

Research on Energy-Saving Control and Sustainable Development Strategies for HVAC Systems Under Green Building Concepts

Peigeng Yang

Anhui Yooth Engineering Co., Ltd., Hefei, Anhui, 230000, China

Keywords: Green Building; HVAC System; Energy-Saving Control; Intelligent Management; Sustainable Development

Abstract: Driven by the dual carbon goals and green building concepts, controlling building energy consumption has become a crucial element in achieving sustainable development. Among building energy sources, HVAC systems represent a primary contributor, making their energy-saving control strategies particularly critical. This paper analyzes the energy-saving requirements imposed on HVAC systems by green building principles and explains the necessity of achieving energy conservation and environmental harmony throughout a building's entire lifecycle. It focuses on exploring energy-saving control technologies and strategies for HVAC systems, including intelligent control methods based on artificial intelligence and the Internet of Things, the integrated application of renewable energy and multi-energy systems, as well as operational optimization and management models that ensure indoor comfort. Combining policy support and regulatory standards, sustainable development pathways and future trends for HVAC systems are proposed. Research indicates that energy-saving control under green building principles not only significantly reduces building energy consumption and carbon emissions but also enhances energy utilization efficiency, providing robust support for the building industry's low-carbon transformation and sustainable development.

1. Introduction

Amid escalating global energy crises and environmental challenges, the building sector—a major contributor to energy consumption and carbon emissions—faces mounting pressure for energy conservation and emission reduction^[1]. Research indicates that buildings account for approximately 30–40% of global energy consumption, with HVAC systems alone representing over 40% of operational energy use. This makes HVAC systems a critical component in advancing green building development and low-carbon transformation^[2]. Under the dual-carbon strategy, achieving enhanced energy efficiency and environmentally friendly development in HVAC systems through scientifically sound energy-saving control measures has become a focal point for both academia and the engineering community.

The green building concept emphasizes balancing energy conservation, environmental protection, and healthy comfort throughout a building's entire lifecycle^[3]. Its core objectives extend beyond reducing energy consumption and environmental pollution to include improving occupant comfort and building operational efficiency^[4]. Guided by this philosophy, HVAC systems—as the core technology for building energy consumption and indoor environmental regulation—directly influence a building's overall green performance through their energy-saving control strategies^[5]. Emerging technologies like IoT, big data, and artificial intelligence offer new possibilities for dynamic energy monitoring, load forecasting, and intelligent control within HVAC systems. The integration of renewable energy and multi-energy systems further provides crucial support for the sustainable development of HVAC systems^[6].

Currently, energy-saving control in HVAC systems faces numerous challenges in practical application, including balancing energy optimization with indoor comfort, operational maintenance complexity, insufficient system integration, and lagging standards and policies. These issues partially constrain the deeper promotion and implementation of green building concepts. Therefore, it is

necessary to systematically study energy-saving control methods and sustainable development pathways for HVAC systems at both theoretical and practical levels.

Building upon an analysis of green building principles and HVAC energy-saving requirements, this paper focuses on exploring energy-saving strategies in areas such as intelligent control technologies, novel energy utilization, and optimized operational management. It proposes systematic sustainable development pathways by integrating policy and standards. The research aims to provide theoretical references and technical support for building energy conservation practices, thereby advancing the efficient application and long-term development of HVAC systems within green buildings.

2. Green Building Concepts and Energy Conservation Requirements for HVAC Systems

The concept of green buildings emerged from the dual pressures of global energy crises and environmental degradation^[7]. Its core principle involves achieving efficient resource utilization and harmonious ecological development through energy conservation and emission reduction across a building's entire lifecycle. Green buildings emphasize not only integrating energy-saving technologies during design and construction but also continuously optimizing energy consumption structures during operation and management^[8]. This ensures the unity of building functionality and environmental sustainability. In this process, HVAC systems—due to their high energy consumption share and prolonged operational duration—become a key focus for energy conservation control in green buildings. To quantify the relationship between capital structure and firm performance, the following equation is employed:

$$Q_{\text{total}} = Q_{\text{transmission}} + Q_{\text{infiltration}} + Q_{\text{internal}} + Q_{\text{solar}} \quad (1)$$

The dynamic interaction between financial risk and asset returns can be expressed as follows:

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

HVAC systems in modern buildings are responsible for maintaining indoor thermal-humidity conditions and air quality, serving as a vital safeguard for building comfort. This system also constitutes one of the primary components of a building's total energy consumption^[9]. Statistics indicate that HVAC energy consumption typically accounts for 40%–60% of a building's total operational energy use, far exceeding other systems like lighting and plumbing. Within the holistic planning of green buildings, reducing HVAC energy consumption and enhancing its efficiency represent critical entry points for achieving energy conservation goals^[10].

