

Research on Residential Building Planning and Design Strategies for Low-Carbon Urban Development

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Abstract: With the growing urgency of global climate change and energy scarcity, low-carbon urban development has become a vital direction for sustainable urban growth. As a vital component of urban architecture, residential buildings account for a significant proportion of a city's total energy consumption and carbon emissions, making them pivotal in low-carbon urban development. This study examines the planning and design of residential buildings for low-carbon urban development. Through theoretical analysis, domestic and international case studies, and strategic evaluation methods, it explores strategies for optimizing the spatial layout of low-carbon residential buildings, applying architectural design and energy-saving technologies, and selecting green materials and construction management approaches. Findings indicate that scientifically planning community layouts, rationally adopting passive energy-saving designs and renewable energy technologies, and optimizing material selection and construction management can significantly reduce building energy consumption and carbon emissions while enhancing residential comfort and sustainability. The proposed planning and design strategies provide practical guidance for low-carbon residential buildings in cities and theoretical support for future low-carbon building technology development and policy formulation.

1. Introduction

Amid escalating global climate change and energy consumption challenges, low-carbon urban development has emerged as a vital strategy for sustainable city growth^[1]. By optimizing energy structures, controlling carbon emissions, and improving environmental quality, low-carbon cities achieve coordinated economic, social, and ecological progress. Residential buildings, as a critical component of urban architecture, account for a substantial proportion of total urban energy consumption and carbon emissions, making them pivotal to low-carbon urban advancement^[2].

Extensive research has been conducted globally on low-carbon cities and buildings^[3]. Internationally, European and American countries have accumulated rich experience in low-carbon community planning, green building design, and energy-saving technology applications. Domestically, China has gradually explored a development path for low-carbon residential buildings with Chinese characteristics through policy promotion and technological innovation^[4]. Some studies focus on energy conservation in individual buildings, lacking systematic planning strategies at the community and city scales. Others pay insufficient attention to the carbon emissions across the entire building lifecycle, making it difficult to comprehensively evaluate the effectiveness of low-carbon design.

This paper examines residential building planning and design for low-carbon urban development, exploring low-carbon design methodologies in spatial layout optimization, architectural design and energy-saving technology application, green material selection, and construction management strategies^[5]. By integrating theoretical analysis, case studies of domestic and international exemplars, and strategy evaluations, this research aims to provide systematic, actionable reference frameworks for the planning and design of low-carbon urban residential buildings, while offering theoretical support for future policy formulation and technological advancement^[6].

2. Theoretical Foundations and Development Trends of Low-Carbon Urban Residential Buildings

A low-carbon city refers to an urban form that achieves carbon emission control and environmental quality improvement through optimized energy structures, green infrastructure development, low-carbon transportation systems, and sustainable urban management^[7]. Its core objective is to balance economic development, social life, and environmental protection, reducing overall urban carbon intensity while enhancing residents' quality of life. Low-carbon cities focus not only on the energy efficiency of individual buildings but also emphasize systematic urban planning and regional carbon management, providing theoretical foundations and practical directions for low-carbon residential design^[8]. The carbon emissions of a building can be calculated based on energy consumption and emission factors:

$$C_{\text{building}} = \sum_i E_i \cdot EF_i \quad (1)$$

Residential buildings account for a significant portion of urban energy consumption, encompassing heating, cooling, lighting, appliance operation, and hot water usage^[9]. Carbon emissions from residential buildings primarily originate during the operational phase, with heating and air conditioning systems being the largest energy consumers. As urbanization accelerates, energy consumption issues in high-rise residential buildings and densely populated areas have become increasingly prominent, making low-carbon residential building design a critical component for cities to achieve energy conservation and emission reduction goals^[10].

The concept of low-carbon building design has evolved from individual energy efficiency measures to comprehensive system optimization. Early research focused primarily on the energy-saving properties of building materials and envelope structures. In recent years, the scope has expanded to encompass integrated building design, renewable energy utilization, intelligent management, and whole-life-cycle carbon emission control. This shift emphasizes the synergistic effects of architectural design, community layout, energy management, and resident behavior. It provides theoretical support for the low-carbon transformation of residential buildings and promotes the integrated application of technological and management strategies.

Future residential building development in low-carbon cities exhibits three trends: holistic planning at the building and community scales, emphasizing optimized traffic organization, green space layout, and public facilities; deep integration of technology and intelligence, including passive energy-saving design, renewable energy systems, and building energy consumption monitoring platforms; and greening of materials and construction management, achieving comprehensive low-carbon goals through green building material selection, construction process carbon emission control, and building lifecycle management. These trends establish a practical foundation for subsequent planning and design strategy research.

