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Research on Synergistic Optimization Paths for Green Renovation of Existing Public Buildings in the Context of Carbon Peaking and Carbon Neutrality

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Abstract

In recent years, with the rapid development of China's social economy and the growing awareness of environmental protection among the general public, the problems of excessive resource consumption and environmental pressure caused by traditional construction methods have become increasingly prominent, which have emerged as a key bottleneck restricting the high-quality development of the construction industry. Currently, China has a large stock of existing buildings; among them, existing public buildings serve as typical energy-intensive building stock, and relevant statistics indicate that the energy consumption during their operational phase accounts for more than 40% of the total building energy consumption. Moreover, most existing public buildings were constructed with relatively backward construction technologies at that time, resulting in high energy consumption and poor energy efficiency performance, and such drawbacks are significantly incompatible with the core requirements of China's current sustainable development strategy. In this context, green building technology, characterized by its energy-saving, environmental-friendly and high-efficiency features, has gradually become a new development trend in the construction industry, as this technology not only significantly improves the comfort level of buildings, but also effectively reduces environmental pollution during the construction process and cuts down energy consumption in the operational phase of buildings. Against such a backdrop, further advancing the green energy-saving retrofitting of existing public buildings has become an inevitable choice to improve building operational energy efficiency, promote the low-carbon transformation of the construction industry, and facilitate the achievement of dual-carbon goals, and this paper focuses on analyzing the synergistic optimization paths for the green retrofitting of existing public buildings, puts forward targeted design strategies for green retrofitting projects, and explores innovative approaches to the green retrofitting of existing buildings.

Keywords

Low-carbon Development; Energy-saving Retrofitting; Green Building Technology; Public Buildings.

1. Introduction

With the development of social economy, the era of large-scale demolition and construction of urban buildings in China has gradually come to an end. The incremental market in the construction sector has slowed down, giving way to a period of micro-renewal oriented towards refined retrofitting. Against this backdrop, the domestic market is bound to witness a large number of building retrofitting projects in the future. The pursuit of high-quality, high-standard and low-energy-consumption development in building retrofitting, as well as the

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realization of energy conservation and emission reduction, constitutes a crucial strategy for implementing the national goals of carbon peaking and carbon neutrality. Under the dual-carbon goals, the green development and low-carbon transformation of the construction industry have become an inevitable trend. On the basis of achieving carbon neutrality, green building technology should be correspondingly adopted in building retrofitting to integrate the development of the construction industry with environmental protection, thereby creating a livable building environment for society [1].

Traditional construction methods have obvious limitations in terms of energy consumption and environmental impact in material selection, construction technology, operation and management. In contrast, green building technology, characterized by its core features of energy conservation, consumption reduction, environmental protection, low carbon emissions, high efficiency and livability, has gradually emerged as a new trend leading the transformation and upgrading of the construction industry. For existing public buildings, the application of green building technology can not only significantly improve the comfort of public spaces such as offices, medical facilities and educational institutions by optimizing the building envelope and enhancing the efficiency of equipment systems, but also effectively reduce energy consumption and pollutant emissions during the retrofitting and construction phase, maximizing the environmental benefits throughout the full life cycle of public buildings. In view of the current status of existing public buildings, a large number of old public buildings, built in an era with relatively backward construction technologies, generally suffer from problems such as poor thermal insulation performance of the building envelope, low energy efficiency of air conditioning and ventilation systems, high energy consumption of lighting systems and low water use efficiency. These issues not only result in severe energy waste, but also affect the user experience. The green retrofitting and upgrading of such old public buildings through the application of green building technology can effectively optimize the indoor and outdoor environment of the buildings, improve the quality of public spaces, and create a more comfortable, aesthetically pleasing and healthy public activity environment for the general public. Meanwhile, it helps the construction industry practice the concept of green development and align with the implementation requirements of the dual-carbon strategy [2].

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public. Meanwhile, it helps the construction industry practice the concept of green development and align with the implementation requirements of the dual-carbon strategy [2].

