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Exploring the Application of Intelligent Energy-Saving Systems in Smart Buildings

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Abstract. The building sector has long suffered from energy waste due to excessive cooling and inefficient lighting, which seriously impedes the realization of carbon neutrality goals. According to the United Nations Environment Programme, building operations account for 36% of global end-use energy consumption and emit up to 10 billion tons of CO_2 annually—three times the combined emissions of global aviation and shipping. In commercial buildings, 35% of air conditioning energy use stems from overcooling, while 22% of lighting energy is consumed in unoccupied areas. Against this backdrop, this study explores the application of intelligent energy-saving systems in smart buildings. It proposes an integrated system architecture based on the Internet of Things (IoT) and Artificial Intelligence(AI), and outlines its applications in ventilation, lighting, and photovoltaic systems. Research shows that establishing a three-tier "perception–prediction–control" framework in ventilation systems, supported by real-time sensor monitoring and AI optimization, can significantly enhance energy efficiency. Lighting systems employing millimeter-wave radar and adaptive dimming technologies effectively reduce false detections and energy waste. Photovoltaic systems integrated with building designs and coordinated with energy storage models can improve energy self-sufficiency. The multidimensional technical synergy of IoT platforms, AI optimization, and user participation further validates the system's effectiveness in reducing energy consumption and supporting carbon neutrality, providing a feasible path for energy savings in smart buildings.

Keywords: Smart buildings, energy efficiency, IoT, AI optimization, photovoltaic integration.

1. Introduction

Currently, building operations account for 36% of global end-use energy consumption and emit up to 10 billion tons of CO_2 annually—three times the emissions from the aviation and shipping industries combined. This extensive energy waste caused by crude management practices contradicts global carbon neutrality goals. The International Energy Agency (IEA) pointed out in its 2023 Global Buildings Decarbonization Roadmap that if building-related carbon emissions are not cut by 75% by 2050, the Paris Agreement temperature targets will be unattainable.

Traditional buildings heavily rely on manual management, leading to energy waste problems such as excessive air conditioning and lighting inefficiencies. Addressing these issues is crucial under

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carbon neutrality objectives, making building energy efficiency a global policy focus. Intelligent energy-saving systems powered by Internet of Things (IoT) and Artificial Intelligence(AI) can reduce energy consumption by 20%-70% compared to conventional systems. For example, Burj Khalifa in Dubai reduced air conditioning energy usage by 28% in 2022 through smart systems while maintaining an indoor temperature of 24°C [1]. Similarly, the Tencent Binhai Building in Shenzhen reduced false lighting shutdown complaints from 15 times per month to zero after introducing millimeter-wave radar-based lighting control. Therefore, the implementation of intelligent energy-saving systems in construction is urgent and necessary.

According to the 2023 China Building and Urban Infrastructure Carbon Emission Report, China's total building-related carbon emissions reached 4.07 billion tCO_2 in 2021, accounting for 38.2% of national emissions [2]. In Beijing, urban residential buildings exceeded 930 million m^2, with building energy consumption accounting for 53% of total social energy use and 54% of total emissions in 2019, indicating immense potential for energy-saving [3-4].

This study aims to construct an IoT and AI-based intelligent energy-saving system framework and empirically evaluate its feasibility in addressing excessive cooling, lighting waste, and unsustainable energy supply in buildings [5-6]. The paper first explores AI-optimized ventilation control via sensors, then analyzes lighting systems enhanced by millimeter-wave radar and adaptive dimming, followed by building-integrated photovoltaic systems with energy storage coordination. Finally, the study verifies comprehensive energy-saving performance through multi-dimensional technology collaboration.

2. Application of intelligent energy-saving systems

Traditional building systems operate on static control logic, leading to structural inefficiencies such as overcooling and ineffective lighting. Intelligent systems, however, enable dynamic sensing, regulation, and closed-loop energy cycles, transforming buildings from energy consumers into efficient producers, thus laying the foundation for carbon neutrality.

2.1. Intelligent ventilation systems

The core of this technology lies in utilizing sensors—specifically CO_2 concentration sensors and temperature-humidity sensors—to monitor indoor air quality in real time. Based on this data, the system dynamically controls parameters such as fresh air volume, airflow speed, and power, aiming to improve energy efficiency, enhance occupant comfort, and reduce ventilation system failure rates. Additionally, AI algorithms can be introduced to predict user demand and adjust operational strategies by analyzing historical data and real-time feedback.

Traditional ventilation systems often operate at fixed power, leading to excessive cooling and energy waste. This study proposes a three-tier intelligent framework of "Perception–Prediction–Control":

(1) Perception Layer

High-precision CO_2 sensors (e.g., Telaire T3000, accuracy ±50 ppm) and temperature-humidity sensors (e.g., Sensirion SHT35, accuracy ±1.5% RH) are deployed to collect real-time indoor air quality data, with a sampling frequency of 0.1 Hz.

(2) Decision Layer

An LSTM (Long Short-Term Memory) neural network is used to build a demand prediction model. It takes historical occupancy, meteorological data, and real-time sensor inputs to generate optimal control parameters for fresh air volume.

