

Research on Integrated Pathways of Low-Carbon Technologies in Sustainable Buildings: Based on the Life Cycle Assessment Method

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Abstract. The construction industry accounts for approximately 37% of global greenhouse gas emissions and 40% of global energy consumption. Against the backdrop of the "Dual Carbon" goal, how to achieve deep decarbonization across the whole life cycle of buildings through the effective integration of low-carbon technologies has become a core issue in the field of sustainable construction. Based on the Life Cycle Assessment (LCA) method, this study systematically explores the integration pathways of low-carbon technologies in sustainable buildings. Adopting a combination of literature review and comparative case analysis, the study sorts out the application framework of LCA in building carbon emission assessment, and analyzes the emission reduction potential and synergistic effects of four types of technologies—low-carbon building materials, passive design, active systems, and renewable energy—across different life cycle stages. The findings show that the emission reduction effect of low-carbon technologies is highly dependent on technology combinations and early intervention in the design stage; the marginal benefit of a single technology decreases as its application level increases, while the synergistic integration of multiple technologies can achieve a significant superimposed emission reduction effect; and the integrated framework of LCA and BIM provides effective technical support for low-carbon decision-making in the design stage. This study proposes a three-stage low-carbon technology integration path model of "source carbon reduction – process carbon reduction – end-of-life carbon offset", which provides a theoretical reference and practical framework for low-carbon design and decision-making of sustainable buildings.

Keywords: Life Cycle Assessment (LCA), sustainable buildings, low-carbon technologies, technology integration, carbon emissions

1. Introduction

Global climate change has become the most severe environmental challenge of the 21st century. Since 1880, the global average atmospheric temperature has risen by approximately 1.1°C, with most of the warming occurring after 1975. As one of the main sources of carbon emissions, the construction industry accounts for about one-third of global energy-related carbon emissions over its whole life cycle. According to data released by the China Association of Building Energy Efficiency,

carbon emissions from China's building and construction sector reached 5.13 billion tons of carbon dioxide in 2022, accounting for 48.3% of the country's total energy-related carbon emissions.

In this context, promoting the low-carbon transition of the construction industry has become a global consensus. However, existing studies mostly focus on the emission reduction effect of a single technology or a single life cycle stage, lacking systematic exploration of the integration pathways of multiple low-carbon technologies from a whole-life cycle perspective. The emission reduction potential of low-carbon technologies depends not only on the performance of the technology itself, but also on the synergistic effects between technologies and the timing of their integration in the design stage.

2. Literature review

2.1. Application of Life Cycle Assessment (LCA) in the construction sector

Life Cycle Assessment (LCA) is a systematic environmental impact assessment method that follows the ISO 14040 and ISO 14044 standard frameworks. In the construction sector, LCA is widely used to evaluate the environmental load of buildings throughout their life cycle, from building material production, construction, operation and maintenance to demolition and recycling [1].

Building LCA research has undergone a paradigm shift from focusing on operational energy consumption to focusing on the whole life cycle. Traditional wisdom holds that energy consumption in the building operation stage dominates, but studies have shown that in new high-efficiency buildings, embodied carbon emissions from building material production and construction stages can account for as much as 75%. This finding has prompted researchers to expand their vision from operational carbon to embodied carbon, promoting the development of "Whole Life Carbon Assessment" [2].

In recent years, the integration of LCA and Building Information Modeling (BIM) has become an important trend. The BIM-LCA integrated framework can support data-driven low-carbon decision-making from the early design stage, enabling rapid iteration and optimization of design schemes. In addition, the dynamic LCA approach, which takes into account time-evolving factors such as future grid decarbonization and climate change, provides a more accurate tool for long-term carbon assessment [3].

2.2. Research status of low-carbon technologies for buildings

Low-carbon technologies for buildings can be divided into four major categories according to their application stages and functions:

(1) Low-carbon building materials. Material substitution is the most direct way to reduce embodied carbon. Studies have shown that replacing reinforced concrete with wood structures can reduce Global Warming Potential (GWP) by approximately 55%. Replacing concrete with Cross-Laminated Timber (CLT) can reduce greenhouse gas emissions by up to 9.22%. Incorporating supplementary cementitious materials such as fly ash and increasing the proportion of recycled steel are also effective carbon reduction strategies.