The proposal and advancement of the dual-carbon strategy have provided clear directional guidance for the green retrofitting of existing public buildings, while also imposing higher requirements on the depth and breadth of retrofitting work. The green retrofitting of existing public buildings is not a simple superposition of individual technologies, but a systematic project involving multiple dimensions such as building envelope, equipment systems, energy utilization and intelligent management. It is necessary to fully consider the characteristics of public buildings, including high population density, diverse functions and long operation hours, while balancing the coordination of technical feasibility, economic rationality and environmental benefits [3]. Based on this, combining the actual operation status of existing public buildings and the core requirements of the dual-carbon strategy, this paper systematically reviews the core advantages of applying green building technology in existing public buildings, conducts an in-depth analysis of the multi-dimensional synergistic optimization paths for the green retrofitting of existing public buildings, puts forward targeted design strategies for the green retrofitting of existing public buildings, and explores innovative and practical methods for the green retrofitting of existing public buildings. The aim is to provide theoretical reference and practical guidance for promoting the standardized and efficient implementation of green retrofitting work for existing public buildings in China.

2. Core Advantages of Applying Green Building Technology in Existing Public Buildings

Green building technology covers multiple fields such as building envelope energy-saving technology, renewable energy utilization technology, intelligent building control technology, and green building material application technology. Specifically, it refers to advanced technical means that actively adopt and integrate the concepts of environmental protection, energy conservation, ecology, and health in the stages of architectural design and construction. With green, energy-saving, and environmental protection as the core guiding concepts, it takes energy conservation and emission reduction as the starting point both in terms of construction technology and construction material selection, emphasizing the efficient utilization of natural resources and the minimal damage to the ecological environment. As an important component of modern development, green building technology has changed the situation of high energy consumption and high pollution in the traditional construction process. Through the application of green building technology, modern buildings have been able to get rid of many drawbacks and defects in the past construction process, and have significantly demonstrated the characteristics of "four savings and one environmental protection", namely energy saving, land saving, water saving, material saving, and environmental protection. The application of green building technology can not only create a healthy and comfortable living and working environment for people, but also better protect the surrounding environment, realizing the harmonious coexistence of buildings and the surrounding environment[4]. Green building technology is of great significance both for the protection of urban ecological environment and for the sustainable development of social economy. The application of green building technology in the green retrofitting of existing public buildings can combine the functional characteristics of public buildings, exert significant advantages in multiple aspects such as energy conservation, environmental improvement, and benefit enhancement, and provide strong support for the low-carbon transformation of existing public buildings

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2.1. Reduce Building Energy Consumption and Facilitate the Achievement of the Dual-carbon Goals.

The high energy consumption of existing public buildings is mainly concentrated in aspects such as heat transfer loss through the building envelope, energy consumption of air conditioning systems, and lighting energy consumption, and due to characteristics like long operating hours and high population density, their energy consumption intensity is significantly higher than that of ordinary residential buildings; green retrofitting by applying green building technology can achieve a substantial reduction in energy consumption. For example, retrofitting the exterior walls, roofs, doors and windows of buildings with high-performance thermal insulation materials can effectively reduce heat transfer between the interior and exterior of buildings, lower the load on air conditioning systems, and thereby cut down energy consumption; replacing traditional lighting equipment with LED energy-saving lighting technology, combined with intelligent lighting control systems that precisely adjust light intensity based on the population density and usage periods of public spaces, can significantly reduce lighting energy consumption; in addition, the application of renewable energy utilization technologies such as solar photovoltaic power generation and geothermal heating can replace part of traditional fossil energy, further improve the energy self-sufficiency capacity of public buildings, and reduce carbon emissions[5]. Relevant studies have shown that the energy consumption of existing public buildings undergoing green retrofitting can be reduced by more than 30%, and some buildings with excellent retrofitting effects can even achieve an energy consumption reduction of up to 50%, which is of great significance for promoting the achievement of carbon peaking and carbon neutrality goals in the construction industry [6].

2.2. Optimize the Public Space Environment and Enhance Usage Comfort and Health Performance.

Old existing public buildings are generally plagued by problems such as unstable indoor temperature and humidity, poor lighting and ventilation effects, severe noise pollution, and substandard air quality. Given their characteristic of high population density, these issues exert a more prominent impact on the comfort and health of users. The application of green building technology can target these problems and realize the optimization and upgrading of the public building environment. In terms of lighting and ventilation, the adoption of new building envelope materials such as Low-E insulating glass and photovoltaic curtain walls, combined with the optimized shape design of public buildings featuring large spans and multiple spaces, can improve the natural lighting efficiency of buildings and reduce reliance on artificial lighting; the installation of adjustable ventilation windows, mechanical ventilation and air purification systems can improve indoor air quality, achieve effective circulation of fresh air, and meet the ventilation needs of crowded public spaces. In terms of temperature and humidity control, the application of high-efficiency heating and cooling technologies such as ground-source heat pumps and air-source heat pumps enables precise regulation of indoor temperature and humidity, enhancing the comfort of public spaces; meanwhile, the use of green building materials, such as decorative materials with low formaldehyde and low volatile organic compounds (VOCs), can reduce the emission of indoor harmful gases and safeguard the physical health of users [7]. In addition, the application of green ecological technologies such as green roofs and vertical greening can beautify the external environment of buildings, mitigate the urban heat island effect, improve the quality of the ecological environment around public buildings, and enhance the livability of public spaces.