3. Research on Low-Carbon Strategies for Residential Building Planning and Design

Within the context of low-carbon urban development, residential building planning and design must extend beyond individual building energy efficiency to systematically optimize community layout, architectural design, and materials/construction management. This paper analyzes three key aspects: Exploring spatial layout optimization strategies to enhance energy efficiency and environmental comfort through rational functional zoning, building density control, and the placement of ecological corridors and public green spaces; Investigating architectural design and energy-saving technology applications, including passive energy-saving design, renewable energy systems, and intelligent building management to achieve low-carbon goals during the operational phase; Analyzing material selection and construction management strategies to further reduce the building carbon footprint through the use of green building materials, lifecycle carbon emission control, and construction process optimization. These three aspects complement each other, collectively forming a systematic strategic framework for low-carbon planning and design in residential buildings.

3.1 Spatial Layout Optimization Strategies

Functional zoning forms the foundation of low-carbon planning for residential areas. By rationally arranging residential, commercial, educational, office, and public service facilities, daily travel distances and transportation energy consumption for residents can be reduced. Concentrating primary living needs within walking distance or accessible by short-distance transportation helps decrease motor vehicle usage frequency, thereby reducing carbon emissions and transportation energy consumption. Scientific functional zoning also enhances community convenience and living comfort, providing institutional support for low-carbon lifestyles. The passive solar energy gain for heating can be expressed as:

$$Q_{\text{solar}} = A_{\text{window}} \cdot \text{SHGC} \cdot I_{\text{solar}} \quad (2)$$

The contribution of renewable energy to the building's total energy demand can be calculated as:

$$P_{\text{RE}} = \frac{E_{\text{RE}}}{E_{\text{total}}} \times 100\% \quad (3)$$

Appropriate building density and height arrangements optimize microclimate conditions, daylighting, and ventilation, thereby improving passive energy efficiency. Excessively high density may cause excessive shading, increasing air conditioning energy consumption; conversely, excessively low density may lead to land resource waste and inefficient public infrastructure. Optimizing building layouts based on climate conditions, solar analysis, and ventilation simulations is a key strategy for achieving low-carbon residential buildings. Figure 1 illustrates the energy consumption distribution of residential buildings by type:

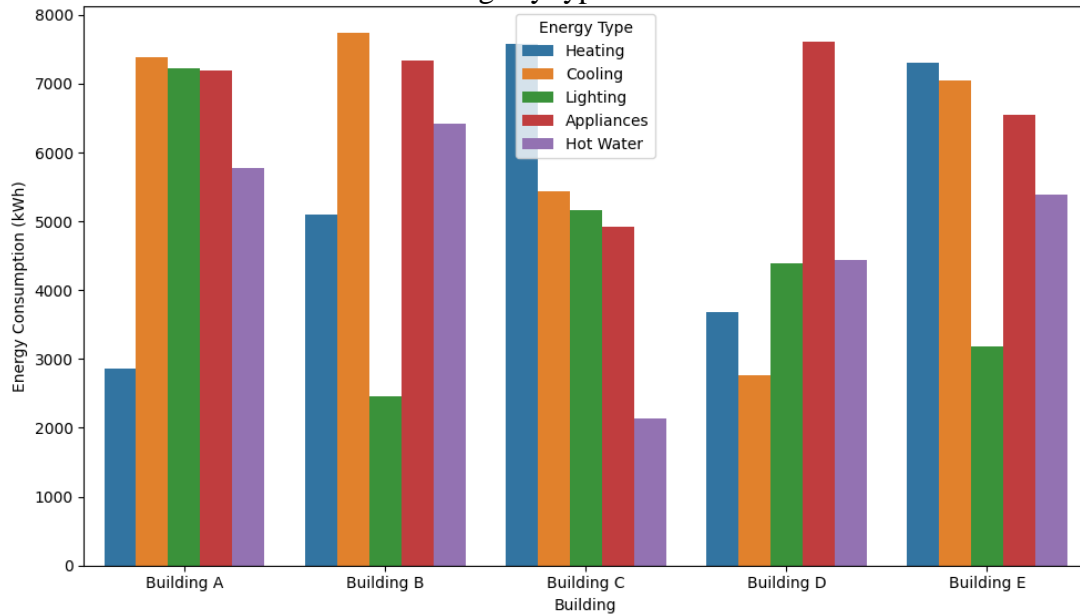


Figure 1 Residential Building Energy Consumption by Type

Community road and transportation network design significantly impacts low-carbon goals. By optimizing road layouts, enhancing walkability and bicycle accessibility, and strategically placing public transit nodes, private vehicle usage can be reduced, lowering transportation energy consumption. Traffic organization and parking management strategies also guide residents toward low-carbon travel options, enabling comprehensive community carbon emission control.

