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

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Abstract: Given the increasing urgency of global climate change and energy shortage, low-carbon urban development has emerged as a crucial approach to sustainable urbanization. As one of the essential types of urban architecture, residential buildings occupy a considerable share in the total energy consumption and carbon emissions in cities, so they play a key role in low-carbon city development. An examination of residential buildings planning and designing for low-carbon cities editing It investigates the optimal layout of low-carbon residential units, architectural design and energy-saving technologies, green materials selection and construction management through theoretical analysis, domestic and foreign case studies, and strategic evaluation methods. The scientific design of the community, rational application of passive energy saving forms and renewable energy technology, reasonable material selection and construction management can effectively reduce building energy consumption and carbon emissions while improving residents comfort level and sustainable development ability. The suggested planning and design strategies offer practical direction for the design of low-carbon residential buildings in cities, and theoretical guidance for future development of low-carbon building technologies and formulation of policies.

1. Introduction

With the increasingly prominent global issue of climate change and energy consumption, low-carbon urban development has become an important way for cities to sustainably develop [1]. As energy structures are optimized, carbon emissions are controlled, and environmental quality is improved, low-carbon cities promote harmonious economic-social-ecological coordinated development. As an essential part of urban architecture, residential buildings account for a considerable share of total energy consumption and carbon emissions in cities, making them crucial to low-carbon urban development [2].

Globally, a substantial amount of research has been conducted on low-carbon cities and buildings [3]. Overseas, countries of Europe and America have accumulated abundant experience in low-carbon community planning, green building design and energy-saving technology applications. In China itself, low-carbon residential buildings with Chinese characteristics have been slowly explored in terms of another development path through the integrated promotion of policies and technological innovation domestically [4]. Some research is limited to energy conservation in individual homes, and the lack of systematic planning strategies at community and city scales. Others do not devote enough attention to the carbon emissions throughout the entire lifetime of a building, making it challenging to effectively compare whether low-carbon design is effective or not.

Low-carbon building planning and design for residential buildings, from exploring low-carbon design methods to spatial layout optimization, architectural design and energy-saving technology application [5], green material selection. Through specializations such as theoretical analysis, cases of domestic and international models, and evaluation of related strategies, the research aims to present systematic, actionable reference pathways for the planning and design of low-carbon urban residential buildings and theoretical support for future policy formulation [6].

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

The low-carbon city is a new urban form that can control carbon emissions and improve environmental quality by optimizing energy structure, developing green infrastructure, forming low-carbon transportation systems and realizing sustainable urban management [7]. The core goal of this is to strike a balance between economic development, social life, and environmental protection while decreasing socpression urban carbon intensity and helping improve the quality of life for residents. Low-carbon cities not only examine the energy-saving potential of single buildings, but also emphasize systematic urban planning and regional carbon management, which has important theoretical guidance and practical significance for low-carbon residential design [8]. The net carbon balance can be expressed as emissions minus reductions and sequestration:

$$C_{\text{net}}=C_{\text{emissions}}-C_{\text{reduction}}-C_{\text{sequestration}}(1)$$

The carbon emissions of a building can be calculated based on energy consumption and emission factors:

$$C_{\text{building}}=\sum_i E_i \cdot \text{EF}_i(2)$$

The bulk of energy use in cities comes from residential buildings, which collectively include heating, cooling, lighting, appliance operation and usage of hot water [9]. Operational carbon emissions from residential buildings account for the majority of their embodied carbon, and heating and air conditioning systems are concrete on energy consumers. With the pace of urbanization, energy consumption problems in high-rise residential buildings and urban areas are becoming increasingly prominent, thus making low-carbon residential building design an important direction for cities to reach energy conservation and emission reduction targets [10].

The design of low-carbon buildings evolved from a collection of energy efficiency measures to the optimisation of an entire system. It was noted that early research mainly targeted energy-saving properties of materials and envelope structures. With the realization that carbon pollutant emissions are more than just building pollutants, and due to specific periods in the past few years, integrated building design, renewable energy utilization, intelligent management, whole-life-cycle carbon emission control (delivered stage + operational phase) have become within the scope of assessment. It also highlights the synergistic effects of architectural design, community layout, energy management and resident behaviour. It supports the low-carbon evolution of residential buildings from a theoretical perspective and promotes the integrated application of science & technology (S&T) and management methods.

