydrothermal carbonisation).

BECCS and pyrolysis together are worth considering. Biochar produced by pyrolysis is relatively stable, and its carbon can be stored for a long time; if CO_2 in the pyrolysis gas is also captured, both the effects of carbon sequestration and emission reduction can be achieved at the same time. Scalability of BECCS also refers to the sustainability of the upstream biomass supply, the technical integration level of the intermediate link, and the degree of match with downstream application scenarios. The combined effect of these links will determine how much pollution is reduced.

DAC directly extracts CO_2 from the air, and the location or concentration of the emission source does not matter. Although the cost of DAC is not yet favourable at present, it is still feasible as a supplement to the scope of emission reduction covered by traditional methods [7]. The "Several Measures on Promoting the Cultivation and Development of the Carbon Capture, Utilisation and Storage Industry" released by Beijing in 2026 has added biomass carbon capture and direct air carbon capture to the scope of support for negative carbon technology research.

The emission reduction effect of carbon sinks is in two categories: lowering net-zero emissions through carbon abatement in the current era, and removing CO_2 at the source of emission into the atmosphere via sinks such as forests. Combined, it is to be expected that the net result will be a reduction. The large-scale promotion of BECCS and DAC still has many practical problems: whether the raw materials can be stably supplied, whether they will occupy land, and whether energy consumption and costs can be reduced. In the coming rounds of technological research, policy design and standard development, these problems will gradually be resolved.

5. Integration and Coupling of CCUS with Renewable Energy Systems

The above coupling model concentrates on the movement and use of carbon. The collection process has a high energy and heat loss; therefore, some of the reduced greenhouse gas emissions will be offset by the additional power needed for this stage. CCUS + renewable energy are now being combined to reduce carbon emissions during the carbon capture stage [8]. At present, the first plan for the use of clean energy is to harness wind and solar power to reduce emissions by converting CO2 into liquid carbon dioxide and storing it.

The combination of CCUS and renewable energy can be done at many levels. Figure 5 illustrates the three levels of integrating CCUS with renewable energy. At the power level, after supplying power to the compressors, pumps and fans in the system from renewable energy, the indirect carbon emissions caused by the capture process will also be reduced. At the thermal end, a large

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quantity of low-grade heat energy is needed to regenerate the absorbent in the chemical absorption method, and this part of heat energy can be used multiple times via solar heating or industrial waste heat. At the system level, the CCUS device can be used as a flexible load for the power system to increase capture power when the output of renewable energy is abundant and reduce it when there is a power shortage, providing peak shaving services for the power grid [9].

