Modeling and Optimization of Renewable Energy Integrated HVAC Systems for Low Carbon Buildings

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Abstract: In the context of global energy structure transformation and the "dual carbon" goal, the low-carbon development of the construction industry, as a key area of energy consumption and carbon emissions, is imperative. The core of low-carbon buildings lies in optimizing design to reduce operational energy consumption, minimize environmental load, and achieve efficient resource utilization and ecological sustainability. Among them, the HVAC system, as the main component of building energy consumption, directly determines the overall energy efficiency level and living comfort of the building based on its energy-saving performance. This article focuses on renewable energy integrated HVAC systems for low-carbon buildings, system modeling and multi-objective optimization research, with a focus on key technical aspects such as diversified configuration of cold and heat sources, fresh air heat recovery strategies, and collaborative design of kitchen exhaust systems. At the same time, we will delve into the collaborative mechanism between passive design principles and active HVAC systems in ultra-low energy residential buildings, and propose a system solution that balances energy efficiency, comfort, and economy. The research results aim to provide feasible and replicable technological paths and design references for green and low-carbon housing, and to assist the high-quality development of China's construction industry towards energy-saving, low-carbon, and intelligent directions.

1. Introduction

In the macro context of the continuous intensification of global climate change and the acceleration of carbon neutrality goals, the contradiction between energy consumption and ecological environment protection is becoming increasingly acute. As a key area of global energy consumption and greenhouse gas emissions, the low-carbon transformation of the construction industry has become a core issue for achieving sustainable development [1]. With the acceleration of urbanization and the improvement of residents' quality of life, the proportion of building energy consumption continues to rise. The policy orientation of shifting from dual control of energy consumption and intensity to dual control of carbon emissions has put forward systematic and urgent requirements for building energy conservation and carbon reduction [2]. In this context, the traditional high-energy consumption and extensive HVAC design concept is no longer able to meet the needs of green and low-carbon development in the new era [3]. It is particularly noteworthy that the air conditioning system, as a subsystem with long operating time, large load fluctuations, and high energy consumption ratio in buildings, has a leverage effect on overall carbon reduction through energy-saving optimization, and should become the core focus of the building design stage [4].

Currently, the development of green and energy-saving technologies provides strong support for the innovation of HVAC systems. By integrating renewable energy sources such as solar energy and ground source heat pumps, utilizing efficient heat recovery devices, intelligent control systems, and low-energy equipment, not only can the system significantly reduce operating energy consumption and carbon footprint, but it can also simultaneously improve indoor air quality (IAQ) and thermal comfort [5]. Ultra low energy consumption residential buildings are a concentrated embodiment of this concept-while minimizing operational energy consumption, their refined design

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often provides residents with better temperature and humidity stability, air freshness, and sound and light environment than conventional residential buildings, truly achieving energy conservation without reducing comfort [6]. However, there are still significant shortcomings in existing research. On the one hand, most of the achievements focus on the optimization of central heating systems in cold northern regions, and research on HVAC design strategies, technology selection, and climate adaptability in the emerging form of ultra-low energy residential buildings is still weak, especially lacking customized solutions that combine regional climate characteristics, residents' energy consumption habits, and personalized comfort needs [7].

On the other hand, residential buildings lack systematic evaluation and empirical support for the system performance, user feedback, and energy efficiency of ultra-low energy residential buildings in real living scenarios due to their diverse user behaviors, complex spatial functions, long data collection cycles, and scarce long-term operational test data. As a result, existing research is mostly focused on public buildings such as offices and schools [8]. In response to the above issues, this article focuses on integrating renewable energy HVAC systems for low-carbon buildings, constructing a multi physics coupled system simulation model, and conducting collaborative optimization research with energy efficiency, economy, and comfort as multiple objectives. The focus covers key technical aspects such as diversified configuration strategies for cold and heat sources, improvement paths for fresh air heat recovery efficiency, and collaborative design of kitchen exhaust and overall ventilation systems. At the same time, a deep analysis of the coupling mechanism between passive design and active HVAC systems is conducted, exploring the system integration path of passive priority and active optimization, and ultimately proposing a HVAC system solution that balances technical feasibility, economic rationality, and residential comfort.

