

# Research on Decarbonisation Path and Technological Innovation of Architectural Design under the Perspective of Sustainable Development

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**Abstract:** Against the backdrop of global climate change and the “dual carbon goals,” the building sector—a major contributor to energy consumption and carbon emissions—has made its low-carbon transformation a critical component of sustainable development. This paper systematically examines low-carbon pathways and technological innovation directions in architectural design from a sustainability perspective. It articulates the necessity of low-carbon building design across ecological, economic, and social dimensions, emphasizing the logical foundation for harmonizing architectural design with environmental development. Exploring pathways to low-carbon buildings across three dimensions—planning and design, construction and operation, and policy and evaluation systems—it highlights the importance of controlling carbon emissions throughout the entire life cycle and fostering multi-stakeholder collaboration. Focusing on cutting-edge innovations such as digital intelligent technologies, renewable energy integration, and novel low-carbon building materials, the study analyzes their potential and trends in driving the sector's low-carbon transformation. Findings indicate that the organic integration of low-carbon pathways and technological innovation will provide robust support for the green development of the construction industry and the achievement of the “dual carbon” strategic goals.

## 1. Introduction

As global climate change intensifies, energy consumption and carbon emissions have become core challenges constraining sustainable human development <sup>[1]</sup>. The building sector, accounting for a significant share of total energy consumption and carbon emissions, is regarded as a critical domain for achieving low-carbon transformation <sup>[2]</sup>. As the most fundamental and upfront stage in a building's entire lifecycle, architectural design not only determines spatial layout, energy utilization, and material selection but also directly influences carbon emissions during subsequent construction and operation phases <sup>[3]</sup>. Exploring low-carbon pathways for architectural design from a sustainable development perspective holds significant theoretical and practical value <sup>[4]</sup>. Domestic and international scholars and industry practitioners have continuously explored the application of energy-efficient design and green technologies, forming a research framework centered on green building standards, energy efficiency regulations, and renewable energy utilization <sup>[5]</sup>. However, challenges persist, including insufficiently systematic approaches, inadequate technological innovation, and disconnects between policy and practice <sup>[6]</sup>. This paper attempts to start from the macro-level goals of sustainable development, delve into the logical foundations and practical demands of low-carbon architectural design, explore low-carbon pathways across planning, construction, and operation phases, and focus on the role of emerging technological innovations in driving the low-carbon transformation of the construction industry <sup>[7]</sup>. Through theoretical review and pathway analysis, it aims to provide reference ideas for the green development of the construction industry and contribute academic and practical value toward achieving the “dual carbon” goals <sup>[8]</sup>.

## 2. The Sustainability Logic of Low-Carbon Architectural Design

Low-carbon architectural design is fundamentally rooted in the overarching strategy of sustainable development <sup>[9]</sup>. Sustainable development emphasizes the coordinated unity of economic, social, and environmental dimensions <sup>[10]</sup>. As a vital medium for human life and production, architectural design involves not only functionality and aesthetics but is also intrinsically linked to energy utilization, resource consumption, and ecological conservation. Within this logic, low-carbon architectural design represents not merely a technical choice for energy conservation and emission reduction but a crucial pathway for driving societal sustainable transformation. By guiding architectural design toward energy efficiency, environmental protection, and health, we can effectively alleviate the construction industry's environmental pressure and foster harmonious coexistence between humanity and nature. Building Energy Balance

$$E_{\text{total}} = E_{\text{heating}} + E_{\text{cooling}} + E_{\text{lighting}} + E_{\text{appliances}} \quad (1)$$

Low-carbon architectural design holds significant environmental value. The energy consumption and carbon emissions throughout the building lifecycle account for a substantial proportion of global carbon emissions. Particularly against the backdrop of rapid urbanization, the energy demands of the construction sector continue to rise. By integrating green principles and low-carbon strategies during the design phase, energy consumption and greenhouse gas emissions can be substantially reduced, thereby alleviating ecological burdens. Simultaneously, thoughtful design optimizes natural ventilation, daylighting, and thermal performance, reducing reliance on mechanical systems while maximizing the use of natural resources to achieve harmonious interaction with the environment.

From an economic perspective, low-carbon building design drives industrial upgrading and green economic development. While initial construction costs may increase, long-term economic returns are often achieved through reduced operational energy consumption and maintenance savings. As green finance policies and carbon market mechanisms mature, low-carbon buildings will gain greater policy and financial support, further highlighting their economic benefits. For developers and users, low-carbon buildings represent not only cost control and value enhancement but also a key strategy for boosting market competitiveness.

