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Integrating Carbon Capture and Storage Across the Building Life Cycle for Material Decarbonization

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Abstract. The construction industry, accounting for nearly 40% of global carbon emissions, faces pressing demands for energy conservation and emission reduction. Concrete, as a major source of carbon emissions, requires a green transition to mitigate its environmental impact. This article focuses on Carbon Capture and Storage (CCS) technology and explores its application potential and strategies for reducing the carbon footprint of building materials across their entire life cycle. By analyzing the technical principles of CCS and its integration within the construction sector, this study demonstrates that CCS can address direct emissions from building operations and be embedded into the material life cycle through carbon utilization—such as carbon curing and mixing during production, and enhancing recycled aggregates at the end of life—thereby establishing a multi-stage carbon cycle. In conclusion, CCS technology is essential for achieving deep decarbonization in the construction sector. However, its large-scale deployment relies on standardization, policy incentives, and cross-sector collaboration.

Keywords: carbon capture and storage, carbon reduction, building materials

1. Introduction

The process of carbon dioxide generation in buildings spans their entire life cycle, from material production, construction, daily operation to final demolition and disposal [1]. Each stage directly or indirectly generates a large amount of carbon dioxide. As the stock of existing buildings grows, retrofitting them for carbon reduction offers a significant opportunity to minimize the carbon footprint of the construction sector. Currently, traditional residential construction models generally feature high-carbon emission processes and material systems, which strains ecological carrying capacity and complicates efforts to meet sustainable development goals in urbanizing areas [2]. As a key carrier for the low-carbon transformation of the construction industry, eco-friendly building materials can effectively enhance living comfort and ecological benefits by optimizing their energy consumption. Concrete, as an important material for infrastructure, is the most consumed artificial material in construction. According to calculations, most of the carbon dioxide (CO_2) emissions from concrete come from cement production and material transportation, with each ton of cement production generating a corresponding amount of CO_2 emissions. The production of other raw materials in concrete, such as aggregates, admixtures, and the construction process, are also reasons for high carbon emissions. The existing carbon reduction renovation technologies mainly include

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passive technologies, active technologies, renewable energy technologies, and carbon capture and storage (CCS) technology [3]. CCS is the most practical and efficient method for achieving carbon reduction, carbon peak, and carbon neutrality. This study has systematically analyzed the application potential of CCS technology for carbon reduction across the building life cycle, focusing on its technical principles, practical application scenarios, and typical cases. It also combines carbon reduction strategies for building materials from production, use to disposal, and proposes an integrated path and policy recommendations for CCS in the building field to promote the low-carbon transformation and sustainable development of the construction industry [4].

2. Principle of CCS technology

2.1. CO2 capture technology

CO_2 capture is the first step in the CCS process. The method involves separating, collecting, purifying and compressing CO_2 from the emission sources of combustion to reduce the CO_2 emissions from factories and thereby lower the CO_2 content in the atmosphere. There are mainly three types of CO_2 capture technologies: post-combustion capture, pre-combustion capture and oxy-fuel combustion technology [5].

Post-combustion capture technology involves capturing or separating CO_2 from the combustion products after fuel combustion. Most existing thermal power generation technologies, including new construction and retrofits, can only use post-combustion capture for CO_2 separation, which has a wide range of applications. However, the large volume of flue gas, combined with its low pressure and low CO_2 concentration, results in high operating costs. Post-combustion capture can be directly applied to traditional power plants. This technology route captures CO_2 from the flue gas of traditional power plants with relatively low investment [6]. Pre-combustion capture technology converts carbon-containing substances into other substances before fuel combustion and then separates out CO_2. This technology is based on the integrated gasification combined cycle (IGCC) technology. It first gasifies coal into clean gas energy, thereby separating CO_2 before combustion and preventing it from entering the combustion process. Moreover, the concentration and pressure of CO_2 increase as a result, making separation more convenient. It is currently the most cost-effective capture technology and is highly regarded by the academic community. However, the problem lies in that traditional power plants cannot apply this technology and instead need to build dedicated IGCC power stations, which cost more than twice as much as existing traditional power plants. Pure oxygen combustion technology mainly utilizes an air separation system to obtain oxygen-rich or pure oxygen. The fuel and oxygen enter a specially designed pure oxygen combustion furnace for combustion. The combustion exhaust gas needs to be reinjected into the combustion furnace. On the one hand, this reduces the temperature; on the other hand, it increases the proportion of CO_2 in the overall volume of the specific gas mixture. Due to the high proportion of CO_2 in the exhaust gas, the energy consumption for CO_2 capture can be reduced. However, it is necessary to adopt a dedicated pure oxygen combustion technology, which requires specific materials for pure oxygen combustion equipment and an air separation system. This will significantly increase the system cost. Large-scale pure oxygen combustion technology is still in the research and experimental stage.