As green building concepts gain traction, the energy-saving requirements for HVAC systems exhibit multidimensional characteristics. On one hand, energy waste must be minimized through high-efficiency equipment and optimized system design. Intelligent control methods are also needed to dynamically adjust energy consumption in response to real-time changes in building loads. The integration of renewable energy sources and multi-energy systems has become another vital direction for meeting green building energy conservation requirements. These demands extend beyond mere energy savings targets, reflecting the comprehensive pursuit of health, comfort, and low-carbon living under the green building philosophy.

A fundamental tension exists between energy conservation and indoor comfort, as excessive energy savings may compromise occupant well-being. The diversification of building functions and complex operational environments further complicate energy control challenges. While smart technologies and renewable energy applications show promise, their widespread adoption remains limited, and supporting standards and regulations require refinement. Thoroughly analyzing HVAC energy requirements within the green building framework holds both theoretical significance and practical necessity for advancing industry technology and policy implementation.

3. Energy-Saving Control Technologies and Strategies for HVAC Systems

Guided by green building principles, energy-saving control for HVAC systems relies not only on high-efficiency equipment but also demands systematic, intelligent, and sustainable integrated strategies. Technologically, energy-saving control can be broadly categorized into three directions: First, leveraging cutting-edge technologies like artificial intelligence and the Internet of Things to achieve intelligent control and energy consumption optimization; second, enhancing overall system efficiency by integrating renewable energy sources such as solar power and ground-source heat pumps, while promoting multi-energy integration; Third, balancing energy savings with indoor comfort through comprehensive considerations of operational management and user experience. The following sections explore these three aspects in detail.

3.1 Intelligent Control Technologies and Energy Optimization

With rapid advancements in information technology, IoT, AI, and big data analytics are increasingly integrated into HVAC energy control, driving systems from traditional fixed operating modes toward intelligent, dynamic approaches. Compared to conventional methods relying on manual experience or fixed parameter settings, intelligent technologies enable real-time sensing and precise adjustment of building environments and equipment operating states, effectively preventing energy waste. The cost of capital optimization model is defined in the subsequent equation:

$$Q_{cool} = \dot{m} \cdot c_p \cdot (T_{in} - T_{supply}) \quad (3)$$

At the application level, intelligent control manifests primarily in three aspects: Real-time monitoring technologies based on sensors and IoT comprehensively collect indoor/outdoor environmental parameters, equipment operation data, and occupancy information, forming a big data foundation; AI algorithms optimize control strategies—such as equipment start/stop timing, airflow regulation, and cooling load distribution. through load demand prediction and modeling; Cloud-based centralized management enables large public buildings or complexes to achieve multi-system coordination and distributed collaborative management, thereby enhancing overall energy efficiency.

Intelligent control technologies deliver significant energy savings during building operation. For instance, implementing predictive control-based HVAC load management systems can reduce energy consumption by 10–20% while maintaining indoor comfort. AI-driven adaptive control methods further adjust operational strategies flexibly across varying climatic conditions and occupancy levels, maximizing both energy efficiency and comfort. These technologies have become the core enabler for HVAC system optimization in green buildings.

3.2 New Energy Sources and System Integration

Under the principles of green building, energy optimization of HVAC systems relies not only on intelligent controls but also on introducing clean, efficient new energy sources at the supply end. Utilizing renewable energy—such as solar power, ground-source heat pumps, and air-source heat pumps—can significantly reduce dependence on traditional fossil fuels while meeting cooling and heating demands. The advantages of these new energy sources lie in their cleanliness and sustainability, effectively reducing carbon emissions during building operations and providing crucial support for achieving the “dual carbon” goals. To evaluate the impact of leverage on profitability, the following mathematical expression is adopted:

$$COP = \frac{Q_{out}}{W_{in}} \quad (4)$$

In practical applications, a single energy form often struggles to meet the diverse demands of complex building environments. Therefore, multi-energy complementarity and system integration have become key development directions. Combining solar photovoltaic with solar thermal technology can provide electricity for buildings while also assisting in hot water and heating supply. while the combined use of ground-source and air-source heat pumps allows flexible mode switching

across different seasons and climatic conditions, maximizing energy utilization efficiency. The promotion of combined cooling, heating, and power (CCHP) systems in large public buildings also provides effective solutions for energy-efficient and stable operation of HVAC systems.

System integration of new energy sources not only enhances energy utilization efficiency but also drives the transformation of building energy structures. By establishing integrated energy management platforms to coordinate and optimize diverse energy systems, operational costs can be reduced and energy waste minimized throughout the entire lifecycle. Pilot green building projects demonstrate that multi-energy system integration can achieve overall energy efficiency improvements of 15%–30%. The integration of new energy sources and systems represents a critical pathway for HVAC system energy conservation and sustainable development, as well as a key future research and application direction in the building sector.