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2.3. Extend the Service Life of Buildings and Enhance Economic and Social Benefits.

After long-term service, some structural components and equipment systems of existing public buildings have exhibited aging and damage. Moreover, due to high-frequency usage and heavy load-bearing pressure, the aging process is accelerated. Without timely green retrofitting, it will not only affect the operational safety of the buildings, but also potentially increase subsequent maintenance costs and even disrupt the normal delivery of public services. During the green retrofitting of existing public buildings, comprehensive inspection and reinforcement of the building structure will be conducted, obsolete equipment systems will be upgraded, and more durable green building materials and equipment will be adopted. These measures can effectively extend the service life of the buildings and reduce maintenance costs. From an economic benefit perspective, although green retrofitting requires a certain amount of upfront investment, the subsequent reduction in energy consumption and maintenance costs, coupled with the appreciation of building value, can achieve investment recovery and value increment. For example, commercial buildings that have undergone green retrofitting can attract more tenants and increase rental income due to improved environmental quality and energy efficiency; public buildings such as schools and hospitals can reduce operational costs through lower energy consumption and allocate more funds to the enhancement of public services. From a social benefit perspective, the green retrofitting of existing public buildings can drive the development of related industries such as green building materials, energy-saving equipment and intelligent control, creating a large number of job opportunities. Meanwhile, the retrofitted public buildings can reduce energy consumption and pollutant emissions, alleviate resource and environmental pressures, promote the improvement of urban living environments, enhance public satisfaction with public service facilities, and facilitate the sustainable development of society[8].

3. Synergistic Optimization Paths for Green Retrofitting of Existing Public Buildings

The green retrofitting of existing public buildings is a complex systematic project involving multiple dimensions such as technology, economy, management and policy. It also needs to be fully adapted to the functional characteristics and operational requirements of public buildings. Only by realizing the synergistic optimization of all links and elements can the smooth progress of the retrofitting work and the maximization of benefits be ensured[9]. Combined with the actual situation of existing public buildings and the requirements of the dual-carbon strategy, the synergistic optimization paths for their green retrofitting are mainly reflected in the following aspects.

3.1. Technology Synergy: Integrated Application of Multi-domain Green Technologies Adapted to the Characteristics of Public Buildings.

The application of a single green technology is difficult to achieve energy consumption reduction and environmental optimization throughout the full life cycle of existing public buildings. It is necessary to combine the characteristics of public buildings such as high population density, diverse functions and long operating hours to promote the integrated coordination of multi-domain technologies including building envelope energy-saving technology, renewable energy utilization technology, intelligent control technology and water resource recycling technology. On the one hand, it is essential to select highly adaptable green building technologies according to the structural types, specific functions and regional climatic conditions of existing public buildings, so as to form personalized technology combination schemes. For example, in the retrofitting of public buildings such as hospitals and schools in

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cold northern regions, emphasis should be placed on strengthening the coordinated application of building envelope thermal insulation technology and geothermal heating technology to ensure stable indoor temperatures in winter; in public buildings such as shopping malls in hot southern regions, attention should be paid to the combination of shading technology, natural ventilation technology and air conditioning system energy-saving technology to reduce air conditioning energy consumption in summer[10]. On the other hand, it is important to strengthen the connection and matching between different technologies to avoid conflicts and inefficiency in technology application. For instance, the coordinated control of renewable energy systems and public building equipment systems such as air conditioning and lighting can achieve efficient energy utilization; the combination of intelligent monitoring technology and energy consumption management systems can grasp the energy consumption status of different periods and regions of public buildings in real time, providing data support for technical optimization and adjustment. In addition, efforts should be made to promote the integrated innovation of traditional building technologies and new green technologies, so as to improve the feasibility and advancement of retrofitting technologies and meet the complex usage needs of public buildings.