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(3) Execution Layer

Variable frequency fans and air dampers are linked to dynamically adjust the air supply volume (range: 0.5–5 m^3/s), ensuring CO_2 concentration remains below 800 ppm and temperature fluctuation stays within ±0.5°C.

(4) Empirical Results

In a pilot project at the office area of Shanghai Tower, this system reduced ventilation energy consumption from 12.7 kWh/m^2·year under the traditional model to 7.3 kWh/m^2·year—a 42.5% reduction. The failure rate dropped by 60% due to the AI-powered fault prediction mechanism, and user satisfaction increased by 32%, attributed to the PMV (Predicted Mean Vote) thermal comfort index being consistently maintained within the range of -0.5 to +0.5 [5].

2.2. Intelligent lighting systems

This approach uses infrared sensors to detect human presence, enabling lights to turn off when unoccupied. Adaptive dimming adjusts brightness based on time and ambient light. Despite higher upfront costs, LED lifespan extends over three times that of traditional lights, reducing waste from frequent replacements [7].

The system employs a “space-time-light” coordinated control: 60GHz millimeter-wave radar (e.g., Infineon BGT60LTR11AIP) detects static presence (e.g., breathing), with >99% accuracy across 15m × 15m areas. An astronomical clock algorithm predicts daily lighting needs based on building coordinates. Illuminance sensors (e.g., ams TSL2591) measure light (0–100klx) and adjust LED output (e.g., Philips Hue) via PWM drivers to maintain 500±50lx (ISO 8995). Tencent Binhai Building cut lighting energy from 862,000 kWh to 417,000 kWh per year (51.6% reduction), and complaints of premature light shutdowns dropped to zero, despite being 2.3× more expensive, smart lights last 52,000 hours vs. 18,000 hours for conventional bulbs, with a payback period of just 2.7 years [3].

2.3. Photovoltaic systems in smart buildings

Building-integrated photovoltaics (BIPV) embed solar panels into façades and roofs, paired with lithium or hydrogen energy storage for day-night power balancing. This setup reduces CO_2 emissions and enhances sustainability.

The proposed “BIPV + Multi-Modal Storage” architecture includes: Cadmium telluride thin-film PV (e.g., First Solar Series 6) with 19.3% efficiency, replacing traditional building materials and reducing installation costs by 35%. Lithium-ion batteries store electricity during off-peak hours (0.3 RMB/kWh) and release it during peak hours (1.2 RMB/kWh). Seasonal adjustments involve hydrogen production using PEM electrolyzers (e.g., Siemens Silyzer 200), storing excess energy as green hydrogen (75% efficiency) .

Model predictive control (MPC) uses electricity pricing, weather, and load forecasts to optimize storage usage. At Beijing Daxing Airport's Eastern Aviation Base, the system generated 2.4 GWh annually, covering 43% of building energy use and reducing CO_2 by 1,860 tons/year. Hydrogen storage supplied 1.2 GWh of winter heating, replacing 180,000 m^3 of natural gas [4].

3. Case study: Tencent Binhai building

The upgrades addressed lighting issues such as always-on public areas, which caused 22% energy waste, and frequent false shutoffs due to unreliable infrared sensors that resulted in 15 monthly

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complaints.

Solutions implemented included Millimeter-Wave Radar, which uses 60GHz technology (with a 5mm wavelength) to detect static presence through micro-movements like breathing, achieving a 99% accuracy rate. Additionally, adaptive dimming was introduced, where lights turn off 10 seconds after vacancy is detected and adjust their brightness based on ambient light levels (ranging from 0 to 100 klx) to maintain a consistent 500 lux.

The outcomes of these measures were significant. Complaints dropped to zero for 18 consecutive months, and lighting energy use decreased by 51.6%, resulting in an annual saving of 445,000 kWh. The lighting systems now last approximately 52,000 hours due to smoother dimming transitions. Moreover, user experience improved with seamless brightness changes and glare reduction under natural lighting conditions, achieving what can be described as “invisible” energy savings.

4. Multidimensional technological synergy in smart buildings

Smart building synergy refers to the integration and coordination of multiple technologies in design, construction, and operation to achieve intelligent, efficient, and sustainable management. Key aspects include sensor monitoring, which detects anomalies and initiates maintenance, thereby reducing downtime and energy waste. IoT automation automatically controls systems such as lighting based on occupancy and ambient conditions. AI prediction analyzes energy usage trends and forecasts peak demand, enabling cost-effective load balancing. Additionally, user feedback gathered through surveys and interviews guides energy distribution, minimizing waste and optimizing the use of stored power [8].

5. Conclusion

This study investigated the application of IoT and AI-based intelligent energy-saving systems in smart buildings through case studies and technical analysis. Ventilation systems using the “perception–prediction–control” model reduced energy use by 42.5%. Lighting systems utilizing millimeter-wave radar and adaptive dimming cut energy use by 51.6%. BIPV systems with energy storage met 43% of building demand and reduced carbon emissions significantly.Integrated IoT platforms, AI optimization, and user participation further validated the system's ability to reduce energy use by 20%-70%.

Future Work: Further research can explore customized solutions for different building types (residential, commercial) and long-term operation and maintenance strategies. This study provides a practical roadmap for smart building energy efficiency and supports carbon reduction in the built environment.

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