In summary, the future development of residential buildings in low-carbon cities will focus on three aspects: large-scale planning and design at the building-community level; highly integrated technology and intelligentization (including passive energy-saving design, renewable energy systems at solar- or proton source schools/establishments, usage policies such as utility billing of energy consumption, building energy conservation management platforms for performance measurement); greening of materials and construction management consisting of green building material selection selective construction process carbon emissions control management-building cycle conclusion. These trends form an empirical basis for later investigation of planning and design strategy.

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

For low-carbon urban development, planning and design of residential buildings must not only focus on energy efficiency at the individual building level but to also systematically optimize components such as community layout/environment, architecture and materials/construction management. The structure of this paper is organized around three core pillars: Investigating optimization strategies for spatial layout, designing rational function zoning and architectural scale models to realize energy conservation and environmental comfort; Subsequent detailing of building design coupled with relevant energy-efficient technology applications, including zero-emission systems that inform low-carbon targets during the service period; A meanwhile exploration of material selection and construction management guidelines to reduce consumption through green materials, lifecycle carbon emissions management and process route methods. The above three are interrelated and together construct a systematic strategic framework for the low-carbon planning and design of residential buildings.

3.1 Spatial Layout Optimization Strategies

This type of zoning forms the basis for low-carbon planning of residential neighborhoods. To reduce daily travel distance and transportation energy use of residents by rational layout of residential, commercial, education, offices, and public service facilities. When main living needs are aggregated into a few places that are in the walking distance or short-distance transport, it will also reduce the frequency of use of motor vehicles and carbon emissions as well as transportation energy consumption. Functional zoning based on scientific planning not only increases local convenience and livability but also serves as an institutional guarantee for a low-carbon lifestyle. The passive solar energy gain for heating can be expressed as:

$$Q_{\mathrm{solar}}=A_{\mathrm{window}} \cdot SHGC \cdot I_{\mathrm{solar}} \quad (3)$$

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

$$P_{\mathrm{RE}}=\frac{E_{\mathrm{RE}}}{E_{\mathrm{total}}}\times 100\% \quad (4)$$

Well-organized design densities and heights can lead to optimized microclimatic conditions, daylighting, and ventilation and enhance the passive energy efficiency. Excess density can result in too much shade and increase the amount of energy used for air conditioning, while insufficient density can waste land resources and lead to ineffective public facilities. As one of the main strategies toward low-carbon residential buildings, optimizing various building layouts based on climate conditions, solar analysis and ventilation simulations should be performed. Figure 1 illustrates the energy consumption distribution of residential buildings by type:

