Intelligent Building Management: Leveraging AI and VAV for Sustainable HVAC Performance

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ABSTRACT

This review explores the integration of Artificial Intelligence (AI) driven Variable Air Volume (VAV) systems and Building Management Systems (BMS) to enhance thermal comfort and energy efficiency in commercial buildings. With HVAC systems accounting for up to 70 percent of energy use in Malaysian commercial sectors, improving their performance is both an economic and environmental imperative. The paper evaluates how intelligent BMS architectures comprising field devices, automation controls, and centralized management layers enable real-time data driven optimization of indoor climate. Special emphasis is placed on the role of VAV systems in enabling zone-specific climate regulation and reducing energy waste. National initiatives such as MS 1525:2019, the Energy Efficiency and Conservation Act 2024, and the National Energy Transition Roadmap (NETR) are examined to contextualize Malaysia's policy framework for sustainable building practices. Despite technical and financial barriers such as outdated infrastructure, high retrofitting costs, and control complexity, the convergence of IoT technologies and AI based predictive control shows strong potential to overcome these limitations. This review highlights critical pathways for future research and industry adoption toward more resilient, efficient, and occupant centric building environments.

Keywords: Building Management System (BMS), Variable Air Volume (VAV) Systems, Thermal Comfort, Energy Efficiency.

INTRODUCTION

Thermal comfort is important because it affects people's comfort, health, and productivity in buildings. HVAC systems help control temperature and air quality, but they use a lot of energy, especially in Malaysia. To reduce energy use, technologies like BMS, IoT, and AI are used for better control and monitoring. The Thermal Comfort and HVAC Energy section explain comfort and energy use. The Building Management System (BMS) and Integration of Variable Air Volume (VAV) Systems sections explain how systems improve efficiency and comfort.

The objective of this paper is to explain how AI-driven Building Management Systems (BMS) and Variable Air Volume (VAV) systems can improve thermal comfort while reducing energy consumption in HVAC systems.

Thermal Comfort and HVAC Energy

Thermal comfort is a fundamental aspect of indoor environmental quality and is increasingly recognized as a critical parameter in sustainable building design. Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" [5]. Achieving this state involves maintaining an optimal balance of air temperature, humidity, air velocity, and radiant heat. These elements must be addressed holistically throughout the building lifecycle, from design and construction to daily operations. Complementary guidelines recommend maintaining indoor air temperatures between 68 to 76 degrees Fahrenheit and humidity levels within 20% to 60% to support both comfort and indoor air quality [27].

The significance of thermal comfort extends beyond occupant satisfaction. It directly affects health, mental focus, and work performance. Previous studies have indicated that productivity tends to peak at around 22 degrees Celsius, with measurable declines occurring as temperatures rise above 24 degrees Celsius [3]. Suboptimal thermal conditions, either excessively warm or cool are associated with reduced cognitive function, discomfort, and physiological stress. Thermal comfort contributes not only to immediate well-being but also to longer-term outcomes such as morale, absenteeism rates, and energy-related behavior [19].

To meet thermal comfort needs, buildings primarily rely on HVAC systems. These systems regulate indoor temperature, humidity, and air quality to maintain stable environmental conditions. With the integration of IoT-enabled sensors and adaptive control algorithms, modern HVAC systems now offer more precise and efficient regulation based on real-time environmental data [17]. This advancement has positioned HVAC systems as a key focus area in the pursuit of energy efficiency and sustainability.

A case study evaluating the effectiveness of intelligent control approaches in building energy performance, focusing on a single thermal zone building, demonstrated that HVAC systems maintained comfortable temperature levels approximately 99% and 97% of the time while achieving energy savings of up to 9% [2]. In response to these figures, advanced control strategies such as Model Predictive Control (MPC) integrated with Genetic Algorithms (GA) have been developed to improve operational efficiency while maintaining thermal comfort, with some studies reporting energy savings of up to 9% IoT-based HVAC platforms further enable buildings to self-adjust environmental parameters dynamically, supporting both comfort optimization and energy conservation [12].

