Optimization of the Application Pathway of Carbon Capture, Utilization and Storage in Energy Conservation and Carbon Reduction in Chemical Industrial Parks

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Abstract: The practical challenges of carbon emission accumulation and insufficient technological adaptability in chemical industrial parks are addressed. Based on the unique characteristics of chemical industrial parks, an optimized application path is proposed from three dimensions: source reduction and carbon sequestration synergy, process capture and transportation adaptation, and end-of-pipe storage and resource utilization upgrading. A supporting implementation guarantee system is established, in which policy mechanisms, technological innovation, risk control, and performance evaluation are integrated. Through differentiated technology combinations and end-to-end system integration, the deep integration of carbon sequestration technologies with chemical industrial park processes is promoted, and a balance between emission reduction stability and economic feasibility is achieved. Scientifically feasible technical support and guarantee solutions are provided for the large-scale deployment of Carbon Capture, Utilization and Storage (CCUS) in chemical industrial parks, thereby enabling the realization of energy conservation and carbon reduction objectives.

Keywords: chemical industrial park; Carbon Capture, Utilization and Storage; energy conservation and carbon reduction; application path optimization; implementation guarantee

DOI: 10.69979/3041-0843.26.01.051

Introduction

Currently, carbon emissions from chemical industrial parks are characterized by concentration and continuity. The balance between deep decarbonization and industrial development demands is difficult to be achieved through traditional emission reduction methods. Carbon Capture, Utilization, and Storage (CCUS) is regarded as a key support for overcoming this predicament. However, bottlenecks are encountered in the application of existing CCUS technologies in chemical industrial parks, including high costs, insufficient system integration, and inadequate process compatibility, which limit large-scale deployment. Based on the specific characteristics of chemical industrial park scenarios, the application path of CCUS is optimized, and a supporting implementation system is established. A scientifically grounded solution is provided for simultaneously achieving energy conservation, carbon reduction, and economic benefits in chemical industrial parks, and significant practical and academic value is demonstrated in promoting the green transformation of the chemical industry and improving application models for industrial carbon sequestration technologies.

1 Application Fundamentals and Adaptability Analysis of Carbon Capture, Utilization and Storage in Chemical Industrial Parks

1.1 Carbon Emission Characteristics and Carbon Sequestration Requirements of Chemical Industrial Parks

The core sources of carbon emissions in chemical industrial parks are identified as fossil fuel consumption and process emissions, and concentrated and continuous characteristics are highlighted. Energy consumption is identified as being concentrated in key aspects such as production unit operation and heating. Process emissions are identified as being directly related to core processes such as synthesis and cracking. Due to differences in industrial positioning, different carbon sequestration requirements are identified among different types of chemical industrial parks. Larger-scale carbon sequestration requirements are identified in heavy chemical industrial parks, and a focus on deep decarbonization is emphasized. Greater attention is identified as being placed on the compatibility of carbon sequestration technologies with production processes and on improvements in energy efficiency in fine chemical industrial parks. Appropriate carbon sequestration targets and implementation paths are identified as needing to be clarified by chemical industrial parks based on industrial structure and emission intensity.

1.2 Adaptability of Carbon Capture, Utilization and Storage Types to Chemical Industrial Park Scenarios

The carbon capture, utilization, and storage system is identified as covering three key stages: capture, transport, and storage. In the field of capture technologies, post-combustion capture is identified as being suitable for dispersed emission scenarios with multiple pollution sources in chemical industrial parks, pre-combustion capture is identified as being suitable for specific process systems such as coal gasification, and oxygen-enriched combustion is identified as having efficiency advantages in high-concentration emission scenarios. In the transport stage, pipeline transport is identified as meeting the requirements of large-scale and long-distance carbon transfer, while tanker transport is identified as being more suitable for small- to medium-scale or dispersed source scenarios. In terms of storage and utilization technologies, geological storage is identified as relying on the geological reservoir conditions surrounding the chemical industrial park. Chemical conversion is identified as needing to synergize with the existing industrial chain of the chemical industrial park. Technology selection is identified as needing to closely align with the industrial layout, energy structure, and geographical conditions of the chemical industrial park. Microalgae-based biocarbon fixation, characterized by high photosynthetic efficiency and rapid carbon conversion, is identified as being suitable for scenarios such as low-concentration CO_2 tail gas utilization and idle site renovation in chemical industrial parks, and is identified as being particularly suitable for chemical industrial parks equipped with industrial wastewater treatment facilities.