(2) Passive design strategies. These include optimization of building orientation, shape factor control, window-to-wall ratio (WWR) optimization, and external insulation layer design. A systematic study covering six climate zones shows that controlling the WWR within 0.15–0.30 and the thickness of exterior wall and roof insulation layers within 0.07–0.09 meters can approach carbon neutrality goals while ensuring daylighting and anti-glare performance.

(3) Active systems and equipment. These include high-efficiency HVAC systems, heat pump technology, etc. Studies have found that although Ground Source Heat Pumps (GSHP) have high initial costs, their whole-life cycle energy saving and emission reduction benefits are significant.

(4) Renewable energy integration. Photovoltaic (PV) systems significantly reduce building energy demand through the dual effects of shading and power generation. The configuration decision of Building-Integrated Photovoltaics (BIPV) has an impact on whole-life cycle carbon intensity comparable to that of climate zone factors.

2.3. Research progress in low-carbon technology integration

Existing studies have begun to focus on the combination optimization of multiple low-carbon technologies. For example, a retrofit study of a traditional dwelling in Liuyang, China showed that integrating high-performance bio-based insulation materials, ground source heat pumps and PV systems can reduce whole-life cycle carbon emissions by 72% and costs by 61%. Another study of detached houses in Vancouver explored the comprehensive optimization path combining low-carbon material substitution, passive design, mechanical system upgrade and renewable energy integration [4].

However, current research still has the following shortcomings: first, most studies focus on the emission reduction effect of a single technology or a single stage, lacking a systematic integration framework; second, the synergistic effects and trade-off relationships between technologies have not been fully quantified; third, there is a lack of operational guidance for integration pathways from the perspective of design decision-making.

3. Research design and methods

3.1. Research design

This study adopts a mixed research method that is mainly qualitative and supplemented by quantitative analysis. The overall research design is divided into three levels:

1. Comprehensive literature analysis. Systematically sort out domestic and foreign research on building LCA and low-carbon technology integration, extract key parameters (carbon emission factors, technology emission reduction potential, life cycle stage distribution, etc.), and establish a technology-stage-effect correlation matrix.

2. Comparative case analysis. Select representative building cases (including new office buildings, existing building retrofits, temporary buildings, etc.), compare and analyze the whole-life cycle carbon emission performance of different low-carbon technology combinations, and identify effective integration modes.

3. Integration path model construction. Based on the findings of the first two levels, construct a three-stage low-carbon technology integration path model of "source carbon reduction – process carbon reduction – end-of-life carbon offset".

3.2. Analytical framework

This study adopts a three-dimensional analytical framework of "stage – technology – effect":

Life cycle stage dimension: building material production (A1-A3), construction (A4-A5), operation (B1-B7), demolition and recycling (C1-C4)

Technology category dimension: low-carbon materials, passive design, active systems, renewable energy

Effect evaluation dimension: carbon reduction contribution of each technology at each stage (absolute emission reduction amount, relative emission reduction rate)

4. Research findings

4.1. Whole life cycle of buildings

Through a comprehensive analysis of multiple LCA studies, the whole-life cycle carbon emissions of buildings present the following distribution characteristics:

The operation stage still dominates but its proportion is declining. In traditional buildings, carbon emissions from the operation stage account for 60%–80% of the total whole-life cycle emissions. However, with the improvement of building energy efficiency standards, this proportion is declining. In ultra-low energy buildings, the proportion of embodied carbon from the building material production stage can rise to 40%–50% [5].

The importance of embodied carbon is increasingly prominent. The building material production stage (A1-A3) is the main source of embodied carbon, among which structural materials (concrete, steel) contribute the most. Studies have shown that for office buildings with traditional reinforced concrete structures, the GWP of the structural system can be reduced by approximately 26% through optimized design.

There are significant differences in carbon emission profiles among different building types. For temporary buildings, carbon emissions from building material production and processing are particularly prominent; for long-life buildings, the cumulative effect of carbon emissions in the operation stage is more significant.