Figure 1. Electricity consumption in Peninsular Malaysia

	Q1 2021	Q2 2021	Q3 2021	Q4 2021	Q1 2022	Q2 2022	Q3 2022	Q4 2022
● Perindustrian *Industrial*	11,163.27	11,717.43	9,543.87	11,542.40	11,268.31	11,362.93	11,732.39	11,245.58
● Perdagangan *Commercial*	8,397.08	9,102.01	7,515.24	9,045.37	9,398.60	9,985.01	9,858.59	10,050.05
● Domestik *Domestic*	7,422.92	8,051.83	8,240.45	7,770.21	7,699.43	8,216.41	8,077.46	7,507.92
● Lampu Awam *Public Lighting*	376.66	372.48	371.38	378.71	384.71	377.27	442.40	391.25
● Pertanian *Agriculture*	164.51	171.31	178.07	168.99	162.06	168.40	169.64	168.47
● Perlombongan *Mining*	35.92	43.86	35.92	48.11	46.21	49.64	67.00	51.90

The need for efficient HVAC systems is especially relevant in Malaysia, where climate conditions and increasing urban development intensify cooling demands. Figure 1 shows the data from Peninsular Malaysia indicate a steady rise in electricity consumption across the commercial sector, from 7,515.24 gigawatt-hours in Q3 2021 to 10,050.05 gigawatt-hours in Q4 2022 [33]. HVAC systems remain a significant contributor to this trend, accounting for 50% to 70% of total energy use in commercial and industrial buildings.

In response, the Malaysian government has introduced a range of policies and frameworks aimed at promoting energy-efficient building operations. These include MS 1525:2019, a standard emphasizing efficient air-conditioning system design [8], the Energy Efficiency and Conservation Act 2024 (EECA 2024), which provides a regulatory structure for energy reduction [21] and the National Energy Transition Roadmap (NETR 2050), a strategic vision for decarbonization and sustainability [19]. AI-driven BMS and VAV systems directly support NETR 2050 goals by optimizing building energy use and reducing carbon emissions. AI-enabled control predicts demand, coordinates HVAC operation, and enables load shifting, while VAV systems provide zone-level airflow and temperature adjustments to minimize energy waste. Together, they enhance occupant comfort, improve operational efficiency, and contribute to Malaysia's decarbonization and sustainable building objectives.

An analysis of electricity consumption by sector between Q1 2021 and Q4 2022 shows that the industrial, commercial, and residential sectors consistently accounted for the highest usage. The industrial sector led overall demand, peaking at approximately 11,700 gigawatt-hours in Q2 2021 and Q3 2022. The commercial sector followed a steady upward trajectory, while the residential sector showed periodic fluctuations. These three sectors collectively consumed significantly more energy than others such as agriculture, mining, and public lighting underscoring the importance of targeting HVAC optimization in building-based energy interventions.

Figure 2. Quarterly Electric Consumption by Sector (Q1 2021 – Q4 2022)]