1.3 Analysis of Current Application Bottlenecks and Optimization Directions

Currently, the application of carbon capture, utilization, and storage in chemical industrial parks is identified as being confronted with multiple bottlenecks. Large-scale implementation is identified as being limited by high technology costs. Low efficiency in the connection between various links is identified as being caused by insufficient system integration. Overall operational efficiency is identified as being affected by a lack of deep integration with existing production processes. Bio-utilization technologies such as microalgae-based carbon fixation are identified as facing practical challenges including insufficient stability of cultivation systems, low added value of carbon conversion products, and high costs associated with large-scale cultivation. Optimization is identified as needing to focus on synergy, efficiency, and resource utilization, and emphasis is identified as needing to be placed on strengthening the collaborative design of technologies and processes, improving system integration to reduce energy costs, expanding pathways for carbon resource utilization, and achieving the dual objectives of emission reduction and efficiency improvement.

2 Optimization Design of the Application Path of CCUS Industrial Carbon Sequestration Technology in Chemical Industrial Parks

2.1 Optimization Path of Source Emission Reduction and Carbon Sequestration

The synergy between source reduction and carbon sequestration is required to focus on production process restructuring, and key measures such as raw material substitution and energy efficiency improvement are integrated to form a deeply coupled solution combining low-emission processes and targeted carbon sequestration technologies. In terms of raw material substitution, the promotion of low-carbon alternatives such as green hydrogen and biomass fuels is implemented to gradually reduce dependence on fossil fuels and to reduce total carbon emissions at the source. For high-emission processes such as ammonia synthesis and ethylene production, reaction conditions and catalyst systems are optimized to reduce carbon emissions during the process. Energy efficiency improvement is focused on the entire production process, and waste heat and process pressure are recovered to supply energy to the carbon sequestration system and to reduce additional energy consumption. Through process simulation and system optimization, unit loads and operating parameters are adjusted to achieve energy complementarity between production systems and carbon sequestration systems.

The synergistic solution is adapted to the differentiated industrial structure of the chemical industrial park. In heavy chemical industrial parks, a combination of “low-carbon raw materials + pre-combustion capture” is adopted, and system load is reduced by leveraging the inherent compatibility between processes such as coal gasification and capture technologies. In fine chemical industrial parks, focus is placed on the synergy of “process optimization + post-combustion capture”, and emission intensity is reduced by adjusting reaction pathways, while interference with the production process is reduced through the application of flexible and efficient capture technologies. In chemical industrial parks with suitable conditions, microalgae cultivation areas are simultaneously planned, waste heat from production equipment is utilized to regulate cultivation temperature, and industrial wastewater is relied upon to provide nitrogen and phosphorus nutrients, thereby achieving source-level synergy between “low-emission processes + microalgae carbon sequestration” and ultimately realizing the dual benefits of emission reduction and carbon sequestration.

2.2 Adaptation Path for High-Efficiency Capture and Transport Technology

In view of the characteristics of the coexistence of multiple pollution sources and significant differences in emission concentration in chemical industrial parks, the optimization of the layout of distributed–centralized coupled capture systems is identified as the core approach for efficiency improvement. For high-concentration emission sources such as boiler flue gas, centralized capture technology is adopted, and efficient separation is achieved through combination with mature processes such as solvent absorption and pressure swing adsorption. Post-combustion capture is defined as a technology in which CO_2 is directly captured from industrial emission flue gas. At present, solvent absorption and membrane separation are identified as the most advanced and urgently needed technologies, and the following characteristics are exhibited. Solvent absorption technology is characterized by the selective removal of gas-phase components that are easily soluble in absorbent liquids through chemical reactions using liquid-phase solutions. Chemical absorption, physical absorption, physicochemical absorption, and ionic liquid absorption are included, among which phase-change absorption is identified as a current research hotspot. This technology is characterized by low equipment investment cost, good separation performance, stable operation, and relatively mature technological development, and wide application has been achieved in chemical, food, and other industries. Membrane separation technology is characterized by the utilization of differences in physical or chemical interactions between gas components and membrane materials to achieve selective permeation and separation. According to the separation mechanism, two categories are identified, namely separation membranes and absorption membranes. During implementation, the coordinated operation of both membrane types is generally required to complete the separation process [1].

