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

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Abstract: Under the dual carbon goals and green building concept, controlling building energy consumption is one of the key means to achieve sustainable development. Among energy sources in buildings, the HVAC systems are a main contributor and their energy-saving control strategies are of special importance. This paper explores the constraints on HVAC systems brought about by green principles and describes the need for energy saving and eco-friendly harmony through out whole lifecycle of one building. It emphasizes the study of energy-saving control technologies and strategies, which cover intelligent control methods based on artificial intelligence and Internet of Things technology for HVAC systems, combined application methods for renewable energy and multi-energy systems, as well as operational optimization and management models that enable indoor comfort. Finally, sustainable development paths and the future trends of HVAC under both policy support and regulatory standards are proposed. Energy-saving control under green building principles lowers building energy consumption and carbon emissions substantially, while improving energy utilization efficiency, according to research, offering a strong foundation for low-carbon transformation and sustainable development for the building industry.

1. Introduction

Against the backdrop of a deteriorating global energy crisis and environmental catastrophe, the building sector is under increasing pressure to conserve energy and reduce emissions [1] due to its high share in overall energy consumption and carbon emissions. According to research, buildings contribute to an estimated 30 – 40% in global energy consumption, with HVAC systems representing over 40% of operational energy usage. As such, HVAC systems are a key factor in the development of green buildings and low-carbon transformation [2]. As improving energy efficiency and green development in HVAC systems through scientific energy-saving control methods has become a research hotspot phenomenon for both academia and engineering community under dual-carbon strategy.

Green construction is a holistic approach that balances energy efficiency, environmental conservation and healthy comfort throughout the entire lifecycle of a building [3]. Beyond lessening energy consumption and environmental pollution, its primary goals also encompass occupant comfort as well as building operating efficiency [4]. Driven by this philosophy, the HVAC system constitutes a key form of technology in relations to building energy consumption and indoor environmental regulation, impacting directly a given building overall green performance depending on its energy saving control strategies [5]. Emerging technologies such as IoT, Big-data and Artificial Intelligence provide new possibilities for dynamic energy monitoring, load forecasting and intelligent control in HVAC systems. In addition, the integration of renewable energy and multi-energy system also promotes the sustainable development of HVAC systems [6].

The application of current energy-saving control in HVAC systems has various challenges, such as balancing energy optimization and indoor comfort, operational maintenance complexity, lack of efficient system integration and lagging standards and policies. These problems also limit the further development and application of green building elements. Thus, the systematic study of energy-storage control methods and sustainable development paths for heating, ventilation, and air conditioning (HVAC) systems on theoretical and practical levels is an urgent task.

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Based on the analysis of research content for green building principles and specific HVAC energy-saving technical approaches, this paper takes energy-saving strategies in intelligent control technology, new energy utilization mode application and operation management optimization as the exploration focus. Advocates policy and standards integration for systematic sustainable development pathways. The significance of this work is to offer theoretical references and technical specifications for building energy saving exploration which can facilitate the efficient promotion and sustainable development of HVAC systems in green constructions.

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

The idea of green buildings had arisen due to the dual forces [7] of global energy crises and environmental deterioration. Its underlying rationale includes energy saving and emission reduction throughout the whole life cycle of a building to maximize resource efficiency and coordinated ecological progress. Green buildings focus on the integration of energy-saving technology in building design and construction to agree, but also in daily operation and management for energy consumption structure optimization [8]. So, building functionality must go hand in hand with environmental sustainability. As a result, HVAC systemsrepresent the largest portion of energy consumption and longest time workingcomponent, these make them an attractive target for energy savingscontrol in green buildings. To quantify the relationship between capital structure and firm performance, the following equation is employed:

$$Q_{total}=Q_{transmission}+Q_{infiltration}+Q_{internal}+Q_{solar} \tag{1}$$

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

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

HVAC systems are pivotal in modern civic buildings for maintaining indoor thermal-humidity conditions and air quality and ensuring the comfort of building occupants. The system also ranks as one of the major components of a building's overall energy usage [9]. HVAC energy consumption alone typically contributes to 40%–60% of a buildings total operational energy use, according to statistics—much greater than other systems such as lighting and plumbing. Within the framework of overall green buildings planning, reducing HVAC energy consumption and increasing efficiency are key links for achieving energy conservation targets among others [10].

As building concepts move towards greener approaches, the energy conservation demand of HVAC systems presents multidimensional features. On the one hand, high-efficiency equipment and an optimized system design are needed to decrease energy waste. Dynamic building load changes lead to the need for dynamic energy consumption adjustment processes based on intelligent control methods. Integrating renewable energy sources and multi-energy systems is another important direction for meeting green building energy conservation requirements. In energy saving goals, these demands go beyond just efficiency; they are the reflection of a holistic health, comfort and low-energy life under the green building concept.