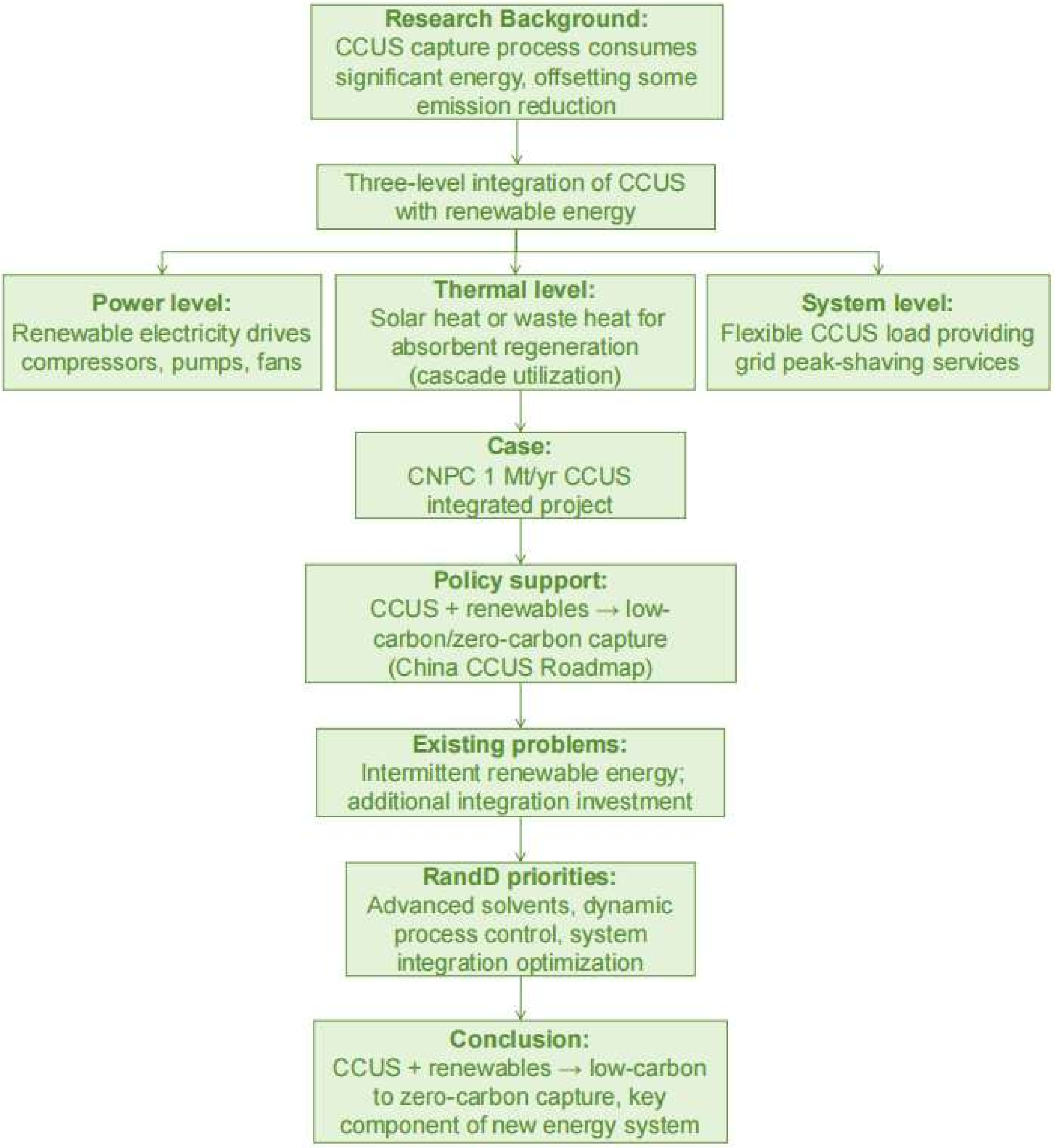

Figure 5. Schematic diagram of the CCUS-renewable energy integration framework

CNPC's 1-million-tonne per annum carbon capture integrated project is a typical case. In 2025, the core compressor units of this project will be supplied by Shaan Gu Power Co., Ltd. As the first "new energy + coal-fired power + CCUS" integrated project in China, it is expected to reduce carbon dioxide emissions by 107,600 tons and save 43,800 tons of standard coal annually after startup. This project connects new-energy power generation with carbon-capture coal-fired power generation to explore how to reduce carbon emissions from traditional energy use and develop new-energy and traditional-energy systems together.

Drive carbon capture with renewable energy to reduce indirect carbon emissions from the capture process significantly. As the replacement rate of fossil-fuel-based power generation

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with renewable energy increases, the net emission reduction effect of CCUS technology will be strengthened. The China 21st Century Agenda Management Center has clearly stated in the "China CCUS Technology Development Roadmap" that, by combining with renewable energy, CCUS will reach a low-carbon or zero-carbon state and serve as an essential part of the new-energy system.

This link of connection also has actual problems. Renewable energy is intermittent and fluctuating; thus, the carbon capture system needs to have strong load-regulation capabilities, but most carbon capture processes have not considered the flexibility of variable-load operation in their design. Economically speaking, it is also a problem; although the cost per kilowatt-hour of renewable energy is declining, additional engineering investment and system optimisation are still required for integration with the CCUS system. In the future, the three focuses of technological research and development will be new solvents, dynamic process control and optimisation of the system.

6. Cluster Deployment and System Integration Optimization

The first four chapters introduced the four coupling modes in sequence. However, to fully realise the scale effect, one needs to advance to a higher level of integration and form-up: CCUS cluster deployment. This is an all-encompassing form of multi-technology coupling that has moved from individual demonstration projects to regional cooperation [10]. The integrated framework for the clustered deployment of CCUS is shown in Figure 6.