2.2. Transportation and storage technologies of CO_2

CO_2 transportation technology is currently well-developed and widely applied. Its main transportation methods include pipeline transportation and tank transportation. Pipeline

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transportation can be divided into gaseous, liquid and supercritical state transportation. Due to the different phases of the transported medium, the transportation processes also have certain differences. Currently, pipeline transportation mainly adopts supercritical state transportation. In China's oil fields, internal pipelines mostly use gaseous or liquid transportation. The technology of pipeline transportation is relatively mature. This method is well-suited for long-distance transport of large CO_2 volumes and is one of the most common transportation approaches. It is one of the most commonly used methods for transporting CO_2. Its disadvantage is that the one-time investment cost is relatively high. Tank transportation mainly uses railway or road transportation. Its characteristics are that it is suitable for small-scale short-distance transportation. The disadvantage is that it is not economically viable for large-scale use. After the transportation of CO_2 is completed, a systematic and rigorous storage process is required to control the entry of CO_2 into the atmosphere. It mainly includes three methods: geological storage, ocean storage, and chemical storage. Geological storage refers to injecting CO_2 into different geological bodies such as subsea salt marshes, oil and gas layers, and coal mines. The depth of geological storage of CO_2 is generally below 800 meters, as such temperature and pressure can keep CO_2 in a supercritical state. Geological storage is expected to be the mainstream storage method in the future. Oil and gas field storage is the main method of geological storage. Reinjecting CO_2 into oil and gas fields where oil and gas recovery is difficult can significantly increase the recovery rate of oil and gas fields, improve the utilization of resources, and accordingly extend the production life of oil wells. According to statistics, the amount of CO_2 that can be stored in the world's depleted oil and gas fields is approximately 9,230 billion tons, equivalent to the amount of CO_2 emitted by global fossil fuel-fired power plants over 125 years. Ocean storage refers to storing CO_2 in deep-sea water or on the seabed. Chemical storage involves a series of complex chemical reactions to convert CO_2 into stable carbonates, thereby achieving permanent storage of CO_2 [7].

3. Full-life carbon reduction of building materials

The carbon emissions from building materials like concrete occur throughout their life cycle. Deep integration of CCS technology with each stage of their life cycle is the key to achieving deep decarbonization in the construction industry. Its application is no longer limited to traditional end-of-pipe capture and storage, but extends forward to carbon capture and utilization (CCU), forming a closed-loop system of "capture - utilization - storage" [8].

3.1. Pre-service stage

The carbon emissions during the pre-service stage of concrete mainly come from cement production. At this stage, the core of applying CCS technology is CCU, which converts captured CO_2 into resources, directly reducing the net emissions during the production process. Post-combustion capture technology is deployed in cement plants to capture CO_2 from the flue gas at the kiln tail. These captured CO_2 are not all sequestered but can be utilized as resources. During the curing stage, after the concrete precast components are formed, CO_2 is injected into the curing kiln. CO_2 undergoes mineralization reactions with the hydration products of cement, generating stable calcium carbonate. This not only permanently stores CO_2 but also enhances the early strength of concrete and reduces the amount of cement used. During the mixing stage, CO_2 is directly injected into the concrete mixing process, improving the workability and early performance of fresh concrete through mineralization reactions, achieving carbon sequestration during production. Alternatively, captured CO_2 can be reacted with industrial waste (such as steel slag and fly ash) to produce carbon-negative

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artificial aggregates or new types of cementitious materials, fundamentally replacing traditional high-carbon cement [9].