3.3 Balancing Energy-Efficient Operation Management with User Comfort

HVAC system operation directly impacts both building energy consumption and indoor environmental comfort. Implementing energy-saving controls often involves a fundamental trade-off: reducing energy use to meet green building goals while ensuring temperature, humidity, and air quality meet user requirements. Overemphasizing energy savings may degrade indoor environmental quality, adversely affecting occupant health and productivity. Thus, balancing energy efficiency and comfort is central to HVAC operational management. The risk-adjusted performance index is calculated using the formula below:

$$\min E_{\text{total}} = \sum_{t=1}^T (P_{\text{HVAC}}(t) \cdot \Delta t) \quad (5)$$

To achieve this equilibrium, operational management requires a layered and zoned control strategy. In high-occupancy office areas, ventilation rates can be appropriately increased to safeguard air quality. Conversely, in low-usage zones, demand-based adjustments or equipment shutdowns can minimize unnecessary energy consumption. Integrating dynamic load forecasting with real-time monitoring enables more flexible system operation, ensuring energy-saving measures do not significantly compromise indoor comfort. The following chart illustrates the simulated distribution of capital structure ratios across different industries, as shown in Figure 1:

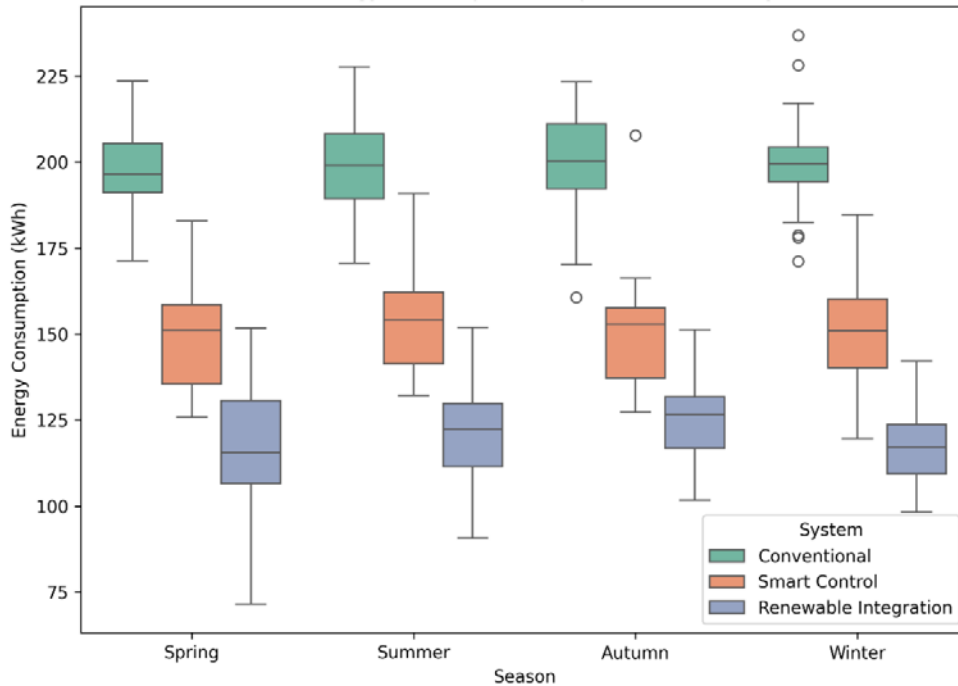


Figure 1 Seasonal Energy Consumption Comparison of HVAC Systems

From a building lifecycle perspective, operations management extends beyond daily operations to include regular system maintenance and performance optimization. Establishing an energy consumption monitoring platform for long-term tracking and analysis of operational data enables timely detection of efficiency declines and implementation of corresponding optimization measures. Regular cleaning of air filters, duct leakage inspections, and adjustments to cooling water system parameters can significantly reduce energy consumption without compromising comfort.

Energy-efficient operation management will increasingly rely on the integration of artificial intelligence and user feedback mechanisms. Machine learning-based adaptive control can automatically adjust operating strategies according to environmental conditions and usage patterns. Meanwhile, users can participate in energy consumption regulation via mobile terminals or smart panels, achieving “human-centered” comfort optimization. This human-machine collaborative operation management model will enable HVAC systems to achieve higher levels of energy savings while maintaining comfort.