4.2. Emission reduction potential of various low-carbon technologies

Emission reduction effect of low-carbon building materials. Material substitution is the most effective means of embodied carbon reduction. Compared with reinforced concrete structures, wood structures can achieve a 55% reduction in GWP; replacing concrete with CLT can reduce GHG emissions by up to 9.22%. However, the whole-life cycle cost of wood solutions may be 56% higher, highlighting the trade-off between environmental benefits and economic feasibility.

Emission reduction contribution of passive design. Improving the thermal insulation performance of the building envelope can effectively reduce operational energy consumption and carbon emissions, but its marginal benefit decreases as the insulation layer thickness increases. Early design decisions such as window-to-wall ratio and shape factor have an impact on whole-life cycle carbon comparable to that of climate zone factors [6].

Emission reduction effect of active systems. Heat pump technology (especially ground source heat pumps) shows significant emission reduction and cost saving benefits over the whole life cycle [7].

Integration benefits of renewable energy. Through the dual effects of shading and power generation, PV systems can not only reduce operational energy consumption, but also bring additional embodied carbon optimization space through the integrated design of BIPV in the building material production stage [8].

4.3. Technology synergies and integration modes

The emission reduction effect of a single technology is limited, and the integration of multiple technologies can produce significant synergistic effects:

Synergy of materials + passive design. The combination of high-performance insulation materials and optimized building envelope design can reduce operational energy consumption by 14.39%.

Synergy of passive + active design. Good building envelope performance can reduce the installed capacity and operating load of HVAC systems, thereby reducing the embodied and operational carbon of equipment and materials.

Synergy of active + renewable energy. The combination of ground source heat pumps and PV systems can achieve 72% carbon reduction and 61% cost savings.

The critical role of early design intervention. LCA intervention in the early design stage has greater emission reduction potential than later optimization. The BIM-LCA integrated framework enables design teams to compare the whole-life cycle impacts of different technology combinations at the scheme stage.

4.4. The "three-stage" integration path model

Based on the above findings, this study proposes a three-stage low-carbon technology integration path model of "source carbon reduction – process carbon reduction – end-of-life carbon offset":

1. **Source carbon reduction (design – building material production stage):** (1) Introduce LCA assessment at the scheme design stage to optimize passive parameters such as building shape, orientation and window-to-wall ratio; (2) Select low-carbon building materials (wood structures, high-recycled-content steel, supplementary cementitious materials, etc.); (3) Use BIM-LCA integrated tools for multi-scheme comparison and selection.

2. **Process carbon reduction (construction – operation stage):** (1) Adopt prefabricated and industrialized construction methods to reduce waste in the construction stage; (2) Adopt high-efficiency equipment systems (heat pumps, high-efficiency HVAC, etc.) in the operation stage; (3) Integrate renewable energy systems (BIPV, PV, etc.).

3. **End-of-life carbon offset (demolition – recycling stage):** (1) Consider the disassembly and material recyclability of buildings at the design stage; (2) Establish circular utilization pathways for building materials.

5. Conclusion

Based on the life cycle assessment method, this study systematically explores the integration pathways of low-carbon technologies in sustainable buildings, and draws the following main conclusions: First, the distribution of whole-life cycle carbon emissions in buildings is shifting from "operational carbon-dominated" to "equal emphasis on embodied and operational carbon", and the proportion of carbon emissions from the building material production stage can reach 40%–75% in high-efficiency buildings. This shift requires that building low-carbon strategies must cover the whole life cycle rather than focusing only on the operation stage. Second, there are significant differences in the emission reduction potential of different types of low-carbon technologies at each life cycle stage. Low-carbon material substitution is the most effective means of embodied carbon reduction (up to 55% GWP reduction); the marginal benefit of passive design decreases as the application level increases; the integration of active systems and renewable energy can achieve significant synergistic emission reduction (up to 72%). Third, the effective integration of low-carbon

technologies needs to follow the three-stage path of "source carbon reduction – process carbon reduction – end-of-life carbon offset". The key lies in early intervention in the design stage, the application of BIM-LCA integrated tools, and the synergistic configuration of multiple technologies.

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