2. Principles and Problems of HVAC Design

2.1 HVAC Design Principles

Currently, with the deepening of the global concept of sustainable development, green buildings have evolved from a peripheral concept to a mainstream paradigm in the industry [9]. Its core lies in balancing ecological laws, resource efficiency, and economic feasibility. Through scientific design and technological innovation, while ensuring building functionality and comfort, it maximizes the reduction of energy consumption and environmental load throughout the entire lifecycle [10]. As the "main force" of building energy consumption, the design concept of HVAC urgently needs to be comprehensively upgraded from traditional "meeting temperature control needs" to "green, intelligent, collaborative, and low-carbon". In the context of green building, HVAC design should follow three core principles. Firstly, the principle of prioritizing ecological friendliness and renewable energy. The design should prioritize the use of environmentally friendly materials with low pollution, recyclability, and low carbon footprint, and actively integrate clean and renewable energy sources such as solar energy, ground source heat pumps, and air source heat pumps to build a composite energy supply system dominated by natural energy and supplemented by traditional energy. By scientifically configuring collectors, energy storage devices, and intelligent scheduling systems, we aim to maximize the utilization of renewable energy, reduce dependence on fossil fuels, lower carbon emissions from the source, and achieve a "green energy structure".

Secondly, the principle of maximizing system energy efficiency. Energy conservation should not be limited to equipment selection, but should be integrated throughout the entire system design process. High energy efficiency ratio (COP/EER) equipment should be used to optimize the layout of hydraulic and air ducts, strengthen the insulation performance of building envelope structures, and reduce thermal losses. At the same time, an intelligent building control system is introduced to dynamically adjust the operation strategy based on indoor and outdoor environmental parameters, personnel density, and usage periods, achieving on-demand energy supply and precise temperature control, eliminating the "big horse pulling small car" energy waste, and significantly improving the overall energy efficiency of the system. Thirdly, the principle of energy cascade utilization and circular regeneration. Design should pay attention to the "drying and squeezing" of energy within the system, such as using exhaust heat recovery devices to recover cold and heat from exhaust air for pre-treatment of fresh air; Kitchen exhaust waste heat is used for preheating domestic hot water; Condensation heat recovery is used for dehumidification or heating assistance. By constructing a closed-loop path of "energy waste heat reuse", the comprehensive utilization efficiency of energy can be improved, operating costs can be reduced, and the impact of thermal emissions on the microenvironment can be alleviated.

2.2 Existing Problems

Currently, although the concept of green energy conservation has been widely advocated, the technical implementation effect in HVAC design practice is still not ideal, mainly due to the three bottlenecks of cognition, technology, and systematicity. Firstly, the industry's emphasis on green and energy-saving technologies still remains at the policy level, with design units, owners, and even some engineers lacking a profound understanding of their economic, long-term benefits, and environmental value, resulting in low willingness to adopt the technology and insufficient motivation for application. At the same time, a large number of designers have incomplete understanding of current green building standards, energy-saving regulations, and renewable energy integration guidelines. During the design process, there are often details such as parameter misjudgment, improper system selection, and missing energy efficiency indicators, which not only affect construction quality but also lay hidden dangers such as excessive operating energy consumption and frequent system failures. Secondly, the design process of HVAC systems is fragmented and poorly coordinated, with various subsystems (such as heating, ventilation, smoke exhaust, and fresh air) often being designed separately, lacking overall energy efficiency optimization thinking.