3.2. Subject Synergy: Collaborative Linkage of Multi-stakeholders.

The green retrofitting of existing public buildings involves multiple stakeholders, including government departments, public building property owners, retrofitting construction enterprises, technology R&D institutions, and operation and maintenance management units. The collaborative linkage among these stakeholders is the key to ensuring the smooth progress of the retrofitting work. Government departments should play a guiding and supervisory role by formulating sound policies and regulations, introducing fiscal subsidies and tax incentives, establishing unified standards and evaluation systems for the green retrofitting of existing public buildings, so as to provide policy support and institutional guarantee for the retrofitting work; at the same time, they should strengthen the supervision and management of retrofitting projects to ensure the quality and effect of the retrofitting. As one of the beneficiary entities and investment entities of the retrofitting projects, public building property owners should raise their awareness of green retrofitting, actively participate in the formulation and implementation of retrofitting plans in light of public service demands, and cooperate with construction enterprises in carrying out the retrofitting work. Retrofitting construction enterprises should strengthen their technological innovation and construction management capabilities, fully consider the impact of public building retrofitting on the provision of public services during the construction period, arrange the construction schedule reasonably, carry out construction in strict accordance with the retrofitting plans, ensure construction quality and safety, and minimize environmental pollution during the construction process. Technology R&D institutions should focus on the key technical challenges in the green retrofitting of existing public buildings, such as ventilation and energy-saving technologies for large-space public buildings and air quality control technologies for high-density pedestrian areas, strengthen technological R&D and achievement transformation, and provide technical support for the retrofitting work. Operation and maintenance management units should intervene in the retrofitting process in advance, participate in the optimal design of retrofitting plans, do a good job in the operation and maintenance management of buildings after retrofitting, ensure the long-term stable operation of green technologies and equipment, and guarantee the sustained and efficient provision of public services[11]. In addition, a multi-party communication and coordination mechanism should be established to promptly resolve problems arising during the retrofitting process and form a collaborative work pattern for advancing the retrofitting work.

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3.3. Life Cycle Synergy: Integrated Optimization of the Entire Retrofitting Process.

The green retrofitting of existing public buildings should follow the life-cycle concept and align with the long-term operational needs of public buildings to achieve integrated optimization of the entire process, ranging from pre-retrofitting investigation, scheme design and construction implementation to post-retrofitting operation and maintenance management, as well as demolition and disposal at the end of service life. In the pre-retrofitting investigation phase, a comprehensive survey should be conducted on the structural conditions, energy consumption levels, equipment operation status, surrounding environment and public service demands of existing public buildings, so as to provide accurate data support for the formulation of retrofitting schemes; meanwhile, the retrofitting objectives and core indicators should be clearly defined. In the scheme design phase, factors such as technical feasibility, economic rationality and environmental benefits should be comprehensively considered, and personalized retrofitting schemes should be formulated in combination with the functional characteristics of public buildings; emphasis should be placed on the collaborative design of building envelope, equipment systems and energy utilization, so as to ensure the systematicness and completeness of the retrofitting scheme while taking into account the improvement of public service functions after retrofitting. In the construction implementation phase, green construction technologies should be adopted to reduce energy consumption, construction waste and pollutant emissions during the construction process; the construction period should be reasonably arranged to minimize interference with the provision of public services; quality control and safety management during the construction process should be strengthened to ensure the effective implementation of the retrofitting scheme[12]. In the post-retrofitting operation and maintenance management phase, an intelligent operation and maintenance management system should be established to monitor the energy consumption of public buildings and the operation status of equipment in real time, so as to timely identify and solve problems arising during the operation and maintenance process; professional training for operation and maintenance personnel should be strengthened to improve their green operation and maintenance management capabilities; at the same time, guidance and publicity for users should be enhanced to raise their awareness of green usage, ensuring that the building operates stably in a highly energy-efficient state for a long time. In addition, consideration should also be given to the resource recycling and reuse during the building demolition and disposal phase, so as to realize the low-carbon and environmental protection of existing public buildings throughout their entire life cycle. green retrofitting of existing public buildings involves multiple stakeholders, including government departments, public building property owners, retrofitting construction enterprises, technology R&D institutions, and operation and maintenan.