For low-concentration and dispersed emission sources, such as exhaust gasses from various production units, capture is achieved through the deployment of distributed membrane separation or adsorption capture units. After localized enrichment, the captured gasses are introduced into a centralized treatment system, thereby reducing the energy consumption associated with low-concentration flue gas capture. For certain low-concentration CO_2 exhaust gasses, direct introduction into microalgae cultivation systems within chemical industrial parks is enabled, and pretreatment steps such as capture and compression are avoided, further reducing overall system energy consumption. Transportation modes are required to be adapted to differences in carbon emission scale and transportation distance. For large-scale and long-distance transportation, pipeline transport is prioritized, and interconnection among multiple sources and sinks is achieved through optimized pipeline network layouts, thereby reducing transshipment losses. For small-scale or short-distance transportation, tanker truck intermodal transport is adopted, and flexible connections between dispersed capture units and storage or utilization sites are established, forming a transportation network characterized as "pipeline-based with tanker truck supplementation." The design of capture–transport coupling is required to be strengthened, and compression and drying pretreatment modules are configured at capture unit outlets to match the pressure and medium requirements of the transportation system. A dynamic control mechanism for the transportation network is established, through which transportation routes and capacity allocation are adjusted in response to load variations among emission sources, pipeline congestion and resource idleness are avoided, and the operational efficiency of integrated capture and transport systems is improved.

2.3 Upgrading Path of End-of-Life Storage and Resource Utilization

A dual pathway of "storage and preservation + resource utilization and value-added processing" is constructed in the end-of-pipe treatment system to balance emission reduction stability and economic benefits. From a geological storage perspective, the selection of storage sites, including saline aquifers and depleted oil and gas reservoirs, is expanded. A multi-dimensional assessment method is adopted to comprehensively evaluate geological conditions, storage capacity, and safety risks. A long-term monitoring system for storage sites is established, relying on downhole sensors and surface monitoring networks to track CO_2 occurrence status in real time and to prevent leakage risks. Diversified technological pathways are required for resource utilization. In the direction of chemical conversion, processes such as CO_2 hydrogenation to methanol, synthetic urea production, and polycarbonate synthesis are developed. The existing chemical industry chain in the chemical industrial park is utilized to achieve on-site product consumption. In the direction of biological utilization, technologies such as microalgae-based carbon fixation and microbial conversion are explored. High-temperature-resistant microalgae strains with high carbon fixation rates are selected, and photobioreactors or open culture ponds are integrated, so that a circular cultivation system is constructed using tail gas and wastewater resources from the chemical industrial park. CO_2 is converted into biofuel or high-protein feed to meet the ecological development needs of chemical industrial parks. Mineralization is combined with industrial solid waste treatment. Fly ash, steel slag, and other solid wastes are reacted with CO_2 to produce stable carbonate products, and synergy between solid waste disposal and carbon storage is achieved [2]. Technology integration and model innovation are promoted to form an end-of-pipe treatment system in which "geological storage is ensured as the bottom line for emission reduction, and resource utilization is enhanced to increase economic value," thereby improving the sustainability of Carbon Capture, Utilization and Storage (CCUS) in chemical industrial parks.