Low-carbon building design embodies social value and humanistic care. Against the backdrop of the global deepening of the “healthy building” concept, low-carbon architectural design improves indoor environmental quality, enhances comfort and safety in living and usage, thereby elevating people's quality of life. The promotion of low-carbon building design helps raise public environmental awareness and foster green lifestyles. Its societal significance extends beyond reducing carbon emissions to building a green, shared, and sustainable model of social development, providing support for the long-term sustainable development of both people and society. Carbon Emission Calculation

$$C = \sum_{i=1}^n (E_i \times EF_i) \quad (2)$$

### 3. Exploring Pathways for Low-Carbon Building Design

Achieving low-carbon building design relies not on a single approach but requires systematic consideration from a full life-cycle perspective, accomplished through multi-dimensional, multi-stage collaborative advancement. From preliminary planning and design, through mid-to-late-stage construction and operation, to macro-level policy and evaluation system support—these three phases are both distinct and interconnected, collectively forming the complete pathway to building decarbonization. Only by integrating design philosophy, construction practices, and policy mechanisms can the construction industry genuinely advance toward energy conservation, carbon reduction, and sustainable development goals.

#### 3.1 Low-Carbon Pathways in Planning and Design

Planning and design serve as the critical starting point in building decarbonization. Site selection and overall layout directly determine a building's energy efficiency and ecological impact. Scientific site selection should avoid ecologically fragile areas and high-energy-consumption zones, prioritizing locations with convenient transportation and suitable resource conditions to reduce energy consumption and carbon emissions at the source. Reasonable building cluster layouts optimize natural ventilation, daylighting, and

microclimate conditions through spatial organization. This reduces reliance on mechanical systems during the operational phase, laying the foundation for subsequent low-carbon design.

Passive energy-saving design is a vital approach to achieving low-carbon buildings. Through rational building orientation, optimized facade construction, and shading systems, indoor thermal comfort can be enhanced while reducing air conditioning and lighting energy consumption. The integration of natural daylight and ventilation not only reduces electricity consumption but also improves indoor environmental quality. Simultaneously, site-specific design tailored to regional climate characteristics—such as prioritizing thermal insulation in cold regions and emphasizing ventilation and heat dissipation in hot regions—further enhances energy efficiency. Life Cycle Carbon Emission (LCA)

$$C_{LCA} = C_{\text{design}} + C_{\text{construction}} + C_{\text{operation}} + C_{\text{demolition}} \quad (3)$$

The selection of green materials is equally critical during the design phase. Designers should prioritize renewable materials, low-carbon building products, and recyclable items to minimize the carbon footprint across the building's entire lifecycle. The application of timber structures, recycled concrete, and low-energy glass not only reduces carbon emissions but also promotes the green transformation of the building materials industry. Emphasis should be placed on durability and maintainability during material selection to avoid resource waste from frequent replacements, thereby achieving low-carbonization at the material level.

Integrated design concepts provide a systematic pathway to low-carbon buildings. By incorporating digital tools like Building Information Modeling (BIM) during the design phase, precise simulations and predictions of energy consumption and carbon emissions can be achieved during the conceptual development stage, aiding design optimization. Adopting an integrated design approach that fosters multidisciplinary collaboration—organically combining architecture, environmental science, and engineering technology—enhances the scientific rigor and sustainability of designs. Consequently, the low-carbon pathway during planning and design phases becomes not merely a series of isolated breakthroughs but a process of systematic, synergistic optimization, laying a solid foundation for low-carbon development throughout the entire building lifecycle.

### 3.2 Low-Carbon Strategies for Construction and Operations Phases

The construction phase represents a critical stage in resource consumption and carbon emissions throughout a building's entire lifecycle, meaning its level of low-carbon implementation directly impacts overall emission reduction outcomes. During construction, promoting prefabricated and modular building methods can significantly reduce on-site work time and energy consumption while effectively minimizing construction waste generation. Implementing green construction techniques—such as sorting and recycling construction waste, reusing water resources, and utilizing energy-efficient construction equipment—not only reduces environmental impacts during construction but also lays the foundation for the building's sustainable development, showed in Figure 1

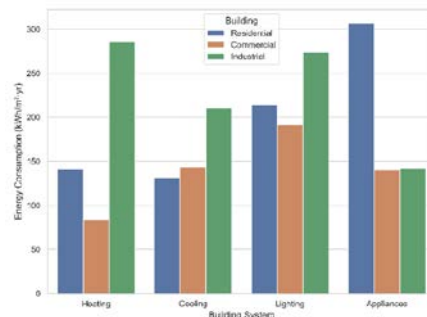


Figure 1 Building energy consumption by system and building type

In the building operation and maintenance phase, energy efficiency management is central to achieving low-carbon goals. Traditional buildings often suffer from energy waste due to inefficient operational management. Modern intelligent management systems, however, enable real-time monitoring and data

analysis to dynamically adjust lighting, air conditioning, elevators, and other equipment, maximizing energy utilization efficiency. IoT-based building energy consumption monitoring platforms can issue early warnings for abnormal energy usage, allowing timely implementation of energy-saving measures and significantly reducing carbon emissions during operations.