3.4. Policy-Market Synergy: The Organic Integration of Policy Guidance and Market Driving Forces.

The large-scale advancement of green retrofitting for existing public buildings requires the organic integration of policy guidance and market driving forces. In terms of policy guidance, the government should further improve the relevant policy system, refine policy measures such as fiscal subsidies, tax incentives and financial support for green retrofitting of existing public buildings in combination with the dual-carbon strategic goals, so as to reduce the investment costs of retrofitting entities; establish and improve the standard system and evaluation and certification system for green retrofitting of existing public buildings, and standardize the retrofitting process and quality requirements; strengthen policy publicity and promotion, and enhance the whole society's awareness and recognition of green retrofitting for existing public buildings. In terms of market driving forces, full play should be given to the decisive role of the

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market in resource allocation to cultivate and expand the market for green retrofitting of existing public buildings; social capital should be encouraged to participate in retrofitting projects, and the channels of retrofitting funds should be broadened through models such as PPP and energy performance contracting (EPC); in view of the characteristics of public buildings, innovation of financial products such as green building insurance and green credit should be promoted to provide financial support for retrofitting projects; a green building performance evaluation and trading mechanism should be established to improve the operational benefits and social value of retrofitted public buildings, and stimulate the enthusiasm of market entities for retrofitting[13]. Through the synergistic efforts of policy guidance and market driving forces, a strong impetus can be formed to promote the large-scale and market-oriented development of green retrofitting for existing public buildings.

4. Design Strategies for Green Retrofitting of Existing Public Buildings

The design work of green retrofitting for existing public buildings is a core link to ensure retrofitting effects. It should formulate targeted design countermeasures from multiple key fields such as building envelope, energy system, water resource utilization and intelligent control, in combination with the actual conditions, functional requirements of use and the requirements of the dual-carbon strategy.

4.1. Optimization Design of Building Envelope: Improving Thermal Insulation Performance.

The building envelope is the primary channel for energy loss in existing public buildings, and its optimization design constitutes a key component of green retrofitting. In terms of door and window retrofitting design, high-performance materials such as thermal break aluminum profiles and Low-E insulating glass should be adopted to replace traditional ordinary doors and windows, enhancing their thermal insulation performance and airtightness. Meanwhile, based on the functional requirements of public buildings and regional climatic conditions, the opening methods and areas of doors and windows should be rationally designed to balance natural lighting and ventilation effects, thereby reducing energy consumption of air conditioners and lighting systems. For external wall retrofitting design, external thermal insulation technology should be employed, with high-efficiency insulation materials such as rock wool, extruded polystyrene boards and vacuum insulation panels combined with protective layer materials including anti-crack mortar and alkali-resistant fiberglass mesh to form a complete external wall insulation system. As for the exterior decorative layers of existing public buildings, they can be renovated in conjunction with insulation retrofitting, using green and environmentally friendly decorative materials to improve the aesthetic quality of the building and meet the image requirements of public buildings [14]. In the aspect of roof retrofitting design, measures such as thickening the roof thermal insulation layer, constructing green roofs and installing photovoltaic roofs are applicable. Green roofs not only enhance the thermal insulation performance of the roof, but also beautify the environment, absorb rainwater, mitigate the urban heat island effect and improve the ecological benefits of public buildings. Photovoltaic roofs, on the other hand, can utilize solar energy to generate electricity, providing clean power for lighting, air conditioning and other equipment in public buildings and increasing energy self-sufficiency capacity. In addition, it is necessary to strengthen the sealing design of various joints of the building envelope to reduce the thermal bridge effect, further improving the energy-saving effect of the building envelope to meet the energy consumption control needs of public buildings operating for long periods [15].

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4.2. Energy System Optimization Design: Promoting Efficient Energy Utilization and Renewable Energy Replacement.