3 Application Implementation Guarantee System and Energy Conservation and Carbon Reduction Efficiency Improvement

3.1 Policy Mechanisms and Standard Norms Guarantee

Policy mechanisms and standards constitute the core support for the large-scale implementation of Carbon Capture, Utilization, and Storage (CCUS) in chemical industrial parks. From an incentive policy perspective, a subsidy mechanism linked to the carbon trading market is established, carbon emission reductions generated by CCUS in chemical industrial parks are incorporated into carbon quota trading, and market mechanisms are used to compensate for project investment and operating costs. Special fiscal subsidies or tax incentives are provided for low-carbon raw material substitution and the application of efficient carbon sequestration technologies, thereby lowering the barriers to technological upgrading for enterprises. At the standards level, technical standards covering the entire CCUS process are improved, and key indicators such as capture efficiency, transportation safety, and storage stability are clarified. Standards for carbon emission accounting and carbon sequestration effect verification at the chemical industrial park level are formulated, and data statistical standards and monitoring methods are unified. A third-party evaluation mechanism is introduced to conduct regular assessments of technology adaptability, emission reduction authenticity, and environmental safety, forming a closed-loop management system of "policy incentives – standard constraints – evaluation and supervision." Institutional guarantees are thus provided for the compliant promotion and continuous optimization of CCUS in chemical industrial parks, and policy barriers and regulatory gaps in technology deployment are addressed and overcome [3].

3.2 Technological Innovation and Engineering Support System

Technological innovation and engineering support focus on breakthroughs in key bottlenecks and industrialization. Key technological breakthroughs focus on the research and development of core equipment and materials, such as low-cost and high-efficiency capture materials, long-distance and low-loss transportation equipment, and CO_2 conversion catalysts under mild conditions. Technical bottlenecks such as high energy consumption in low-concentration CO_2 capture and difficulties in ensuring the safety control of geological storage are addressed, and system optimization models adapted to multi-source collaboration in chemical industrial parks are developed to improve the integrated efficiency of capture, transportation, storage, and utilization. The construction of engineering platforms relies on leading enterprises in chemical industrial parks, and pilot-scale demonstration bases are jointly established with research institutions to conduct technology verification under different scales and process scenarios. Practical experience in engineering design, construction, operation, and maintenance is accumulated, technology-sharing and achievement transformation mechanisms are established, and high-quality industrial resources are integrated to build technology service platforms that provide customized technical solutions and engineering guidance for small and medium-sized chemical industrial parks. The integration of digital technologies with Carbon Capture, Utilization, and Storage promotes the application of simulation, real-time monitoring, and other tools to optimize project design and operating parameters, thereby reducing engineering risks and operating costs.

3.3 Risk Prevention and Control and Full-Cycle Effectiveness Assessment

Risk prevention and control and full-cycle performance evaluation constitute the key guarantee for the sustainable operation of Carbon

Capture, Utilization, and Storage (CCUS). In the risk prevention and control dimension, a multi-level environmental risk monitoring network is established. For risk points such as CO_2 leakage, geological disturbance, and process adaptability, ground sensors, downhole monitoring devices, and UAV patrol systems are deployed to achieve real-time risk warning. Graded emergency response plans are formulated, response procedures and disposal measures for sudden events such as leakage and equipment failure are clarified, and special equipment and materials such as emergency sealing and gas recovery are reserved to reduce environmental and safety risks. In performance evaluation, a full-cycle indicator system covering energy consumption, carbon emission reduction, economic performance, and environmental impact is constructed, and comprehensive assessments are conducted from the technological, economic, and environmental dimensions. At the technical level, parameters such as capture efficiency, transportation loss, and storage stability are monitored. At the economic level, investment returns, operating costs, and carbon revenues are calculated, and at the environmental level, potential impacts on surrounding ecosystems, soil, and water quality are tracked. An evaluation result feedback mechanism is established to promote the continuous optimization of technical parameters and operational strategies based on evaluation data, ensuring that energy conservation and carbon reduction efficiency are maximized and risks remain controllable throughout the entire project life cycle.

4 Conclusion

This paper focuses on the application of Carbon Capture, Utilization, and Storage in chemical industrial parks and on the goals of energy conservation and carbon reduction. Beginning with a basic compatibility analysis, the carbon emission characteristics of chemical industrial parks and the logic of technology adaptation are clarified. Existing bottlenecks are addressed, and a comprehensive optimization pathway is constructed, supported by a multi-dimensional guarantee system that encompasses policy mechanisms, technological innovation, risk prevention and control, and performance evaluation. Adaptable technical solutions and implementation guarantee models are thus provided, offering systematic support for the large-scale deployment of Carbon Capture, Utilization, and Storage in chemical industrial parks. The green and low-carbon transformation of the chemical industry is thereby facilitated, and valuable reference is provided for the scenario-based application of carbon sequestration technologies in the industrial sector.

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