Especially in the integration of renewable energy, although clean energy sources such as solar thermal/photovoltaic, ground source heat pumps, and air source heat pumps have mature technologies, they have not yet been widely applied in residential and small to medium-sized projects due to high initial investment, complex design, and lack of localized case support, resulting in an awkward situation of "technology reserves but gaps in implementation". The deeper problem lies in the lack of systematic thinking. Green HVAC design is a complex interdisciplinary and multi-objective collaborative project that requires coordination of climate adaptability, user behavior, equipment matching, intelligent control, and later operation and maintenance. However, current designs often prioritize equipment over systems, neglecting dynamic simulation of cooling and heating loads, energy cascade utilization, and waste heat recovery mechanisms, resulting in system redundancy, rigid regulation, and low energy efficiency. In addition, due to the disconnect between technological innovation and engineering practice, many independently developed technologies remain in the laboratory or demonstration project stage, lacking standardized and modular promotion paths, making it difficult to form economies of scale.

3. Optimization Design and Application Effect Analysis of HVAC

3.1 HVAC Optimization Design

The key to achieving year-round low-energy operation in ultra-low energy residential buildings in cold regions lies in the systematic design strategy of "passive priority, active optimization". Among them, efficient insulation enclosure structure is the foundation. Traditional mineral insulation materials such as rock wool and glass wool are widely used in exterior walls, roofs, and areas prone to thermal bridges due to their excellent thermal conductivity, fire resistance, and durability. They effectively block indoor and outdoor heat conduction paths and significantly reduce winter heat loss. The main energy consumption of buildings is concentrated in winter heating, summer cooling, and year-round domestic hot water supply. Based on the national "dual carbon" strategy and renewable energy promotion policies, this article selects a ground source heat pump system as the core cooling and heating source, and its principle is shown in Figure 1. This system utilizes the constant temperature characteristics of shallow underground soil to achieve efficient, stable, and low-noise energy conversion, saving 30% to 50% energy compared to traditional boiler+air conditioning systems. Passive solar energy design is an important means of energy conservation and efficiency improvement in cold regions.