Controlling a building's full lifecycle carbon emissions requires prioritizing renewable energy utilization during the operation and maintenance phase. Deep integration of clean energy systems—such as photovoltaic power generation, wind energy, or geothermal heat pumps—not only reduces reliance on traditional fossil fuels but also enhances a building's energy self-sufficiency. Building-Integrated Photovoltaics (BIPV) technology combines photovoltaic panels with building facades, achieving dual benefits of energy savings and power generation while providing clean energy support for building operations.

$$Q = U \times A \times (T_{in} - T_{out}) \quad (4)$$

Low-carbon operations also require user engagement and behavior management. By guiding and incentivizing building occupants to develop energy-saving awareness and green living habits, carbon emissions can be further reduced during daily operations. Simultaneously, establishing an O&M evaluation system and a post-performance feedback mechanism helps promptly identify operational issues and continuously optimize building performance. Low-carbon strategies in the construction and O&M phases extend beyond technology and equipment; they require the organic integration of management innovation and behavioral guidance to ensure the achievement of low-carbon development goals throughout the building's entire lifecycle.

### 3.3 Policy and Evaluation System Support

Policy guidance and institutional safeguards play a pivotal role in advancing low-carbon building development. National and local governments provide clear direction for the industry through relevant laws, regulations, energy efficiency standards, and carbon reduction targets. The implementation of green building action plans, building energy efficiency codes, and the “dual carbon” strategy sets phased objectives and regulatory requirements, compelling construction enterprises to comprehensively consider carbon emissions throughout design, construction, and operation. The mandatory and directive nature of these policies transforms low-carbon principles from theoretical concepts into practical constraints and drivers for action.

$$R = \frac{E_{renewable}}{E_{total}} \times 100\% \quad (5)$$

Green building evaluation systems provide scientific metrics for measuring low-carbon construction. Internationally established frameworks like LEED and BREEAM, alongside China's Green Building Evaluation Labeling System, conduct comprehensive assessments through multi-dimensional indicators covering energy consumption, materials, and environmental impacts. These systems not only quantify a building's low-carbon performance but also provide clear optimization directions for designers and developers. In this process, evaluation systems serve dual roles as both a “yardstick” and a “guide,” driving the construction industry toward establishing sustainable development standards and practical pathways.

Policy incentive mechanisms are equally crucial for promoting low-carbon buildings. Governments can create favorable economic conditions for low-carbon construction through various means, including fiscal subsidies, tax breaks, green finance, and carbon trading. Providing financial support to projects adopting renewable energy systems or achieving green building certification levels can effectively reduce upfront investment pressures and boost the enthusiasm of enterprises and developers. As carbon markets mature, carbon emission quotas and trading in the building sector will also become important economic levers driving enterprises to proactively reduce emissions.

Achieving low-carbon buildings requires multi-stakeholder collaboration and societal engagement. Governments, industry associations, research institutions, and end-users must jointly establish a cooperative platform to foster synergistic interactions among policy formulation, technological innovation, market promotion, and user participation. Governments provide strategic direction through top-level

design, research institutions drive technological advancement, industry associations promote standardization, while users support the low-carbon transition through green consumption and energy-saving behaviors. Support from policy and evaluation systems is not merely about constraints and incentives; it is a crucial safeguard for fostering a systematic low-carbon development framework within the construction industry.