4. Sustainable Development Pathways for HVAC Systems

Achieving sustainable development for HVAC systems first requires robust policy and standard support. In recent years, national and local governments have successively introduced a series of policies related to building energy efficiency and green buildings, setting clear requirements for HVAC system energy performance levels. For example, standards such as the Green Building Evaluation Standard and the Building Energy Efficiency Design Standard not only provide unified technical guidance for the industry but also lay the institutional foundation for implementing energy-saving measures. Through an evolving policy framework, the overall energy efficiency of the industry can be effectively enhanced, promoting the widespread adoption of energy-saving technologies. The government policy intervention mechanism can be represented by the following equation:

$$C = \sum_{i=1}^n (E_i \cdot \gamma_i) \quad (6)$$

From a full lifecycle perspective, the sustainable development of HVAC systems should encompass the entire process from design and construction to operation and end-of-life recycling. During the design phase, priority should be given to high-efficiency equipment and rational system configurations. In the construction phase, scientific and standardized installation and system commissioning must be ensured. During operation, intelligent management should be leveraged to achieve dynamic optimization of energy consumption. and during decommissioning, explore the recycling and reuse of equipment components. This holistic management approach not only reduces operational energy consumption but also minimizes resource waste, delivering dual environmental and economic benefits. The comparative analysis of risk-adjusted returns under various financial scenarios is presented in Figure 2:

Technological innovation serves as a vital driver for the sustainable development of HVAC systems. With the continuous advancement of cutting-edge technologies such as artificial intelligence, the Internet of Things, cloud computing, and big data, future HVAC systems will become increasingly intelligent and adaptive. AI-based load forecasting enhances control precision, blockchain-enabled energy trading mechanisms improve utilization efficiency, while advanced heat exchange materials and novel refrigerants hold promise for fundamentally reducing energy consumption and carbon emissions. These emerging technologies open vast possibilities for HVAC system sustainability.

Sustainable development also requires effective promotion models and market mechanisms. Beyond policy guidance and technological breakthroughs, the industry must establish robust incentive systems to drive energy-saving retrofits and large-scale adoption of green technologies. Measures such as Energy Performance Contracting (EPC), green finance, and carbon trading can encourage corporate participation in energy-saving projects. Public education on green awareness

should be strengthened to guide users toward choosing green buildings and high-efficiency HVAC products. Only by forming a virtuous cycle involving governments, enterprises, and users can the sustainable development goals for HVAC systems be truly achieved.

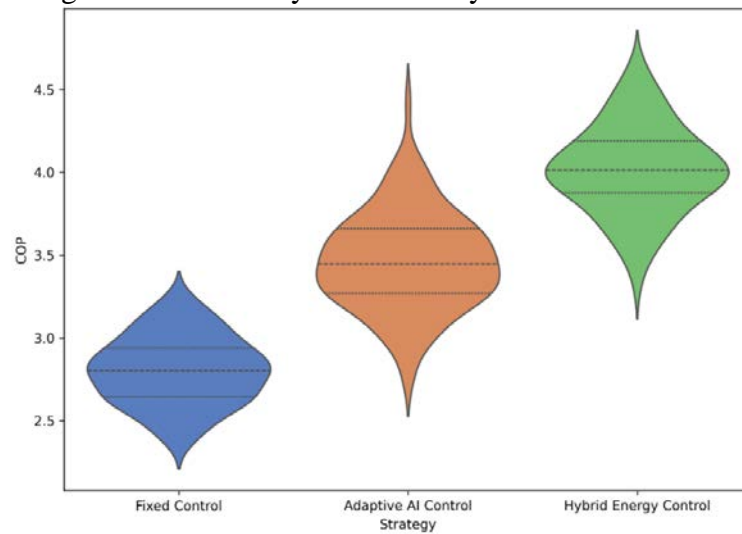


Figure 2 Coefficient of Performance (COP) Distribution Across Control Strategies

5. Conclusion

This paper explores energy-saving control and sustainable development pathways for HVAC systems under the concept of green buildings. Analysis of green building principles and HVAC energy-saving requirements reveals that HVAC systems play a decisive role in building energy consumption control, serving as a critical breakthrough for achieving building greening and decarbonization. Further exploration indicates that multidimensional strategies—including intelligent control technologies, novel energy sources and system integration, and energy-efficient operation management—can reduce energy consumption while maintaining indoor comfort, providing feasible solutions for energy optimization throughout a building's entire lifecycle.

Building upon this foundation and integrating policy support with technological innovation, this paper proposes a sustainable development pathway for HVAC systems. Findings indicate that only by combining energy-saving measures with full-lifecycle management, supplemented by trends toward intelligent, low-carbon, and integrated development, can holistic energy efficiency improvements and sustainable operation of HVAC systems be achieved. Concurrently, the introduction of green finance and market incentive mechanisms will further promote the adoption of energy-saving technologies, fostering a healthy development landscape for the industry.

Energy-saving control of HVAC systems under green building principles not only holds practical significance for reducing energy consumption and emissions but also charts a course for the construction industry's future low-carbon transition. Future research should continue to delve into adaptive optimization of intelligent algorithms, efficient integration of new energy sources, and synergistic policy-market interactions. This will foster the development of a more comprehensive energy-saving control system, enabling the efficient operation and sustainable development of HVAC systems.

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