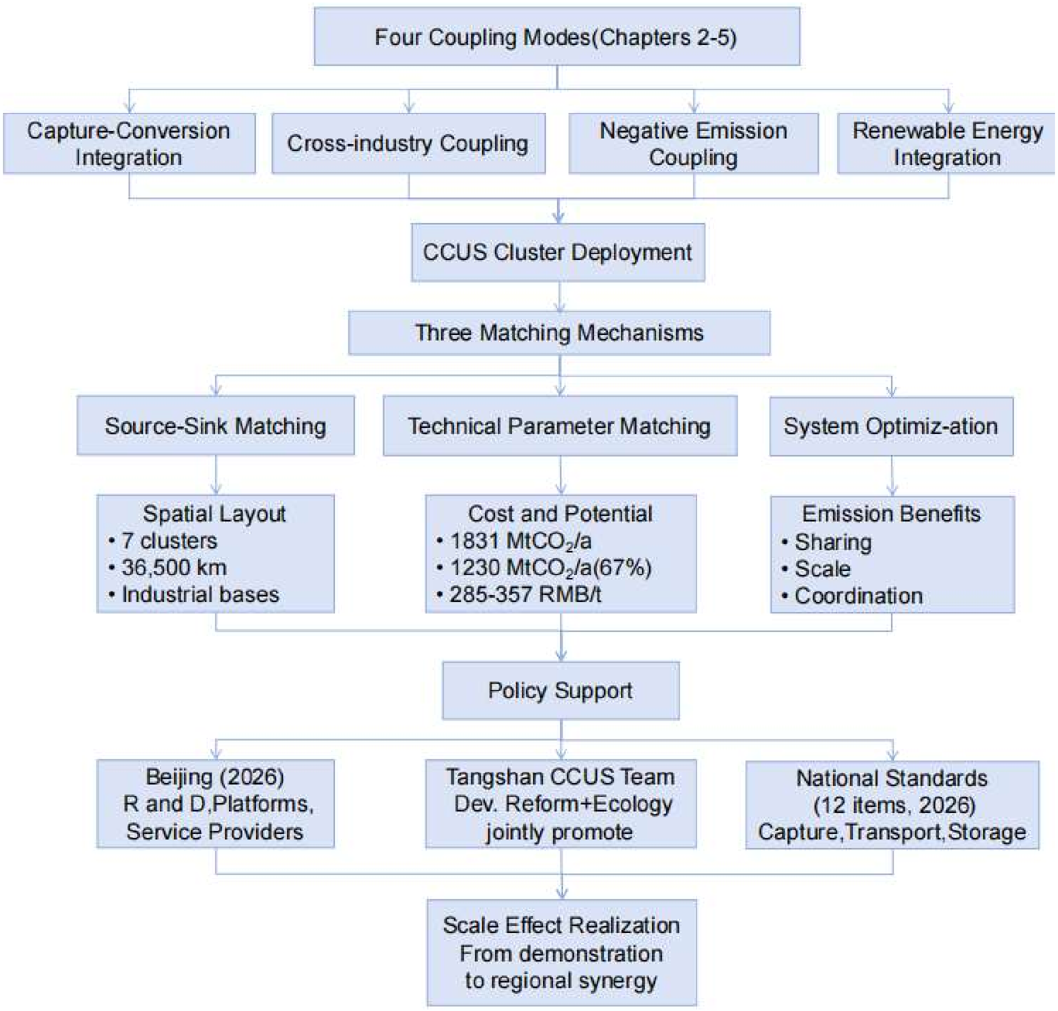

Figure 6. Schematic diagram of the integrated framework for CCUS cluster deployment

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Clues for integrating cluster deployment can be found in research on the entire process of coal-based CCUS. This study combines the entire process technology of coal-based CCUS under three mechanisms. The source-sink matching mechanism is to find a path from the emission source to the storage site that addresses the problem of physical connection for CO_2. The technical parameter matching mechanism coordinates the key working parameters of the capture, storage and use links to ensure the normal operation of the whole chain. A Big Data platform and optimisation algorithms are used in the optimisation module to dynamically adjust the technical chain. The three mechanisms are in conjunction and cannot operate independently.