#### 4. Technological Innovation and Future Trends in Building Decarbonization

The application of digital and intelligent technologies is emerging as a key engine driving building decarbonization. Through emerging technologies like Building Information Modeling (BIM), the Internet of Things (IoT), and digital twins, architects and engineers can precisely simulate and predict building energy consumption and carbon emissions during the design phase. This enables optimized design solutions and reduced resource waste. Intelligent management systems powered by big data and artificial intelligence enable real-time monitoring and dynamic control, ensuring building equipment operates at peak efficiency and significantly boosting energy utilization. This digital transformation not only optimizes lifecycle management but also provides the technological foundation for achieving low-carbon goals ,showed in Figure 2 :

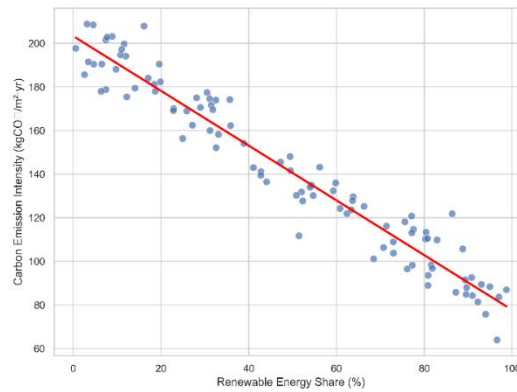


Figure 2 Carbon emission intensity vs renewable energy ratio

The integrated application of renewable energy provides clean energy solutions for buildings. Technologies like Building-Integrated Photovoltaics (BIPV), small-scale wind power systems, and ground-source heat pumps enable buildings to generate and supply their own energy, reducing dependence on fossil fuels. BIPV technology combines photovoltaic panels with building components such as roofs and curtain walls, serving not only as protective structures but also directly providing electricity—a key future direction for green buildings. Advancements in energy storage technologies will enhance the flexibility and stability of building energy systems, thereby strengthening the energy self-sufficiency of low-carbon buildings.

Energy Saving Rate

$$\eta = \frac{E_{\text{baseline}} - E_{\text{optimized}}}{E_{\text{baseline}}} \times 100\% \quad (6)$$

Innovative low-carbon building materials and structural designs open new avenues for emissions reduction in the construction sector. Carbon-capturing materials, ultra-high-performance concrete, recycled concrete, and large-scale timber structures all demonstrate significant potential for reducing building carbon emissions. For instance, timber structures are increasingly becoming a key direction in low-carbon building design due to their inherent carbon sink properties and renewability. Meanwhile, the application of new insulating glass, low-emissivity coatings, and high-efficiency insulation materials can further reduce energy consumption during the operational phase. Breakthroughs in building material technology not only reduce carbon emissions during construction but also drive the formation of green industrial chains.

The future trend of low-carbon buildings will feature interdisciplinary integration and diversified exploration. Low-carbon buildings will no longer rely solely on improvements within the architectural discipline but will require collaborative innovation across fields such as environmental science, information

science, and materials science. The low-carbon concept will also gradually expand from individual buildings to comprehensive planning at the community, city, and regional levels, driving the formation of green cities and low-carbon societies. With the continuous improvement of policy support and market mechanisms, the low-carbon transformation of buildings will demonstrate broader development prospects in the future, becoming a key pathway to achieving the “dual carbon” goals and promoting sustainable development.

## 5. Conclusion

As a major contributor to energy consumption and carbon emissions, the building sector's low-carbon transformation has become an inevitable trend under the backdrop of sustainable development and the “dual carbon” goals. This paper systematically examines the intrinsic value of low-carbon building design from the macro-level logic of sustainable development, highlighting that low-carbonization is not only essential for environmental protection but also a vital pillar for economic growth and social progress. Architectural design, as the starting point of the entire life cycle, exerts a decisive influence on subsequent construction and operation, thus occupying a central position in the green transition.

Exploration of low-carbon building design pathways reveals that systematic advancement in building decarbonization can only be achieved through coordination across three levels: planning and design, construction and operation, and policy and evaluation systems. Scientific site selection and passive energy-saving design in the early stages, green construction and intelligent management during construction and operation, coupled with policy guidance and standardized evaluation systems, collectively form the complete pathway for low-carbon buildings. This holistic control approach facilitates the construction industry's transition from isolated energy savings to systematic carbon reduction.

Technological innovation is emerging as the key driver for low-carbon building development. The application of digital and intelligent technologies enhances the precision of design and operations, while integrated renewable energy systems improve the cleanliness and independence of building energy systems. Novel low-carbon building materials and structural innovations provide fresh solutions for emissions reduction. The trend toward multidisciplinary integration further expands the boundaries of low-carbon building, extending its scope from individual structures to holistic optimization at the urban and regional levels.

Low-carbon building design serves as both a vital pathway to achieving the “dual carbon goals” and an essential requirement for advancing sustainable societal development. In the future, with the continuous refinement of policy frameworks, ongoing technological innovation, and the gradual rise in public environmental awareness, low-carbon buildings will undoubtedly play an increasingly significant role in the transformation and upgrading of the construction industry. How to achieve greater energy savings and emission reductions while maintaining building functionality and quality will become a shared focus for both academia and the industry.

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