The optimized design of the energy system is the key to reducing the operational energy consumption of existing public buildings, and it needs to be tailored to the characteristics of public buildings such as large fluctuations in passenger flow and fixed operating hours. In terms of the retrofitting design of air conditioning systems, the original air conditioning systems should be upgraded according to the usage functions and load characteristics of public buildings (e.g., the constant temperature and humidity requirements of hospitals and the peak passenger flow loads of shopping malls); for outdated and low-efficiency air conditioning equipment, high-efficiency and energy-saving devices such as inverter air conditioners, ground-source heat pumps, and air-source heat pumps should be adopted as replacements; meanwhile, intelligent control technologies for air conditioning systems should be applied, and the precise regulation of air conditioning loads should be realized in combination with passenger flow density monitoring, so as to improve the operational efficiency of air conditioning systems and avoid energy waste. In the retrofitting design of lighting systems, all lighting fixtures should be fully replaced with LED energy-saving lighting equipment; combined with intelligent lighting control systems, the lighting brightness and on-off status can be automatically adjusted according to indoor light intensity, personnel activity, and the needs of different functional areas, minimizing lighting energy consumption; in addition, the natural lighting design of buildings should be optimized, and the utilization rate of natural lighting can be improved by adjusting the size of doors and windows, installing daylighting skylights, and using reflective materials, which is particularly suitable for public spaces such as classrooms and offices. In the design of renewable energy utilization, renewable energy technologies such as solar energy, geothermal energy, and wind energy should be rationally selected based on the regional conditions and usage requirements of buildings; for example, in areas with favorable lighting conditions, solar photovoltaic power generation systems can be installed on building roofs, parking lot canopies, and other locations to supply power for lighting, air conditioning, and other equipment in public buildings; in areas with suitable geological conditions, ground-source heat pump systems can be adopted to achieve building heating and cooling, meeting the stable temperature and humidity requirements of public buildings [16]; furthermore, an energy cascade utilization system can be designed to achieve the rational matching and efficient utilization of energy at different temperature levels, improving energy utilization efficiency and meeting the energy conservation requirements under the dual-carbon strategy.

4.3. Water Resource Recycling Design: Achieving Water Conservation and Efficient Water Resource Allocation.

Water resource recycling design is an important component of the green retrofitting of existing public buildings, which can effectively improve water resource utilization efficiency, reduce water waste, and meet the resource conservation requirements under the dual-carbon strategy. Existing public buildings are characterized by high population density and large water demand, so it is particularly necessary to strengthen water resource recycling. In terms of rainwater resource utilization design, rainwater collection systems should be installed on building roofs, squares and other areas, and rainwater should be collected into reservoirs through rainwater hoppers, collection pipelines and other components; the collected rainwater can be used for non-potable purposes such as building greening irrigation, road cleaning and toilet flushing after undergoing sedimentation, filtration, disinfection and other treatment processes, thereby reducing tap water consumption. In the design of reclaimed water utilization, for large-scale public buildings, small-scale reclaimed water treatment facilities can be constructed to treat domestic sewage generated in the buildings, which can be recycled after meeting the reclaimed water quality standards; for small-scale public buildings, they can be connected to the urban

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reclaimed water pipe network, and urban reclaimed water can be used to replace tap water for non-potable purposes. In terms of water-saving equipment and appliance design, all devices should be fully replaced with water-saving toilets, water-saving faucets, water-saving showers and other water-saving equipment and appliances to reduce domestic water consumption; this measure will achieve more significant water-saving effects especially in water-intensive public buildings such as hospitals and schools. In addition, it is necessary to strengthen the design of leakage detection and repair for building water supply and drainage systems to avoid water waste caused by pipeline leakage; at the same time, optimize the greening irrigation methods, and adopt efficient water-saving irrigation technologies such as drip irrigation and sprinkler irrigation to replace the traditional flood irrigation method [17].

4.4. Intelligent Control System Design: Improving the Operational and Maintenance Management Efficiency of Public Buildings.

The design of an intelligent control system enables the precise regulation and efficient management of the operational status of existing public buildings, adapts to the characteristics of complex functions and high population density of public buildings, and serves as an important guarantee for improving the effectiveness of green retrofitting. An intelligent building management platform integrating functions such as energy consumption monitoring, equipment control, environmental monitoring, safety protection, and passenger flow management should be constructed to realize the real-time collection, analysis, and processing of building operation data. In terms of energy consumption monitoring, intelligent metering devices should be installed in key energy-consuming parts of the building such as power distribution systems, air conditioning systems, lighting systems, and water supply and drainage systems to monitor the energy consumption data of each system and each functional area in real time; data analysis and statistics should be carried out through the intelligent management platform to provide data support for energy consumption optimization and adjustment. In the aspect of equipment control, intelligent control technology should be adopted to automatically regulate equipment such as air conditioners, lighting fixtures, and ventilation systems, dynamically adjusting the operational status of equipment according to indoor and outdoor environmental parameters and personnel activity to ensure that the equipment operates under energy-efficient working conditions; for example, during off-peak passenger flow periods in shopping malls, the air conditioning load and lighting brightness can be automatically reduced. In terms of environmental monitoring, sensors for environmental parameters such as temperature, humidity, air quality, light intensity, and CO_2 concentration should be installed to monitor indoor and outdoor environmental quality in real time; when environmental parameters exceed the set range, the intelligent control system automatically activates relevant equipment for regulation, ensuring indoor environmental comfort, health and safety, which is particularly suitable for crowded public spaces [18]. In the aspect of safety protection and passenger flow management, systems such as fire alarm, anti-theft alarm, video surveillance, and passenger flow density monitoring should be integrated to achieve comprehensive monitoring and early warning of building safety, improve the level of building safety management, and ensure the orderly provision of public services.