In terms of spatial arrangement, large coal bases such as the Junggar Basin in Xinjiang and the Ordos Basin are planning CCUS clusters to support the low-carbon development of the coal industry. At the national level, the research on source-sink matching has identified 7 main CCUS clusters with a total capture potential of about 1831 $MtCO_2$/a and a total length of optimised pipelines of around 36,500 km. Approximately 1230 $MtCO_2$/a of this potential (accounting for 67% of the total) has a levelized cost of carbon avoided (LCCA) between 285 and 357 RMB/t and is suitable for the first deployment. Most of these clusters are based on the existing energy and chemical industrial bases, have concentrated carbon sources and nearby storage facilities, and share infrastructure.

The emission reduction benefits of cluster deployment are shown in the following specific ways. Share CO_2 transportation pipelines and storage sites to reduce infrastructure investment for individual projects. With an increase in scale, the unit application cost of the advanced technology will also decrease. Coordinate the collection load and product structure of all emission sources to expand the joint economic benefits and emission reductions. There are also actions at the level of policy [11]. In March 2026, Beijing introduced industrial cultivation measures, having been led by the industry, would work with universities, research institutions, and upstream and downstream enterprises to conduct technological research, build pilot testing platforms, and cultivate system integration service providers. Tangshan City has formed a CCUS working group, and departments such as the Development and Reform Commission and Ecology and Environment jointly promote technological research and industrialisation. The above measures provide organisational support for cluster deployment.

The four coupling models differ in core logic, key technologies, emission reduction paths, typical projects, and main constraints, as summarized in Table 1.

Table 1. Comparison of Four Multi-Technology Coupling Modes

Dimension	Capture-Conversion Integration	Cross-industry Coupling	Negative Emission Coupling	Renewable Integration
Core logic	Adsorption-catalysis integration, eliminating the desorption step	Cross-industry resource matching, multi-sector synergy	Dual offset via BECCS and DAC	Clean energy-driven carbon capture
Key technologies	bifunctional materials; two-tower circulation	pressure swing adsorption; waste heat cascade utilization	photosynthesis fixation; chemical absorption	renewable power/heat supply
Emission reduction path	Process shortening and reduced energy consumption	Carbon source-sink matching; by-product valorization	Fossil energy substitution; atmospheric CO_2 removal	Replacing fossil electricity; reducing indirect emissions
Typical project	CAS-Shanghai Advanced Research-Baosteel, 200,000 Nm^3/yr	HBIS Tangsteel, CO_2 capture rate >95%	Tsinghua University BECCS pathway study	CNPC 1 Mt/yr
Main constraints	CO_2 purity requirements vary by use	Relies on cross-industry spatial matching	Biomass sustainability and cost	Load flexibility; additional investment

The four modes follow different paths but converge on the same goal: reducing abatement costs, expanding CO_2 utilization value, and integrating them into a cluster deployment framework to realize scale effects.

7. Conclusion

Multi-technology coupling is required to realize the large-scale application of CCUS. The four modes of basic forms of multi-technology coupling are integrated capture and conversion, cross-industry material and energy coupling, synergy of negative emission technologies, and integration of renewable energy. Cluster deployment is the system-integration mode that incorporates them into a single framework. The four channels of this mechanism of action are as follows: At the material level, carbon sources and carbon sinks are connected to reduce intermediate losses; energetically, a cascade utilization of waste heat and pressure is employed to lower the energy consumption of capture; systemically, infrastructure sharing and scale effects are used to distribute unit costs; and value-wise, carbon dioxide is converted into tradable products to achieve economic benefits from emission reduction.

The Deployment Speed of global CCUS is increasing. By the beginning of the first quarter in 2025, the operating collection and storage capacity had exceeded 50 million tonnes. There were 734 commercial projects at all times. However, it is still significantly short of the scale required by the climate goals. Domestic situations also have problems such as high costs, mismatch of source and sink spatial distribution, and an incomplete policy system that has not formed a synergy yet.

The application of multi-technology coupling also has some practical problems, such as the requirement for cross-enterprise and cross-regional cooperation in cluster deployment. The current standard system does not meet the required standard for multi-technology integration. Materials with low-energy capture and efficient conversion are still being researched and developed. The Price Signal of the carbon market has a weak Incentive effect on CCUS investment. The following is a limitation of the current system; strengthening system integration will help address this problem and achieve both technical feasibility and economic viability through multi-technology coupling.

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