There is always a basic tension between energy savings and comfort indoors since higher levels of saving can lead to discomfort for the occupants. Moreover, the variety of building functions and concomitant complex operational environments add to the challenge by supporting energy control complexities. Although smart technologies and renewable energy applications are ahead, based on the supporting standards and regulations, they need to be further refined. The theoretical importance and practical necessity of realizing HVAC energy demand analysis under the framework of the green building model are highly relevant for guiding the development of this industry and formulating a variety of technology policies.

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

Driven by green building principles, energy-saving control for HVAC systems is not only equipment efficiency oriented, but also requires systematic, intelligent and integrated sustainable strategies. Technically, energy-saving control can be divided into three major directions: First of all, artificial intelligence and the Internet of Things and other high-tech technology application to achieve intelligent control, and optimize energy consumption; Secondly, introducing renewable energy sources such as solar energy, ground-source heat pump in the system integration theory research optimization entire system efficiency (multi-energy Synergetic); Finally, considers operation management coordination user experience to balance saving energy target with indoor comfortable experience. The next sections detail these three in turn.

3.1 Intelligent Control Technologies and Energy Optimization

Advances in information technology 1IoT2, AI3, and big data analytics are becoming steadily embedded into HVAC energy control postures as the industry shifts from static operating states toward agile, intelligent systems. In contrast to traditional methods with excessive dependence on manual experience or fixed factors, intelligent technologies can perceive in real-time and accurately adjust the operating state of building environments and equipment to avoid additional energy waste. The cost of capital optimization model is defined in the subsequent equation:

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

At the application layer, intelligent control mainly includes three aspects:Real-time monitoring technologies based on sensors and IoT to comprehensively acquire indoor/outdoor environmental parameters (temperature and humidity), equipment operation data (energy consumption) and occupancy information; AI algorithms to optimize control strategies—such as equipment start/stop timing, airflow regulation, cooling load distribution. Utilizing tariff demand prediction and modeling to achieve centralized control under the cloud; cloud-based centralized management allows for multi-system coordination with distributed collaboration management in large public buildings or complexes, thereby improving overall energy efficiency.

Intelligent control technologies achieve remarkable energy savings in building operation. As per research, building predictive control-based HVAC load management systems can cut energy use by 10–20% without sacrificing indoor comfort. Such AI-driven adaptive control methods are adjusting operational strategies flexibly across climatic conditions and occupancy levels, so energy efficiency and comfort can be maximized. These technologies have emerged as the primary enabler towards optimization of HVAC systems in green buildings.

3.2 New Energy Sources and System Integration

Energy optimization of HVAC systems are not only intelligent control level improvements on the user end, but also introduction and switching to new sources of clean energy at the supply end based changes in line with the green building principles. Exploiting the benefits of renewable energy—through solar, ground-source or air-source heat pumps—can reduce reliance on conventional fossil fuels and provide cooling and heating needs. The new energy sources are clean and sustainable, reducing buildings' carbon footprint as they operate and providing a strong guarantee to achieve the "dual carbon" goals. To evaluate the impact of leverage on profitability, the following mathematical expression is adopted:

$$COP = \frac{Q_{out}}{W_{in}} \tag{4}$$

In practical applications, the inherent limitations of a single energy form cannot properly cater to diverse demands across complex building environments. Hence, complementary integration of multi energy has emerged as an important development direction. Using photovoltaic and solar thermal technology jointly offers electricity for buildings, as well as support for hot water generation and heating supply. While the utilization of geothermal and air-source heat pumps together enables a flexible switching between modes according to season and climatic condition, which maximally improves energy utilization efficiency. Enhanced promotion of combined cooling / heating and power (CCHP) systems is also possible in large public buildings, making consistent operating conditions for HVAC energy-efficient.

It can improve the energy utilization efficiency, and promote the transformation of building energy structure The integration is to integrate new sources of energy between devices. They can design cross-energy platforms that integrate different energy systems to align them and optimize them, which in turn helps lower operational costs and waste less energy throughout the lifecycle. The analysis results illustrated that integration of multi-energy system could create improvement on energy efficiency estimated by 15% – 30% based on two pilot green building projects. The introduction of new energy sources and new energy systems into the HVAC system is a key approach to achieving energy saving and sustainable development in the building industry, which has also become one of the major research and application directions in the field of buildings in the future.

