Research on Design Methods for Green Retrofits of Existing Buildings in the Context of Building Stock Renewal

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Abstract: As China enters the phase of building stock renewal, green retrofits of existing buildings have become a crucial pathway for promoting sustainable urban development and achieving the dual carbon goals. A large number of existing buildings suffer from high energy consumption, inadequate comfort levels, and functional deterioration, urgently requiring renewal and enhancement through scientific design methods. Against the backdrop of building stock renewal, this paper systematically examines the value and significance of green retrofitting for existing buildings. It explores design methodologies across spatial and functional optimization, energy-saving and environmental technologies, as well as smart systems and operational management. Through case studies, it identifies applicable green retrofitting pathways and strategies for diverse building types. Findings indicate that green retrofitting not only substantially reduces energy consumption and enhances user experience but also extends building lifespans while fostering synergistic urban renewal and low-carbon transformation. Moving forward, green retrofitting of existing buildings requires coordinated efforts across policy guidance, technological innovation, and operational management to achieve dual objectives of urban renewal and ecological civilization development.

1. Introduction

With China's socioeconomic transformation and deepening urbanization, the construction industry has gradually shifted from large-scale new construction to a development phase centered on the renewal of existing buildings [1]. A large number of existing buildings constructed during different periods commonly suffer from high energy consumption, functional degradation, and poor environmental quality, failing to meet people's demands for high-quality living and green, low-carbon development [2]. Driven by the “dual carbon goals” and sustainable development strategies, the green retrofitting of existing buildings has increasingly become a crucial component of urban renewal and ecological civilization construction [3]. Green retrofitting extends beyond improving physical building performance to encompass spatial reconfiguration, energy utilization optimization, and innovative operational management models [4]. This holds significant implications for enhancing overall urban environmental quality and advancing energy conservation and emissions reduction [5]. Despite substantial domestic and international exploration in this field in recent years, challenges persist, including insufficient systematic approaches, uneven dissemination of technical pathways, and limited generalizability of case study experiences [6]. This paper examines design methodologies for green retrofitting of existing buildings within the context of stock building renewal. It focuses on strategies for spatial and functional optimization, energy-saving and environmental protection technology applications, as well as smart systems and operational management. Through case studies, it synthesizes practical insights to provide theoretical references and methodological support for systematically advancing green retrofitting of existing buildings in China.

2. The Relationship Between Existing Building Renewal and Green Retrofits

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As China's urban development enters a new phase characterized by “slowing new construction and prioritizing existing stock,” the construction industry has gradually shifted from a new-build focus to a model centered on retrofitting existing buildings [7]. Many existing structures were built decades ago with outdated design standards and technologies, resulting not only in high energy consumption but also an inability to meet contemporary demands for comfort, safety, and functional diversity [8]. Promoting the renewal of existing buildings has become an inevitable choice for urban development, and green retrofitting is a crucial pathway to achieve energy conservation, emission reduction, and quality enhancement [9].

From a value perspective, green retrofitting of existing buildings maximizes the extension of a building's lifecycle [10]. By optimizing spatial layouts, structural systems, and energy systems, it enables the reuse of original resources. This approach not only reduces resource waste and environmental burdens associated with large-scale demolition and reconstruction but also enhances overall building performance through low-carbon and energy-efficient technologies, responding to societal demands for green lifestyles. Green retrofitting thus bridges the gap between existing building renewal and sustainable development. Building Energy Consumption Intensity

$$E_{intensity} = \frac{E_{total}}{A_{floor}} \quad (1)$$

Within the broader framework of urban renewal, green retrofitting injects new developmental momentum into existing buildings. Urban renewal transcends mere physical restructuring, encompassing the integrated coordination of social, economic, and environmental dimensions. Green retrofitting of existing buildings improves residents' living environments, enhances urban operational efficiency, and contributes to achieving the “dual carbon goals” through energy conservation and emissions reduction. It also fosters the development of green industrial chains, drives technological innovation and application, and accelerates cities' transition toward low-carbon and smart development.

The renewal of existing buildings and green retrofitting exhibit high complementarity and consistency. The former provides the practical foundation and demand scenarios for the latter, while the latter infuses the former with sustainable development concepts and methodologies. Their organic integration not only effectively addresses the practical challenges of existing structures but also drives the overall enhancement of urban spatial quality, ultimately forming a green renewal and ecologically symbiotic urban development model. Establishing this relationship lays a solid theoretical foundation for subsequent exploration and practice of design methodologies.