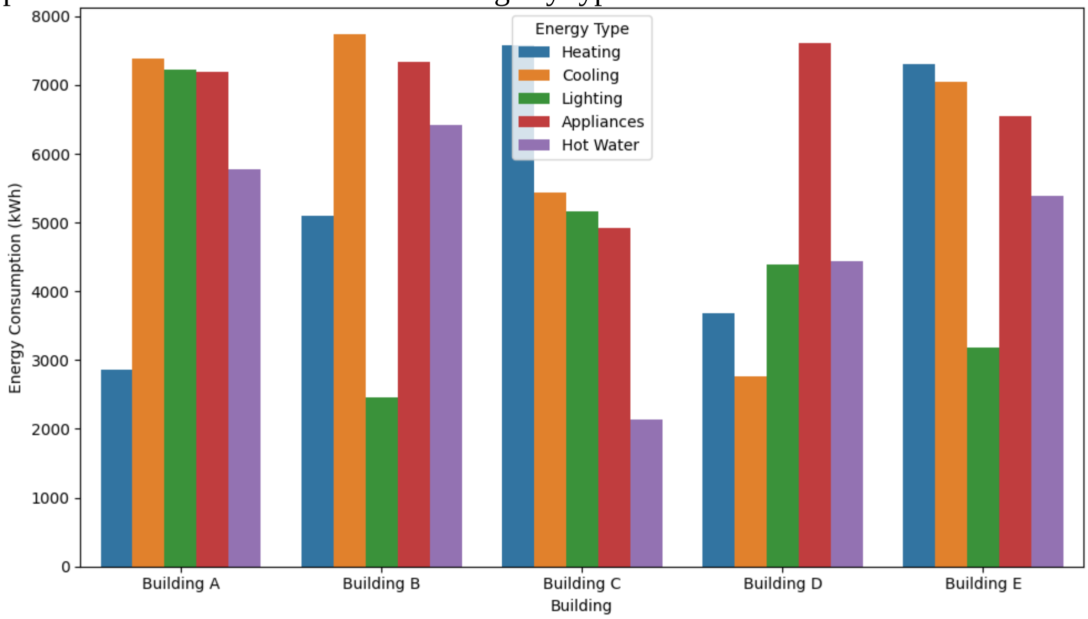

Figure 1 Residential Building Energy Consumption by Type

Design of the community road & transportation network has a great impact on low-carbon objectives. Private vehicles can be reduced, and thus energy consumed in transport is reduced working through optimised layouts of roads, support for walking and cycling, and ensuring nodes for public transit. Traffic organization and parking management strategies, guide residents to low-carbon travel modes, and then to achieve the overall control of community carbon;

Thus public green spaces and ecological corridors have the function to improve microclimates, regulate temperature and humidity as well as increase community ecosystem services, carbon sequestration and stormwater retention. Scientifically planned greenbelts and road landscape corridors can improve air quality, bring thermal comfort (temperature equilibrium), reduce building cooling load and provide recreational space for residents, thereby improving the quality of life. As a key component of the spatial optimization, the planning of ecological corridors and green space in low-carbon residential communities play an important role.

3.2 Architectural Design and Energy-Saving Technology Applications

Green Architecture-Passive energy-saving design minimizes building environment pollution. In winter, good building orientation and window-to-wall ratio maximize solar gain and increase the efficiency of passive heating. Insulating roofs and exterior walls reduces heat transfer, giving rise to passive savings of energy. Furthermore, natural ventilation and shading devices enhance indoor thermal comfort and reduce mechanical energy use.

Renewable energy technologies, including solar photovoltaics, solar water heating, ground-source heat pumps and small-scale wind systems achieve substantial reduction of fossil fuel and carbon emissions during building operation. This includes partial building electricity and heating demand and localized carbon emission-neutral energy generation and consumption with integrated rooftop photovoltaic panels, solar thermal collectors, and district energy systems. Figure 2 shows the monthly CO2 reduction percentage under different low-carbon strategies:

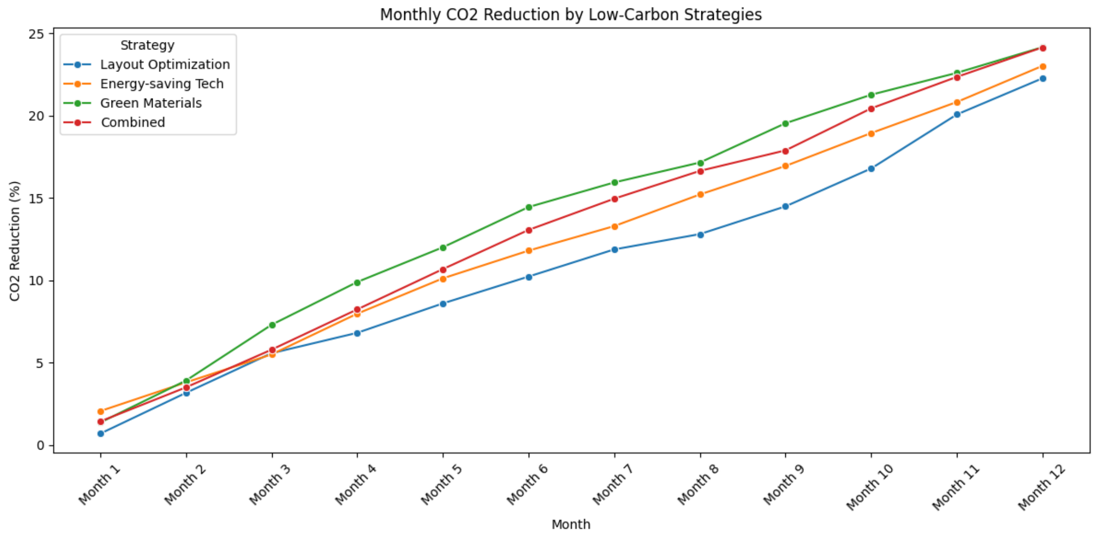

Figure 2 Monthly CO2 Reduction by Low-Carbon Strategies

Collectively, intelligent building systems — very often interconnected through the Internet of Things (IOT) and managed by enterprise software solutions — are designed to monitor, control and optimize energy consumption with sensors and sensors data acquisition systems. This ranges from automatic adjustment of smart lighting, HVAC and hot water systems to big data-based energy analysis and optimization control programs that collectively eliminate energy waste. Intelligent management improves operation efficiency and provides occupants with a comfortable living environment and also provides data to assess building energy performance as well as for building more energy-efficient mechanisms.

Synergistic application of building design and energy-saving technologies are required to achieve optimal low-carbon outcomes. Mutable passive energy-saving measures, renewable energy systems and intelligent management technologies can be integrated together to realize the optimization of energy consumption during the whole life cycle of a building. Through effective integration during design, management during construction, and regulation during operation, such residential buildings can greatly improve energy efficiency, comfort level and environmental sustainability performance to make them practical models for urban low-carbon development.

3.3 Material Selection and Construction Management Strategies

Low-carbon residential buildings rely in large part on green building materials. It is crucial to select low-energy consumption, low-carbon emission or recycled or renewable materials which are used to minimize the carbon footprint during all stages of building lifecycle. So for example, combining high performance insulation materials (like aerogels), green concrete, recycled steeling and wood ensure not only structural performance and comfort but also reduces carbon emissions due to production & transport thus providing the material basis for building decarbonization.

Low-carbon buildings rely on effective full life-cycle management of materials, from procurement through use in construction, maintenance and recycling upon demolition. Carbon emissions in the material phase can be quantified and products with low life-cycle carbon footprints most effective to mitigate environmental impact during both building operation and demolition phases can then be prioritised. Simultaneously, implementing a material information management system promotes resource recycling and sustainable governance of building carbon emissions.

The construction phase is the largest contributor to building carbon emissions and energy consumption. The optimization of construction organization, techniques, and machinery management can lead to reduced energy consumption and carbon emissions during this phase. This could involve optimizing the construction sequence to minimize the frequency of transportation machinery ; Using high-efficiency construction equipment to reduce energy consumption; Using prefabricated components to reduce on-site wet operations and material waste. Improved management of the construction process contributes to project efficiency and lays the groundwork for low-carbon operations in later building stages.

They should help to achieve the low-carbon control of the whole lifecycle of building, synergizing with architectural design and technological applications in material selection and construction management strategy. We can also obtain the overall effect of low carbon during design, construction and operation by applying green materials, lifecycle assessment and optimization in various aspects. This integrated construction method would enable a sensible reduction of energy consumption and carbon emissions in residential buildings while ensuring the being effective and comfort, providing feasible technical and management pathways for urban low-carbon development.

4. Case Analysis and Strategy Effectiveness Evaluation

To verify the implementability and effectiveness of low-carbon planning approaches for residential buildings, a systematic investigation of typical domestic and international low-energy-residential cases is conducted in this paper. Internationally, Germany's Passive Houses and eco-communities in the Netherlands as well as zero-energy homes in Japan have extensively gained experience from spatial layout optimization, passive energy-saving design to renewable energy integration. German Passive Houses rely on smart building orientation and extremely high-performance envelope systems to achieve near-zero operational energy use; Dutch eco-compounds emphasize holistic community design and green mobility systems, facilitating low-carbon journeys for residents; Japanese zero-energy homes implement advanced solar PV systems and intelligent energy management to attain energy self-sufficiency. In domestic cities, low-carbon residential communities in Beijing, Shanghai, and Shenzhen have also achieved remarkable results in intelligent building management, green material application and community layout. For example, rational arrangement of functional zoning and green space can improve residents’ living environment while significantly reducing building energy consumption and carbon emissions. In-depth analysis of these cases in this study grasps its application mode, technology combination and the key elements for a low carbon strategy accumulation demonstrates the practical experience and reference for atmospheric adjustment of low-carbon residential building projects in Chinese cities. The efficiency of carbon reduction strategies can be evaluated using the following formula:

$$\eta_{\text{carbon}} = \frac{C_{\text{baseline}} - C_{\text{actual}}}{C_{\text{baseline}}} \times 100\% \quad (5)$$