3.3 Balancing Energy-Efficient Operation Management with User Comfort

The energy use of buildings and the indoor environmental comfort of occupants are directly affected by HVAC system operation. In addition to energy-efficient systems, real control over these systems is a tradeoff of the requires green target reducing the measure of population power consumption alongside with achieving cooling or heating loads to allow users in providing ambient conditions: temperature, humidity and fresh air for comfort conditions. Overemphasis on energy savings undermines habitability and indoor environmental quality, with adverse health and productivity impacts to people. Consequently, there is a need for energy efficiency balancing with comfort being the most important consideration of HVAC operational management. Formula for the risk-adjusted performance index:

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

This requires a layered and zoned control strategy on top of operational management for such balance to be maintained. Ventilation in a high occupancy office space can be increased to the point where air quality is maintained. Demand-based adjustments or shut down of equipment are used to low-energy consumption in areas with lower usage. The proposed method combines dynamic load forecasting with real-time monitoring to provide the flexibility of operating the system in energy saving mode while maintaining indoor comfort. Figure 1 displays the simulated distribution of capital structure ratios by industry:

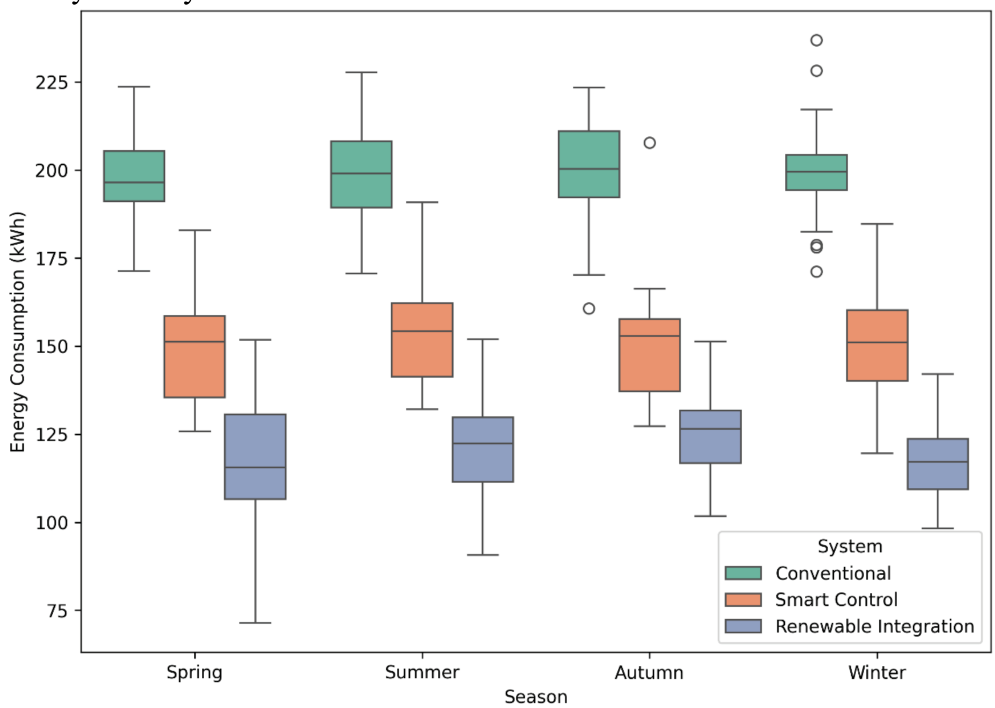

Figure 1 Seasonal Energy Consumption Comparison of HVAC Systems

When observing the operations management in a building lifecycle, It includes routine maintenance to enhance systems performance during its time. This can then be installed into a Building Energy

Management System (BEMS) for longer-term monitoring of energy consumption, enabling operational data to be captured over time so that any efficiency declines can be detected early and the necessary actions taken to optimise accordingly. Moreover, clean air filters on time can significantly lower the energy consumption without impacting comfort by adjusting duct leakage test & cooling water system parameters.

Expect energy-efficient operation management to be powered even more by the combined use of artificial intelligence with mechanisms for user feedback. Adaptive control using machine learning can best adapt operating strategies to environmental and usage patterns. At the same time, users can also participate in energy consumption regulation through mobile terminals or smart panels to achieve “human-centered” comfort optimization. This human-machine collaborative operation management model will allow the HVAC systems to reach more energy-saving effects under the premise of ensuring comfort.