3.2. During service stage

The energy consumption of buildings during operation (heating and cooling) indirectly leads to huge CO_2 emissions. At this stage, the application of CCS technology in coordination with building energy-saving measures can deal with centralized emission sources. For large commercial complexes, regional energy centers or buildings using gas boilers, post-combustion capture technology can be adopted to capture CO_2 from the flue gas of boilers or combined heat and power systems. This directly reduces the direct carbon emissions during the building operation process. Or energy-saving technologies such as phase change energy storage concrete and heat insulation reflective coatings can be utilized to reduce building energy consumption, indirectly reducing carbon emissions from energy sources such as power plants, thereby alleviating the application pressure of CCS systems on the energy side. Both approaches work together from the two dimensions of "energy conservation at the source" and "capture at the end", achieving coordinated carbon reduction [10].

3.3. Post-service period

Concrete waste from demolition represents a substantial resource for recycling. The core value of CCS technology at this stage lies in enhancing the resource utilization rate of construction waste and sequestering carbon in the process. The recycled aggregates obtained by crushing the demolished concrete are placed in a closed reactor and exposed to industrial source captured CO_2. CO_2 reacts with the cement hydration products on the surface of the aggregates to form calcium carbonate. This process not only sequesters CO_2 but also significantly increases the density and strength of the recycled aggregates, reduces their water absorption rate, and makes their performance closer to that of natural aggregates, thereby enhancing the application value and high-grade utilization ratio of the recycled aggregates. If mobile CCU devices can be deployed near the building demolition site to carbonize and strengthen the recycled aggregates, it can greatly reduce the carbon emissions from aggregate transportation and achieve a truly integrated local recycling model of "demolition-waste-production-use".

Through the above path, CCS technology is closely integrated into every stage of the building material life cycle, providing comprehensive support for the carbon neutrality of the construction industry from the source to the end.

4. Typical case analysis

4.1. The carbon capture demonstration project of huaneng group's Beijing gaobeidian thermal power plant

In June 2008, the first set of flue gas CO_2 capture equipment independently designed and constructed by Huaneng Group in China was put into operation at Huaneng Beijing Thermal Power Plant, with an annual capture capacity of 3,000 tons of CO_2. Since its operation, the CO_2 recovery rate has been over 85%, and the purity has reached 99.99%, with all indicators meeting the design values. The reliability of the equipment operation and energy consumption indicators are also at the international advanced level. The food-grade CO_2 captured by the project and used in the refining process can be reused to supply the Beijing carbonated beverage market. As China's first CO_2

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capture project in a coal-fired power plant, the high-purity food-grade CO_2 captured by this project is mainly supplied to the Beijing carbonated beverage market. This model demonstrates a commercial path for CCU. Although it is not directly used in building materials, its successful capture technology and commercial model lay the technical and economic foundation for subsequent applications of CO_2 in industrial fields such as concrete curing and chemical synthesis, including the construction industry [6].

4.2. The CCS demonstration project of huaneng group's Tianjin green coal power IGCC power plant

The 250MW IGCC unit of Huaneng Group's Tianjin Green Coal Power was completed and put into operation in 2011. In 2016, a 400MW IGCC unit equipped with a CO_2 capture device was completed. The demonstration project aims to research and develop, and promote the demonstration of coal-based power generation systems with near-zero CO_2 emissions. At the same time, it can significantly improve power generation efficiency and master the design, construction and operation technology of large-scale coal gasification projects. This project is based on pre-combustion capture technology and is a leading green coal power project in the world. The captured CO_2 has a higher purity and greater pressure, which is very suitable for subsequent geological storage or high-value utilization. For the construction industry, such a stable and large source of CO_2 is an ideal gas source guarantee for the future large-scale application of CCU technologies such as "carbon curing" or "carbon mixing", demonstrating the potential for integrating the low-carbon supply chain from the energy end to the material end.

5. Policy recommendations

5.1. Comparison and implications of international CCS and building carbon reduction policies

To further promote the application of CCS technology in carbon reduction throughout the entire life cycle of buildings, this section selects representative policies from Germany, the United States of America and China regarding CCS, green buildings, and industrial emissions reduction for comparative analysis. The policy contents of each country are shown in Table 1.