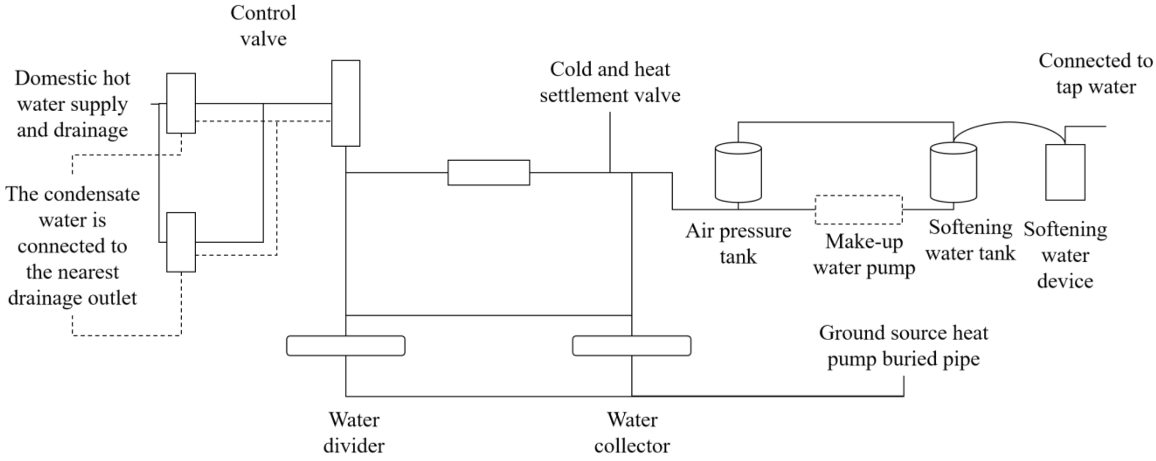

Figure 1 Principle of ground source heat pump system

This article adopts a direct benefit system, with high transparency and low radiation glass windows installed on the south facing facade, combined with indoor high heat capacity walls and floor materials, to achieve "daytime heat storage and nighttime heat release" under low angle sunlight in winter, effectively reducing heating load. At the same time, by combining sunshade components with nighttime insulation curtains, it avoids overheating in summer and achieves bidirectional adjustment between winter and summer. In terms of ventilation organization, the "functional zoning+pressure gradient" airflow strategy is adopted: the bedroom and living room serve as the core guarantee areas for air quality, and are directed by the fresh air system for air supply; The aisle and restaurant serve as transitional buffer zones to promote natural airflow diffusion; The kitchen and bathroom are designed as negative pressure return air zones, forming a closed-loop airflow through exhaust. Specially designed with an "overflow port" to ensure that the bedroom can maintain a slight positive pressure and air circulation even when the door is closed, avoiding dead corners and stagnant polluted air. In addition, the non thermal bridge design runs through the entire process of node construction. For typical thermal bridge areas such as window frames, wall junctions, and balcony connections, thermal insulation profiles, insulation extension structures, and airtight sealing measures are adopted to eliminate local high thermal conductivity paths, avoid condensation and energy leakage, and ensure that the overall thermal performance of the enclosure structure meets the standard.

3.2 Application Effect Analysis

To scientifically evaluate the operational efficiency of ultra-low energy residential buildings in real use environments, the project has constructed a high-precision, fully covered building energy consumption monitoring system within the community. This system can be used for lighting, sockets HVAC、 Measure the sub item electricity consumption of domestic hot water and other electrical equipment, and collect real-time data on the supply and return water temperature, flow rate, and cooling heat of the cold water side and cooling water side of the air conditioning system, comprehensively grasping the energy consumption characteristics of each subsystem. All measuring equipment is calibrated by authorities and has remote data transmission capabilities. It automatically uploads energy consumption data to the central monitoring platform at a set frequency, achieving visualization, traceability, and analysis of energy consumption data, meeting the technical requirements of national building energy efficiency supervision and carbon emission accounting.

Based on the meteorological data of the project location, the system has finely divided the operation strategy of HVAC equipment: the winter heating period is 152 days (November 1 to

March 31 of the following year), of which December 20 to February 3 (45 days) is in severe cold mode and operates at high load; During the initial and final stages of heating, a low load "warm strategy" is adopted for 15 days each, while the rest of the time is in a conventional mode to achieve on-demand energy supply. The summer cooling period lasts for a total of 92 days, with 20 days of peak load days using enhanced cooling strategies, and the remaining 72 days using economic operation modes. All strategies calculate power consumption based on actual usage periods to ensure that the evaluation data truly reflects user behavior and climate impacts. Table 1 provides a detailed list of the measured power of the main equipment under different operating modes, providing solid data support for subsequent energy efficiency benchmarking, system optimization, and energy-saving potential exploration. It also accumulates valuable empirical experience for the large-scale promotion of ultra-low energy consumption residential buildings in similar climate zones.

Table 1 Operating power/kW of related equipment

Equipment	Winter heating	Summer cooling
Unit 1	4.3	4.1
Unit 2	8.2	7.9
Winter circulating pump	0.51	1.9
Summer circulation pump	2.2	none
Underground circulating pump	2.1	2.2

4. Conclusions

With the continuous growth of China's economy and society and the continuous improvement of residents' quality of life, the public's attention to healthy living environment and ecological environment protection is increasing, promoting the construction industry to accelerate its transformation towards green, low-carbon, and sustainable direction. In this context, HVAC, as the core carrier of building energy consumption, must deeply integrate green and energy-saving technologies in its design to achieve multiple goals of energy efficiency improvement, carbon emission reduction, and comfort assurance. This article focuses on the integration of renewable energy HVAC systems under low-carbon guidance, constructing a multi-objective optimization model, and conducting in-depth research on key technical paths such as diversified configuration of cold and heat sources, efficient new air heat recovery, kitchen exhaust and overall ventilation coordination. At the same time, innovative exploration of the coupling mechanism between passive design and active HVAC systems is proposed, and a system integration scheme of "passive priority, active positioning, and intelligent collaboration" is proposed to achieve the organic unity of optimal energy efficiency, economic feasibility, and low-carbon operation while ensuring user comfort experience. The research results not only provide replicable technological paradigms for ultra-low energy residential buildings, but also contribute practical support for the implementation of China's "dual carbon" goals in the construction industry.

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