3. Design Methods for Green Retrofits of Existing Buildings

Green retrofitting existing buildings is a systematic process. It requires rational optimization at the spatial and functional levels to meet contemporary usage demands, while simultaneously reducing resource and environmental consumption during building operation through the application of energy-saving and environmental technologies. Additionally, it should integrate intelligent technologies and operational management models to achieve green management throughout the building's entire lifecycle. These three elements mutually support and synergize, collectively forming the core design methodology system for green retrofitting existing buildings.

4. Spatial and Functional Optimization Methods

Spatial and functional optimization serves as the foundational step in green retrofitting existing buildings. Its core objective is to extend the building's service life while better meeting contemporary societal demands through scientifically sound design. As population structures and lifestyles evolve, the original functional layouts of many existing buildings no longer align with current usage requirements. Therefore, optimizing spatial arrangements and reconfiguring functions become crucial components of green retrofitting. This process not only enhances spatial utilization efficiency but also improves the overall environmental quality and operational performance of the building. Heat Transfer through Building Envelope (steady-state)

$$Q = U \cdot A \cdot (T_{in} - T_{out}) \quad (2)$$

Functional conversion serves as a key strategy for spatial optimization. Existing buildings facing functional vacancy or underutilization due to industrial upgrades or shifts in urban development can be repurposed through green retrofits to accommodate new functions aligned with societal needs. Examples include transforming idle industrial facilities into cultural and creative districts, or converting outdated office buildings into shared workspaces or apartment-style living spaces. Functional conversion prevents resource wastage while enabling the regeneration of building stock, thereby injecting new vitality into urban development.

Spatial reuse emphasizes enhancing flexibility and adaptability through design innovation while preserving the building's primary structure. This encompasses not only internal space reconfiguration and circulation optimization but also facade renewal and public space reimagining to improve the building's relationship with its urban context. Incorporating public gathering areas, green courtyards, or rooftop gardens during renovation elevates spatial quality, fosters user interaction, and creates conditions for cultivating sustainable lifestyles. Overall Heat Transfer Coefficient (U-value)

$$U = \frac{1}{R_{si} + \sum \frac{d_i}{\lambda_i} + R_{se}} \quad (3)$$

Human-centered design is an indispensable aspect of spatial and functional optimization. Green retrofitting should extend beyond energy-saving and environmental technologies to prioritize occupant experience and health needs. By incorporating natural lighting, ventilation, comfortable acoustic and visual environments, and barrier-free design, existing buildings can enhance comfort and health while fulfilling basic functional requirements. This human-centered approach to spatial optimization achieves dual goals: improving building performance and enhancing the living environment, thereby fully realizing the social value of green retrofitting.

5. Application Methods for Energy-Saving and Environmental Protection Technologies

Energy-saving and environmental protection technologies form the core of green retrofitting for existing buildings. Their objective is to reduce energy consumption and environmental impact during building operations through scientific technical means, thereby achieving low-carbon and sustainable development goals. Compared to new constructions, existing buildings often suffer from low energy efficiency standards and outdated facilities. Therefore, retrofitting must prioritize the integration of energy-saving technologies and the implementation of environmental protection measures, ensuring performance enhancements are balanced with ecological benefits.

In practical implementation, energy-saving retrofits of building envelopes are the primary step. Envelope systems—including walls, roofs, and windows—directly impact thermal insulation performance. Methods such as external wall insulation, roof insulation upgrades, and replacement with high-performance windows can significantly reduce heating and cooling energy consumption. Integrating green materials further enhances overall energy efficiency while ensuring safety and aesthetics. These measures feature reasonable investment and significant energy savings, making them the most widely applied technical approach in green retrofits ,showed in Figure 1 ：