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Table 1. Comparison of CCUS and building carbon reduction policies in various countries

Country	Policy Area	Key Measures	Main Characteristics
Germany	Carbon Sequestration Strategy	Legislation promoting offshore storage and cross-border transport; focus on sectors like cement.	Legislative breakthrough, focusing on industrial decarbonization.
	Building Energy Efficiency	Implementation of mandatory energy efficiency certification with whole-process supervision.	Systematic certification, promoting energy saving and carbon reduction.
the United States of America	Storage Safety	Improved regulations ensuring storage safety, with strict monitoring requirements.	Enhanced regulation, emphasizing risk control.
	Green Building	LEED rating system, multi-dimensional assessment.	Market-driven, guiding comprehensive emission reduction.
China	Fiscal Incentives	Central and local subsidies supporting demonstration projects.	Funding guidance, accelerating technology demonstration.
	Construction Methods	Promotion of prefabricated buildings and use of low-carbon building materials.	Model innovation, reducing process emissions.

International experience demonstrates that promoting the application of CCS technology in the construction sector requires a multi-pronged approach. First, it is essential to follow Germany's example by enacting legislation to clarify the strategic position of CCS in hard-to-abate sectors and resolve legal issues associated with storage. Second, reference can be made to the United States' approach of establishing a stringent legal and regulatory framework, particularly concerning environmental supervision, to ensure technological safety. Finally, China's model of utilizing fiscal subsidies to effectively incentivize technology demonstration and early-market expansion can be referenced. Integrating CCS with mature systems such as green building standards and construction industrialization will create synergistic policy effects.

5.2. Suggestions for promoting the application of CCS technology in the construction field in China

Based on the analysis of the CCS technology path throughout the text and drawing on international policy experience, this paper puts forward the following promotion suggestions.

1. Improve the standard system: Incorporate the application of CCS technology into the green building evaluation standards, set up special innovation scores, and focus on evaluating the amount of carbon captured, utilization pathways, and net carbon reduction benefits.

2. Strengthen economic incentives: Establish a special demonstration fund for CCS, provide subsidies or tax incentives based on the amount of carbon captured, and reduce the initial cost of projects.

3. Lay out infrastructure: Plan regional CO_2 pipeline networks to connect emission sources, utilization points and storage sites, form industrial clusters and achieve economies of scale.

4. Promote technological integration: Support the research and development of low-energy consumption capture, modular equipment, and CO_2 mineralization utilization technologies, and encourage their synergy with BIPV, intelligent management, and other technologies [10].

5. Strengthen international collaboration: Participate in the formulation of international standards, draw on the experience of Europe and the United States in site selection, monitoring and risk management for storage, and enhance the implementation capacity of the industry.

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6. Conclusion and outlook

6.1. Conclusion

This article provides a systematic examination of the application potential and technical pathways for integrating CCS technology across the entire building life cycle. The analysis confirms that CCS transcends its traditional role as a solution for centralized emissions from the energy and industrial sectors. Crucially, through CCU methods, it can be deeply embedded into the very fabric of building materials themselves. This integration spans the pre-service stage (e.g., carbon curing and mixing to enhance concrete properties and sequester CO_2), the in-service stage (directly capturing emissions from building energy systems), and the post-service stage (utilizing CO_2 to enhance the quality of recycled aggregates). This creates a transformative "capture-utilization-storage" closed-loop system, positioning CCS as an indispensable technical foundation for achieving deep decarbonization in the construction industry. Synthesizing international policy experiences reveals that scaling up CCS/CCUS in the construction sector necessitates a multi-faceted strategy: establishing robust standard systems and lifecycle assessment protocols, strengthening economic incentives such as targeted subsidies and carbon pricing mechanisms, strategically planning CO_2 transport infrastructure, and actively promoting technological integration with building information modeling (BIM), prefabrication, and renewable energy systems.

6.2. Outlook

While this study outlines a viable pathway for CCS towards carbon neutrality in construction, it acknowledges several limitations, primarily its focus on qualitative technical-pathway analysis and feasibility demonstration. A significant gap remains in the quantitative analysis and comparative cost-effectiveness assessment of different technological solutions (e.g., post-combustion capture vs. direct air capture (DAC) vs. carbonation curing) within specific building contexts. Future research should prioritize developing detailed techno-economic models to evaluate the levelized cost of carbon abatement for various CCS/CCU applications. Such models would provide a critical evidence base for strategic project investment and nuanced policy-making. Furthermore, investigations into long-term material performance, permanent carbon storage verification protocols, and the development of comprehensive regulatory frameworks are essential to ensure environmental integrity and public acceptance. Addressing these challenges through targeted research and international collaboration is paramount to accelerating the transition of CCS from pilot demonstrations to widespread, cost-effective implementation in the built environment.

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