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

$$EUI=\frac{E_{total}}{A_{floor}}(6)$$

In terms of evaluation strategy effectiveness, this paper formulates the assessment system including the indicators like buildings energy consumption, carbon emissions, indoor comfort and outer transport. Operational building energy use, including heating and cooling, lighting, hot water consumption etc., provides a direct measure of success for low-carbon design acting as an operational phase feedback. Carbon emission metrics measure carbon footprint quantity through life-cycle assessment across all phases of material sourcing, construction, and operation. Indoor comfort indicators — such as temperature, humidity, ventilation and lighting conditions — guarantee that low-carbon strategies do not sacrifice occupant well-being. Metrics for carbon emissions from transportation explore the contribution of community planning and travel behavior to overall emissions. Also, similar low-carbon strategies enabled the flexibility and sustainability of real-life residing settings evidenced by resident conduct and satisfaction surveys. Furthermore, through multi-indicator assessment and dimensional analysis of the effectiveness of low-carbon strategies in different fields, and quantifying it to form a scientific basis for planning and design optimization.

Spiritual layout optimization, architectural design and energy-saving technology application, as well as material selection and construction management strategies are all key factors that ensure joint operation of a low-carbon residence. In more detail, rational spatial grouping reduces the energy consumption of transportation at the community level and strengthens the carbon sink effects of public green space and ecological corridors; passive energy-saving design and renewable energy systems lower building operational energy while ensuring indoor comfort; while filtering selection of green building materials and optimization construction process ensures effective control of carbon emissions throughout the whole life cycle. The implementation of these strategies also requires policy support, intelligent building management, as well as active resident participation. These experiences indicate that low carbon residential buildings can achieve energy efficiency both at the individual building level and through systematic planning, community-building, and even urban integrated management. Constructing a multidimensional, life-cycle low-carbon control system serves as replicable practical pathways and technical references for low-carbon urban development in China.

5. Conclusion

The paper systematically explores planning and design principles for the transformation of residential buildings towards low-carbon cities. It summarizes planning and design methodologies and practical experiences for low-carbon residential buildings through theoretical analysis, domestic and international case studies, social strategy effectiveness evaluation. Research shows that the path to low-carbon residential buildings is multidimensional. It involves spatial layout, architectural design and energy-saving technology application, as well as material selection and construction management, leading to systematic full-lifecycle low-carbon control strategies. Subdividing it into multiple functional zones, rationally layout the building density and traffic road form, forms ecological corridors and public green space, optimizes the overall energy consumption and carbon emission of the community. In the building operation stage, energy consumption is greatly reduced through passive energy-saving design, renewable energy systems, and intelligent building management technologies. Incorporating green building materials and using advanced means to optimize construction management not only effectively reduces carbon emissions at the overall level of the project, but also obtains a synergistic low-carbon effect of materials, construction, and usage throughout the whole process.

Domestic and foreign case studies analysis shows that successful implementation of low-carbon strategies need policy support, residents participated in the process, and intelligent management techniques application. The cohesive use of spatial, technical, and management strategies can effectively decrease the energy consumption and carbon emissions of buildings while maintaining the comfortable living conditions that residential areas can offer, which effectively tests and demonstrates practical experience of low-carbon urban development. Low-carbon urban development through systematic, technical and operational residential building planing ＆ design Future studies should continue to quantify carbon emissions throughout the entire building lifecycle, research innovative low-carbon materials, develop intelligent energy consumption management methods, and direct residents' behaviors toward a low-carbon direction. Which will provide a strong theoretical support and practical exploration for the low-carbon urban construction and quickly establish urban low carbon development level.

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