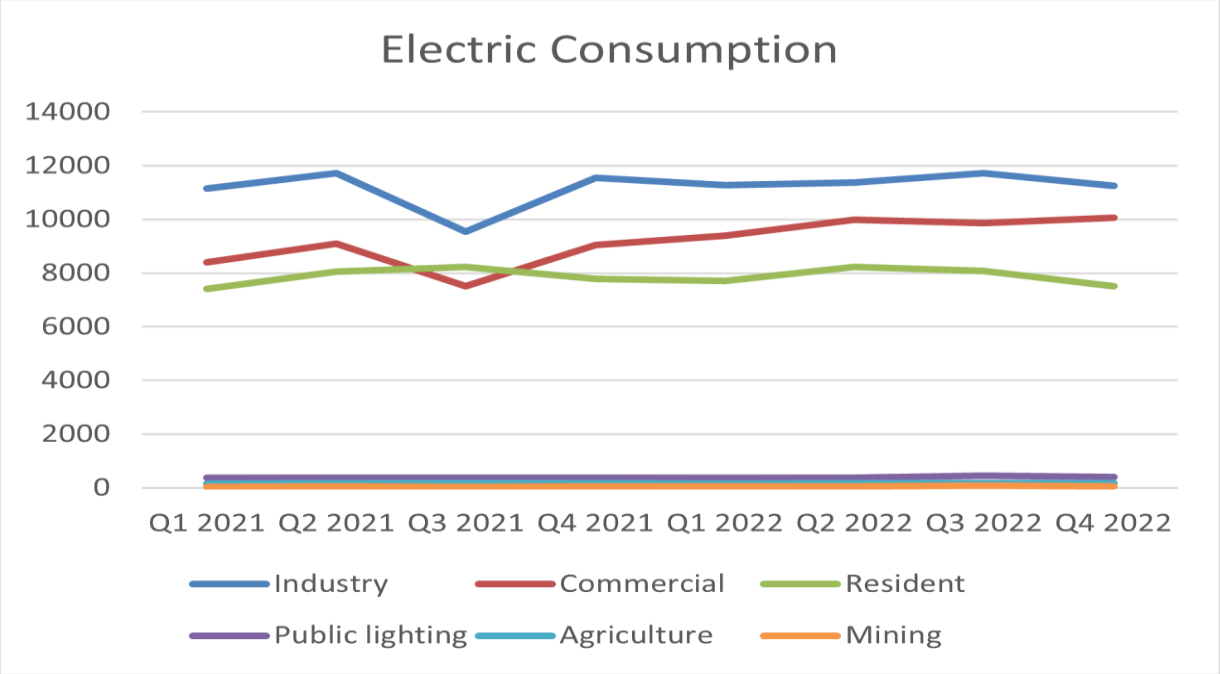


Figure 2 illustrates the electricity consumption trends across various sectors from Q1 2021 to Q4 2022. Among all sectors, Industry, Commercial, and Residential consistently recorded the highest electricity usage. The industrial sector maintained the largest share throughout the period, with consumption peaking in Q2 2021 and Q3 2022 at around 11,700 GWh. The commercial industry followed closely, showing a steady upward trend overall, despite a noticeable dip in Q3 2021. The residential sector exhibited more moderate fluctuations, with a peak in Q3 2021 and Q2 2022, before declining towards Q4 2022. These three sectors dominate overall electric consumption, significantly surpassing other categories such as public lighting, agriculture, and mining.

In this study, the term AI-driven refers to the application of artificial intelligence techniques such as predictive modeling, anomaly detection, and adaptive control to enhance the decision-making capability of HVAC systems. By continuously learning from real-time sensor data, AI-driven control can anticipate temperature fluctuations, detect abnormal equipment behavior, and optimize airflow distribution more efficiently than conventional rule-based systems. This approach enables VAV systems to respond dynamically to changing occupancy and environmental conditions, minimizing energy waste while maintaining occupant comfort. Introducing AI within the Building Management System (BMS) therefore represents a significant advancement toward fully intelligent and self-optimizing building environments.

Building Management System (BMS)

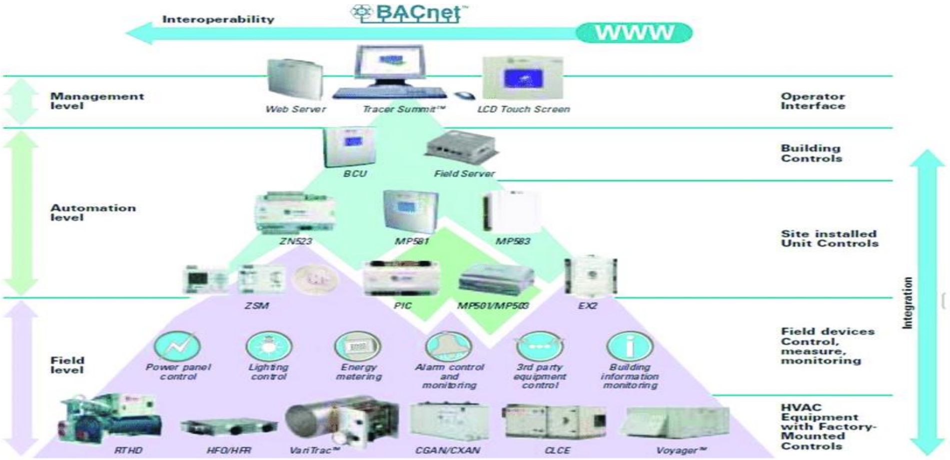
The research highlights the significant impact that buildings have on Malaysia's overall energy consumption, with a large proportion of energy demand stemming from the operation of HVAC systems [13]. This has led to growing interest in technologies that can optimize energy usage in the built environment. Similarly, another research emphasizes the urgent need for more user-friendly and intelligent tools to effectively manage the operation of commercial HVAC systems, which are often complex and prone to inefficiencies when operated manually or through outdated systems [6]. Traditional HVAC control systems typically rely on fixed schedules or manual adjustments, lacking the capability to adapt to dynamic factors such as real-time occupancy, weather conditions, or predictive maintenance needs. This often results in energy wastage and inconsistent indoor comfort.