4. Sustainable Development Pathways for HVAC Systems

The path towards sustainable development for HVAC systems starts with comprehensive supportive policies and standards. The series of policies related to building energy efficiency and green buildings have been introduced successively by national and local national governments in recent years, which clearly defines the requirements for the energy performance level of HVAC systems. Standards like Green Building Evaluation Standard and Building Energy Efficiency Design Standard not only provide a unified technical guidance to the industry but also serve as an institutional foundation for energy saving implementation. This can be achieved via an adaptive policy structure that improves not just the energy efficiency of individual firms but also encourages a collective implementation oftheenergy-savingtechnology. The government policy intervention mechanism can be represented by the following equation:

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

Based on this lifecycle approach, the sustainable HVAC system development focus includes design, construction, operation and end-of-life recycling processes. High-efficiency equipment and rational system configurations should be taken as priorities during design. In the construction stage, it is necessary to ensure scientific and standardized installation and system commissioning. Once in operation, intelligent management should be employed to optimize energy consumption dynamically. and during the demobilization phase, consider the recycling and reuse of equipment. To capitalize on the dual environmental and economic benefits, this holistic management approach not only reduces the typical energy consumption at every stage of operation but also limits resources being wasted. The comparative analysis of risk-adjusted returns under various financial scenarios is presented in Figure 2:

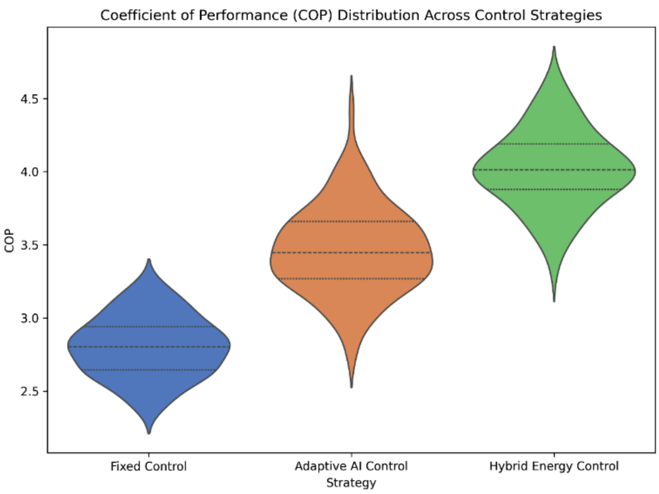

Figure 2 Coefficient of Performance (COP) Distribution Across Control Strategies

Technology innovation is an important approach to ensure the sustainable development of HVAC systems. As technologies like artificial intelligence, the Internet of Things, cloud computing and big data continue to evolve, future HVAC systems will be more intelligent and adaptive than ever. AI-based load forecasting improves the accuracy of real-time energy control; blockchain-driven energy trading systems and their use facilitate the good use of power; new heat exchange materials and refrigerants show prospects for breaking through low carbonization. Emerging technologies open new opportunity for HVAC system sustainability.

Effective promotion models and existing market mechanisms are also essential for sustainable development. Government policy guidance and technological breakthroughs can only go so far without robust incentive systems that drive energy-saving retrofits and transformative green technologies at scale. Promoting corporate participation in energy-saving projects through measures like Energy Performance Contracting (EPC), green finance, and carbon trading services. It is necessary to strengthen the public education on green awareness leading users to choose green preferential parts and high-efficiency HVAC products. Only by establishing a virtuous circle including governments, enterprises and users can we realize the sustainable development goals of HVAC systems.

5. Conclusion

This research addresses the energy-saving control method and sustainable development path of HVAC systems as part of green buildings. Given the function of HVAC systems in buildings and their energy-saving needs based on green building principles, we determined that HVAC systems play a key role in delivering controlled building energy consumption as a breakthrough for achieving actual greening and decarbonization of buildings. Moreover, investigating multidimensional approaches shows that smart control technology, new energy and system coupling systems, as well as an energy-efficient operations manager can lead to decreases in energy consumption while enabling indoor comfort, offering practical solutions for buildings' full lifecycle green-upgrading.

Drawing on this overview of policy and LE technologies, in this paper we explore an HVAC systems roadmap towards sustainable development. It is only through the combination of energy-saving measures and full-lifecycle management, supported by trends towards intelligentness, low-carbonity and integrated development, that overall improvement in energy efficiency and sustainable operations of HVAC systems can be realized. With the exploration of green finance and market incentive mechanism, energy-saving technology popularity will be further promoted, forming favorable industrial ecosystem.

Specifically, the angle of achieving energy efficiency leads to readily applicable practices based on low-energy building essentials, such as energy-saving control of HVAC systems under the green building paradigm, an approach that is crucial in defining viability for construction industry transitioning towards a future with lower carbon emissions. Follow-up studies could investigate the adaptive evolution of intelligent algorithms, efficient integration of new energy sources, and synergistic interactions between policy and market elements. This will promote the construction of a more systematic energy-saving control model which is beneficial for the effective operation and sustainable development of HVAC systems.

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