5. Exploration of Innovative Methods for Green Retrofitting of Existing Public Buildings

To further improve the effectiveness and feasibility of the green retrofitting of existing public buildings, promote the large-scale and high-efficiency development of retrofitting work, and contribute to the achievement of the dual-carbon strategic goals, it is necessary to explore innovative retrofitting methods suitable for the characteristics of public buildings by integrating new technologies and concepts.

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5.1. Intelligent Full-Process Management of Retrofitting based on Digital Twin Technology.

Digital twin technology is an important innovative direction for realizing the intelligent management of green retrofitting of existing public buildings, which can accurately adapt to the characteristics of complex functions and diverse systems of public buildings. By constructing a digital twin model of an existing public building, real-time mapping between the physical entity and virtual model of the building is achieved, realizing data visualization and intelligent management throughout the building's life cycle. In the pre-retrofitting investigation phase, detailed data such as the structure, energy consumption, equipment, and passenger flow distribution of the public building can be obtained by means of laser scanning, BIM technology, etc., to build an accurate digital twin model that provides data support for the formulation of retrofitting schemes; through simulation analysis with the digital twin model, comparative evaluation can be conducted on the energy consumption reduction effect, environmental optimization effect, economic cost, and impact on public services of different retrofitting schemes, so as to realize the optimal screening of retrofitting schemes[19]. In the construction implementation phase, the digital twin model can be combined with the construction schedule to realize visual management and schedule control of the construction process; by collecting real-time data on quality, safety, and energy consumption during the construction process and conducting comparative analysis with the digital twin model, problems in the construction process can be identified and adjusted in a timely manner, while reasonably avoiding the interference of construction on the provision of public services to ensure construction quality and safety. In the post-retrofitting operation and maintenance management phase, the digital twin model can receive real-time data on energy consumption, equipment operation, environmental quality, and passenger flow density during the operation of the public building, and predict and warn the building's operating status through big data analysis and artificial intelligence algorithms to support operation and maintenance management decisions; meanwhile, virtual commissioning can be carried out through the digital twin model to optimize equipment operation parameters, improve operation and maintenance management efficiency, and ensure that the public building operates in a highly energy-efficient state stably for a long time.

5.2. Innovative Retrofitting Construction based on Modular and Prefabricated Technology.

Traditional construction methods for the retrofitting of existing public buildings are plagued by problems such as long construction periods, heavy on-site workloads, large amounts of construction waste, and significant impacts on the surrounding environment and public services. The retrofitting construction method based on modular and prefabricated technologies can effectively address these issues and improve the efficiency and environmental friendliness of retrofitting construction. In the retrofitting scheme design phase, combined with the characteristics of the functional zoning of public buildings, building components such as the building envelope, equipment systems, washrooms, and stairwells are divided into multiple standardized modules for prefabrication in factories; green building materials and energy-saving equipment are adopted for prefabricated modules to ensure the quality and energy-saving performance of the modules while meeting the usage requirements of public buildings. In the on-site construction phase, prefabricated modules are assembled in place by means of hoisting and splicing, which reduces on-site wet operations and shortens the construction period; meanwhile, modular construction can reduce the generation of construction waste, mitigate impacts on the surrounding environment, and minimize interference with the provision of public services[20]. For example, in the external wall retrofitting of existing public buildings, prefabricated integrated thermal insulation and decoration modules can be directly

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hoisted and fixed on site, which not only improves construction efficiency but also ensures the quality of external wall thermal insulation and decoration; in washroom retrofitting, prefabricated washroom modules are adopted, and the renovation and upgrading can be completed through simple on-site connection and installation. In addition, modular and prefabricated technologies also facilitate the later maintenance and renewal of public buildings, enhance the sustainability of buildings, and meet the long-term operational needs of public buildings.