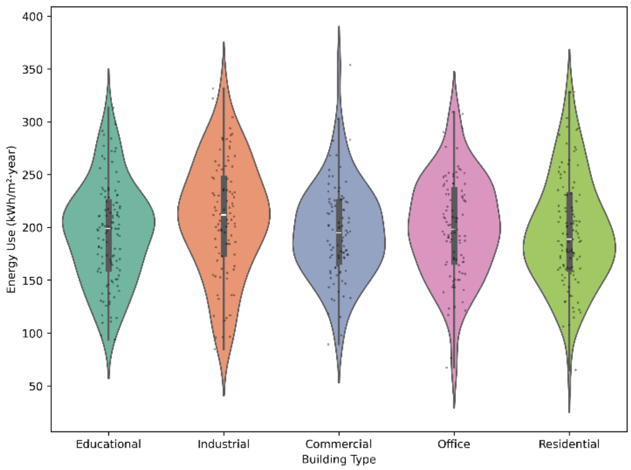

Figure 1 Energy consumption distribution by building type

The integration of renewable energy sources offers new avenues for green retrofitting of existing buildings. Technologies like photovoltaic power generation, ground-source heat pumps, and air-source heat pumps can effectively reduce reliance on traditional fossil fuels and lower carbon emissions. Where feasible, solar photovoltaic panels can be integrated into building facades and roofs through building-integrated photovoltaics (BIPV), enhancing energy efficiency while improving architectural aesthetics and achieving ecological and visual harmony. Energy Savings Rate after Retrofit

$$\eta_{save} = \frac{E_{before} - E_{after}}{E_{before}} \times 100\backslash\% \qquad (4)$$

Water resource and material recycling form another crucial aspect of environmental technologies. During retrofits, installing rainwater harvesting and reuse systems alongside water-efficient plumbing and fixtures can substantially reduce overall building water consumption. Prioritizing recyclable, low-pollution green building materials and maximizing the reprocessing and reuse of existing construction materials not only minimizes resource waste and environmental pollution during construction but also aligns with the principles of a circular economy. Collectively, these measures provide robust support for the sustainability of green retrofits in existing buildings.

6. Smart Technologies and Operational Management Methods

The integration of smart technologies in green retrofits represents both an inevitable technological trend and a critical enabler for enhancing building sustainability. With the proliferation of IoT, big data, and artificial intelligence, building operations are transitioning from manual control to intelligent automation. Smart systems enable real-time monitoring and adjustment of energy consumption and environmental parameters, further reducing operational energy use while improving occupant comfort.

Smart monitoring and energy control form the core of intelligent retrofits. By installing smart sensors and monitoring platforms, data such as indoor/outdoor temperature, humidity, air quality, and light intensity can be captured in real time. These systems integrate with HVAC and lighting systems to enable demand-based energy supply and dynamic adjustments. When occupancy levels are low, the system automatically reduces lighting brightness or airflow volume to prevent energy waste. This data-driven energy-saving approach proves more efficient and flexible than traditional timed or manual management methods. Life Cycle Cost (LCC) of Retrofit

$$LCC = C_{initial} + \sum_{t=1}^{n} \frac{C_{operation}(t) + C_{maintenance}(t)}{(1+r)^t} \qquad (5)$$

In operations and maintenance, smart retrofits emphasize meticulous management throughout the entire lifecycle. By integrating smart management platforms, existing buildings enable remote monitoring and early warnings for equipment status, allowing timely detection and maintenance of potential issues. This prevents energy waste or safety hazards caused by equipment failures. Big data analytics provide operators with energy consumption trend forecasts and optimization recommendations, helping formulate more scientific operational strategies and enhancing overall building management efficiency ,showed in Figure 2 :

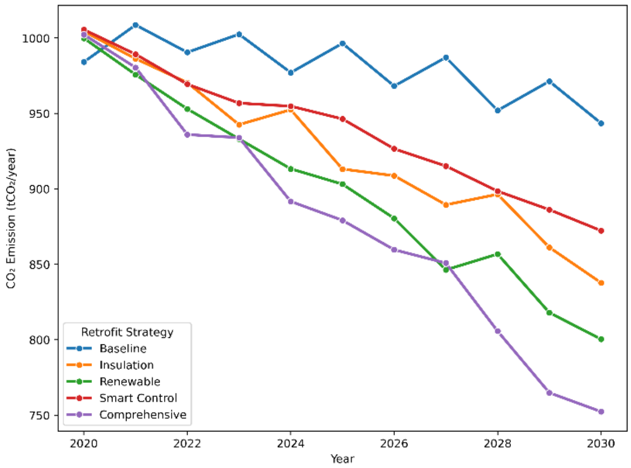

Figure 2 Carbon emission reduction trend with retrofit strategies

Smart solutions extend beyond singular energy-saving objectives, enabling comprehensive green management throughout a building's lifecycle. By integrating intelligent technologies across design, construction, operation, and maintenance phases, buildings achieve end-to-end tracking and optimization of energy consumption and carbon emissions, fostering sustained low-carbon performance. Smart platforms also offer interactive interfaces for users, enhancing public engagement and acceptance of green lifestyles, thereby creating a virtuous cycle among technology, management, and society.