Public green spaces and ecological corridors not only improve microclimates and regulate temperature and humidity but also enhance community ecosystem services, carbon sequestration, and stormwater retention. Scientifically arranged green areas and landscape corridors improve air quality and thermal comfort, reduce building cooling loads, and provide recreational spaces for residents, thereby elevating quality of life. In low-carbon residential community planning, the layout of ecological corridors and green spaces constitutes a vital component of spatial optimization strategies.

3.2 Architectural Design and Energy-Saving Technology Applications

Passive energy-saving design reduces building energy consumption by optimizing architectural form, orientation, daylighting, ventilation, and building envelope systems. Optimal building orientation and window-to-wall ratio maximize solar gain, enhancing winter heating efficiency while reducing summer cooling loads. Insulation in roofs and exterior walls minimizes heat loss, delivering passive energy savings. Additionally, natural ventilation and shading devices improve indoor thermal comfort and decrease mechanical energy consumption.

Renewable energy technologies such as solar photovoltaics, solar water heating, ground-source heat pumps, and small-scale wind systems significantly reduce reliance on fossil fuels and carbon emissions during building operation. The integrated use of rooftop photovoltaic panels, solar thermal collectors, and district energy systems not only meets partial building electricity and heating demands but also enables localized energy production and consumption, enhancing overall energy autonomy and low-carbon benefits. Figure 2 shows the monthly CO₂ reduction percentage under different low-carbon strategies:

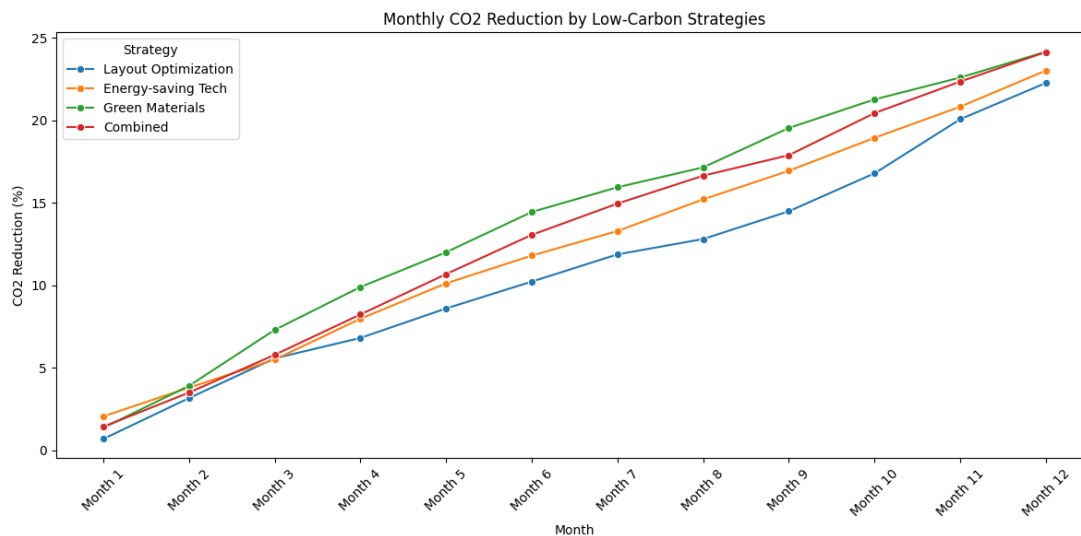


Figure 2 Monthly CO₂ Reduction by Low-Carbon Strategies

Intelligent building systems enable real-time monitoring and optimized management of energy consumption through sensors, data acquisition, and automated controls. This includes automatic adjustments to smart lighting, HVAC, and hot water systems, alongside big data-driven energy analysis and optimization controls, effectively reducing energy waste. Intelligent management not only enhances operational efficiency and provides occupants with a comfortable living environment but also supplies data for evaluating and continuously improving building energy performance.

To achieve optimal low-carbon outcomes, building design and energy-saving technologies must be synergistically applied. Integrating passive energy-saving measures with renewable energy systems and intelligent management technologies enables energy consumption optimization throughout the building's entire lifecycle. Through strategic integration during design, meticulous management during construction, and intelligent regulation during operation, low-carbon residential buildings can achieve significant results in energy efficiency, comfort, and environmental sustainability, providing practical models for urban low-carbon development.