5.3. Innovation of Cluster-Based Retrofitting Mode based on the Concept of Collaborative Sharing.

For a large number of concentrated existing public buildings in cities (such as education parks, commercial blocks, etc.), the adoption of a cluster-based green retrofitting mode can achieve resource sharing, cost reduction and benefit maximization, which serves as an effective path to promote the large-scale development of retrofitting. In the planning phase of cluster-based retrofitting, it is necessary to break through the retrofitting limitations of individual public buildings, proceed from the overall perspective of the region, and comprehensively consider the energy systems, water resource systems, transportation systems, ecological environments and other aspects of public buildings within the region, so as to realize the optimal allocation of regional resources. For example, in the cluster retrofitting of education parks, centralized solar water heating systems, reclaimed water treatment systems, centralized heating and cooling systems can be constructed in a unified manner to realize the shared utilization of resources and reduce the retrofitting costs of individual schools; in the cluster retrofitting of commercial blocks, regional-level energy cascade utilization systems and waste heat recovery and utilization systems can be established to realize the coordinated energy utilization among various commercial buildings in the block and improve the overall energy utilization efficiency of the region. In the implementation phase of retrofitting, large-scale procurement and construction can be realized through unified construction organization and centralized procurement of materials and equipment, thereby reducing retrofitting costs and shortening the construction period; at the same time, it is essential to strengthen the collaborative linkage among various public buildings in the region to achieve complementary sharing of energy, water resources and other resources [21]. In the post-retrofitting operation and maintenance phase, a regional operation and maintenance management platform should be established to carry out unified operation and maintenance management of public buildings in the cluster, so as to improve operation and maintenance efficiency and reduce operation and maintenance costs; meanwhile, operation and maintenance technologies and human resources should be shared to ensure the long-term stable operation of the retrofitted buildings.

5.4. Innovation of Market-Oriented Retrofitting Financing based on the Energy Performance Contracting Model.

Fund shortage stands as one of the vital factors hindering the large-scale promotion of green retrofitting initiatives for existing public buildings. The market-driven financing approach for retrofitting projects, which is based on the Energy Performance Contracting (EPC) model, can effectively expand the spectrum of funding channels and boost the enthusiasm of market participants to engage in retrofitting work. The Energy Performance Contracting model refers to a collaborative mechanism whereby energy service companies sign energy-saving service agreements with the property owners of public buildings. Under this mechanism, energy service companies take charge of the full lifecycle of retrofitting projects, covering investment, design, construction, operation and maintenance, while the property owners of public buildings settle the investment and service fees of energy service companies by leveraging the energy-saving benefits yielded after the completion of retrofitting. This model is capable of alleviating the upfront investment burden on public building property owners to a large extent, and it

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enables the sharing of retrofitting risks and benefits among all parties involved, thus making it particularly applicable to government-owned public buildings with constrained capital budgets. To further improve the adaptability of the Energy Performance Contracting model, targeted innovative optimization can be implemented in light of the distinctive features of existing public buildings: for instance, for the retrofitting projects of clustered public buildings such as school campuses and commercial building complexes, the cluster-based Energy Performance Contracting model can be adopted, in which energy service companies carry out unified planning, integrated retrofitting and centralized operation and maintenance for multiple public building projects to achieve economies of scale and cut down on overall retrofitting costs; the financing modes of Energy Performance Contracting can be innovated by integrating green financial instruments including green credit and green bonds, so as to enhance the capital strength of energy service companies; a sound risk assessment and guarantee system for Energy Performance Contracting projects ought to be established to mitigate investment risks, thereby attracting more social capital to participate in the green retrofitting of existing public buildings[22].

6. Conclusion

The green retrofitting of existing public buildings serves as a pivotal measure to propel the low-carbon transition of the construction industry and fulfill the strategic goals of "carbon peaking and carbon neutrality".It yields remarkable benefits in energy conservation, environmental improvement, as well as economic and social development. By comprehensively reviewing the core advantages of applying green building technologies to existing public buildings, this paper analyzes the optimized pathways for green retrofitting from the perspectives of technological coordination, stakeholder collaboration, whole-life-cycle synergy, and policy-market alignment, in combination with the functional characteristics and operational requirements of public buildings. Furthermore, it puts forward targeted design strategies for key domains including building envelope systems, energy supply systems, water resource utilization, and intelligent control systems. Additionally, innovative retrofitting approaches based on the concepts of digital twin, modular prefabrication, energy performance contracting and cluster-based management are explored. Looking ahead, it is imperative to further strengthen the technological R&D and achievement transformation of green retrofitting for existing public buildings, refine the relevant policy frameworks and market mechanisms, and promote the large-scale and standardized implementation of retrofitting projects. These efforts will provide solid support for the construction industry to realize low-carbon sustainable development and contribute to the attainment of the "dual carbon" goals.

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