7. Case Study Analysis and Methodology Summary

In the practice of green retrofitting existing buildings, exemplary cases offer intuitive references and validation for exploring design methodologies. Reviewing successful domestic and international cases reveals that diverse strategies are often adopted during green retrofits due to variations in contextual conditions, functional requirements, and renovation objectives across different building types. For instance, in Europe and America, many historic building renovations prioritize integrating energy-saving technologies while preserving original aesthetics. In China, efforts focus more on enhancing energy efficiency and improving spatial quality in residential and public buildings.

Consider the case of an industrial factory converted into a cultural and creative park. This project achieved functional repurposing and spatial regeneration by retaining and reusing the original spatial structure. The design team implemented multiple green technologies, including exterior wall insulation and reinforcement, rooftop photovoltaic systems, and rainwater harvesting systems. These measures not only significantly reduced the building's operational energy consumption but also provided sustainable energy support for the complex. Concurrently, the addition of public gathering areas and landscaped courtyards enhanced the overall environmental quality, enabling the building to meet modern functional demands while balancing ecological benefits.

In residential building retrofits, some aging neighborhoods adopted a combined approach of envelope energy efficiency upgrades and equipment modernization. Replacing high-performance windows and doors, adding exterior insulation layers, and introducing intelligent HVAC control systems significantly reduced residents' energy costs and operational loads. Optimizing public spaces and incorporating barrier-free design not only enhances residents' quality of life but also strengthens the community's sustainable development capacity. These cases demonstrate that green retrofits require comprehensive consideration across three dimensions: energy-saving technologies, human-centered needs, and social benefits. Carbon Emission Calculation

$$C_{emission} = \sum_{i=1}^{n} E_i \cdot f_i \quad (6)$$

Through case analysis, several universally applicable design principles emerge: prioritize functional substitution and space reuse to avoid resource waste; Prioritize energy-saving and environmentally friendly technologies to enhance building performance; Fully leverage intelligent solutions to ensure green operations throughout the entire lifecycle; Adhere to a human-centered philosophy, balancing ecological benefits with social value. These approaches offer flexibility and practicality across diverse building types, providing actionable pathways for scaling green retrofits in existing structures.

8. Conclusion

Against the backdrop of building stock renewal, green retrofitting of existing structures has become a vital pathway for advancing urban sustainability and achieving carbon neutrality goals. This paper analyzes the relationship between building stock renewal and green retrofitting, elucidating the significance of green retrofitting in extending building lifespans, reducing energy consumption, enhancing spatial quality, and promoting urban renewal. It identifies core design methodologies across three dimensions: spatial and functional optimization, application of energy-saving and environmentally friendly technologies, and smart solutions and operational management. Finally, it analyzes and summarizes typical case studies to distill universally applicable practical pathways. The research demonstrates that green retrofitting of existing buildings not only effectively improves the operational performance of the buildings themselves but also enhances the overall environmental quality of cities, providing strong support for ecological civilization construction.

Currently, the practice of green retrofitting existing buildings still faces challenges such as high renovation costs, uneven technology adoption, and imperfect operational management systems, which hinder the widespread implementation and depth of retrofitting. Future development requires joint efforts in policy guidance, technological innovation, and social participation. Institutional and policy incentives should be strengthened to foster a market environment conducive to green retrofits. Research and application of green building materials, new energy technologies, and intelligent management systems must be advanced to lower retrofit barriers. Public and user engagement should be enhanced to promote sustainable lifestyles.

Green retrofitting of existing buildings is a systemic endeavor requiring collaboration among design, technology, management, and societal stakeholders. Against the backdrop of deepening urban renewal, green retrofitting will continue to play a vital role, providing robust support for achieving low-carbon development and livable city construction goals.

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