3.3 Material Selection and Construction Management Strategies

Green building materials form a crucial component of low-carbon residential buildings. Selecting low-energy consumption, low-carbon emission, renewable, or recyclable materials significantly reduces the carbon footprint throughout the building's entire lifecycle. For instance, employing high-performance insulation materials, eco-friendly concrete, recycled steel, and wood ensures structural performance and comfort while minimizing carbon emissions from production and transportation, laying the material foundation for building decarbonization.

Full life-cycle management of materials is crucial for achieving low-carbon building goals, encompassing procurement, construction use, maintenance, and demolition recycling. Quantifying material carbon emissions and prioritizing products with low life-cycle carbon footprints effectively reduces environmental impact during building operation and demolition phases. Concurrently, establishing a material information management system facilitates resource recycling and sustainable control of building carbon emissions.

The construction phase represents a significant contributor to building carbon emissions and energy consumption. Optimizing construction organization, techniques, and machinery management can reduce energy use and carbon emissions during this stage. Examples include: rationalizing construction sequencing to minimize machinery transport frequency; deploying high-efficiency construction equipment to lower energy consumption; and utilizing prefabricated components to reduce on-site wet operations and material waste. Refined management of the construction process not only enhances project efficiency but also creates conditions for low-carbon operation in the building's later stages.

Material selection and construction management strategies should synergize with architectural design and technological applications to achieve low-carbon control throughout the building's entire lifecycle. The coordinated use of green materials, lifecycle assessments, and construction process optimization creates a holistic low-carbon effect across design, construction, and operation phases. Through this integrated approach, residential buildings can systematically reduce energy consumption and carbon emissions while ensuring functionality and comfort, providing sustainable technical and management pathways for urban low-carbon development.

4. Case Analysis and Strategy Effectiveness Evaluation

To validate the feasibility and practical outcomes of low-carbon planning strategies for residential buildings, this paper systematically analyzes representative domestic and international low-carbon residential cases. Internationally, Germany's Passive Houses, the Netherlands' eco-communities, and Japan's zero-energy homes have accumulated extensive experience in spatial layout optimization, passive energy-saving design, and renewable energy integration. German Passive Houses achieve minimal operational energy consumption through optimized building orientation and high-performance envelope systems; Dutch eco-communities emphasize holistic community planning and green transportation systems, enabling low-carbon commuting for residents; Japanese zero-energy homes achieve energy self-sufficiency through advanced solar photovoltaic systems and intelligent energy management. Domestically, low-carbon residential districts in Beijing, Shanghai, and Shenzhen have also achieved notable results in intelligent building management, green material application, and community layout. For instance, rational functional zoning and green space arrangements have improved residents' living environments while effectively reducing building energy consumption and carbon emissions. Through comprehensive analysis of these cases, this study identifies application models, technology combinations, and key success factors for low-carbon strategies in practical projects, providing practical experience and reference for promoting low-carbon residential buildings in China's cities. The efficiency of carbon reduction strategies can be evaluated using the following formula:

$$\eta_{\text{carbon}} = \frac{C_{\text{baseline}} - C_{\text{actual}}}{C_{\text{baseline}}} \times 100\% \quad (4)$$

The energy use intensity per unit floor area is commonly used to compare building efficiency:

$$\text{EUI} = \frac{E_{\text{total}}}{A_{\text{floor}}} \quad (5)$$

Regarding strategy effectiveness evaluation, this paper establishes an assessment system covering indicators such as building energy consumption, carbon emissions, indoor comfort, and transportation. Building energy consumption metrics—including heating, cooling, lighting, and hot water usage—directly reflect the effectiveness of low-carbon design during the operational phase. Carbon emission metrics utilize life-cycle assessment to quantify the carbon footprint across material

sourcing, construction, and operational phases. Indoor comfort indicators—including temperature, humidity, ventilation, and lighting conditions—ensure low-carbon strategies do not compromise occupant comfort. Transportation-related carbon emissions metrics examine the impact of community planning and travel patterns on overall emissions. Resident behavior and satisfaction surveys further validate the adaptability and sustainability of low-carbon strategies in real-world living environments. Through comprehensive multi-indicator assessment, the effectiveness of low-carbon strategies can be quantified, providing scientific basis for subsequent planning and design optimization.

The successful implementation of low-carbon residential buildings relies on the synergistic effects of spatial layout optimization, architectural design and energy-saving technology application, as well as material selection and construction management strategies. Rational community layout reduces transportation energy consumption while enhancing the carbon sequestration effects of public green spaces and ecological corridors; passive energy-saving design and renewable energy systems lower building operational energy consumption while ensuring indoor comfort; while the selection of green building materials and optimized construction processes ensure effective control of carbon emissions throughout the building's entire lifecycle. Policy support, intelligent building management, and resident participation are also crucial factors in ensuring the implementation of these strategies. These experiences demonstrate that low-carbon residential buildings must focus on energy efficiency in individual structures while conducting systematic planning and integrated management at the community and even urban scales. This forms a multidimensional, lifecycle-based low-carbon control system, providing replicable practical pathways and technical references for China's low-carbon urban development.

5. Conclusion

This paper systematically investigates planning and design strategies for residential buildings oriented toward low-carbon urban development. Through theoretical analysis, domestic and international case studies, and strategy effectiveness evaluations, it summarizes planning and design methodologies and practical experiences for low-carbon residential buildings. Research indicates that achieving low-carbon residential buildings requires a multidimensional approach encompassing spatial layout, architectural design and energy-saving technology application, as well as material selection and construction management, to form systematic, full-lifecycle low-carbon control strategies. Scientific functional zoning, rational building density and traffic organization, along with ecological corridors and public green space layouts, optimize overall community energy consumption and carbon emissions. Passive energy-saving design, renewable energy systems, and intelligent building management technologies significantly reduce energy consumption during the building operation phase. The selection of green building materials and optimized management throughout the construction process further lower carbon emissions across the building's entire lifecycle, achieving synergistic low-carbon effects in materials, construction, and usage.

Analysis of domestic and international case studies reveals that successful implementation of low-carbon strategies depends on policy support, resident participation, and effective application of intelligent management technologies. The integrated application of spatial, technical, and management strategies can significantly reduce building energy consumption and carbon emissions while ensuring residential comfort, providing practical experience and demonstration effects for low-carbon urban development. Residential building planning and design for low-carbon urban development must balance systematic, technical, and operational considerations. Future research should further focus on quantifying carbon emissions across the entire building lifecycle, innovating low-carbon materials, advancing intelligent energy consumption management, and guiding residents toward low-carbon behaviors. This will continuously enhance the comprehensive performance of low-carbon residential buildings and elevate urban low-carbon development levels, providing scientific support and practical pathways for sustainable urban construction.

References

- [1] Li J, Colombier M. Managing carbon emissions in China through building energy efficiency[J]. *Journal of Environmental Management*, 2009, 90(8):2436-2447
- [2] Wood S, Fletcher D F, Joseph S D, et al. Design and Evaluation of a Porous Burner for the Mitigation of Anthropogenic Methane Emissions[J]. *Environmental Science & Technology*, 2009, 43(24):9329-9334.
- [3] Noorollahi Y, Ahmadi E, Zahedi R, et al. Low carbon solar-based sustainable energy system planning for residential buildings[J]. *Renewable & sustainable energy reviews*, 2025(Jan.):207.
- [4] Guerra O J, Tejada D A, Reklaitis G V. Climate change impacts and adaptation strategies for a hydro-dominated power system via stochastic optimization[J]. *Applied Energy*, 2019, 233-234(JAN.1):584-598.
- [5] Santa Barbara J. How should we live? If you are looking for inspiration and relief from 'post-petroleum stress disorder' or 'climate-change catatonia', Joanna Santa Barbara recommends three books with plenty of ideas on how to create resilient sustainable communities able [J]. *Otolaryngology - Head and Neck Surgery*, 2008, 140(2):154-158.
- [6] A M V N, A D A S, A B L, et al. Facilitating agroforestation of landscapes for sustainable benefits: Tradeoffs between carbon stocks and local development benefits in Indonesia according to the FALLOW model[J]. *Agriculture, Ecosystems & Environment*, 2008, 126(1–2):98-112.
- [7] Shenoy U V. Targeting and design of energy allocation networks for carbon emission reduction[J]. *Chemical Engineering Science*, 2010, 65(23):6155-6168.
- [8] Blair S M, Booth C D, Singh N K, et al. Analysis of Energy Dissipation in Resistive Superconducting Fault-Current Limiters for Optimal Power System Performance[J]. *IEEE Transactions on Applied Superconductivity*, 2011, 21(4):3452-3457.
- [9] Horiike S, Nagano K. DESIGN AND EVALUATION OF ONE OF THE LARGEST GROUND SOURCE HEAT PUMP SYSTEMS IN A LARGE-SCALE RETAIL STORE[J]. *Journal of Environmental Engineering (Transactions of AIJ)*, 2015, 80(709):249-258.
- [10] Tan R R, Ng D K S, Foo D C Y, et al. Crisp and fuzzy integer programming models for optimal carbon sequestration retrofit in the power sector[J]. *Chemical Engineering Research & Design*, 2010, 88(12):1580-1588.