One promising solution to address these challenges is the BMS, a comprehensive and centralized platform designed to monitor, control, and optimize multiple building services. These services typically include HVAC, lighting, security, fire safety, and other critical operational systems. Outdated systems, such as manually controlled or schedule-based HVAC operations, single-zone constant air volume (CAV) systems, and stand-alone controllers, are limited in their ability to adapt to real-time occupancy and environmental changes. Modern BMS directly addresses these shortcomings by enabling centralized monitoring, adaptive control, and system-wide optimization. BMS achieves this by integrating data from various sensors and control devices installed throughout the building, enabling real-time monitoring and automated adjustments to ensure optimal performance. By doing so, BMS not only contributes to substantial energy savings but also improves occupant comfort by maintaining stable indoor conditions. Moreover, this system facilitates preventive maintenance, reduces operational costs, and supports long-term sustainability goals. Given these capabilities, BMS is increasingly being adopted in modern buildings as part of a broader strategy to enhance building intelligence and environmental performance.

BMS Fundamental

In general, the BMS statement encompasses all control components, including hardware, controllers, link networks, and central controllers. The control system is made up of three core components: sensors, controllers, and controlled instruments. The arrangement of these components within a comprehensive BMS is determined during the system design process, [22]. BMS integrates several key components to optimize the performance and efficiency of building systems. These components include the field level, the automation level and the management level [29]. Figure 3 illustrates the three-layered architecture of BMS (Field levels, Automation level and Management level), showcasing interoperability, operator interface, control devices, and integration of HVAC components for real-time monitoring and optimization [14].

Figure 3. The Hierarchical Structure and Functional Levels of a Building Management System (BMS)



The history of BMS began before the 1970s, when buildings were controlled manually or through pneumatic systems that used compressed air to regulate HVAC functions [26]. These early systems were limited in precision and required local operation. In the 1970s and 1980s, the first electronic BMS emerged, introducing centralized control over building systems like HVAC, lighting, and security through analog electronics. This era laid the foundation for more intelligent automation. In the 1980s and 1990s, Direct Digital Control (DDC) became the standard, using microprocessors to allow programmable, more precise control.

Early HVAC and BMS faced many challenges due to limited technology. Pneumatic systems lacked precision because they relied on air pressure, which was easily affected by leaks and environmental changes, resulting in inconsistent temperature control. These systems also required manual or local operation, as centralized control and automation were very limited. Early electronic and DDC systems faced issues such as signal degradation, complex wiring, limited computing power, and poor interoperability between devices. As a result, these early systems were inefficient, required high maintenance, and were costly to operate.

Additionally, this represents a significant improvement over earlier HVAC systems, which were limited by manual control and poor interoperability. By incorporating protocols such as the Building Automation and Control Network (BACnet), modern HVAC systems can communicate across different building systems, enabling more efficient, centralized, and intelligent management [30]. In addition to BACnet, other communication protocols such as Modbus and LonWorks have also supported integration across different building systems, further advancing the development of intelligent and centralized building management systems [24], [4].

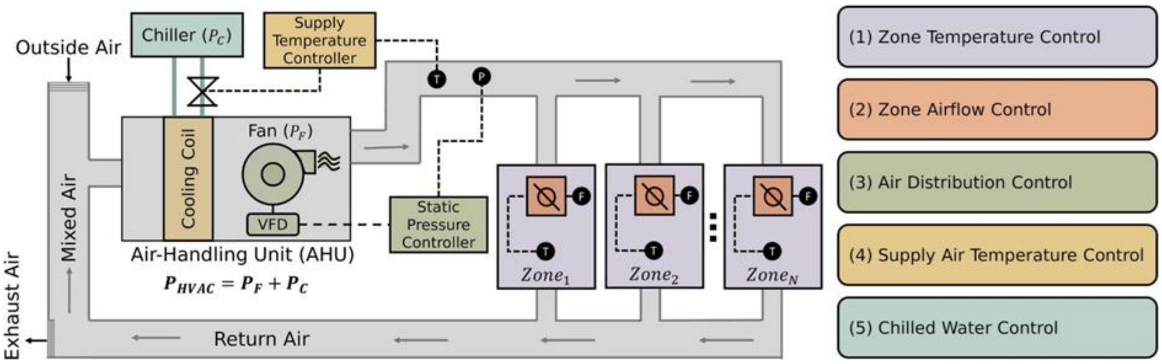
During the 2010s, the integration of the IoT and big data analytics began transforming HVAC systems within BMS. The study state that sensor-driven data collection enabled real-time energy optimization and smarter control strategies, laying the foundation for AI adoption in building energy management [1]. Moving into the 2020s, artificial intelligence and machine learning became central to BMS development and demonstrated how hybrid approaches that combine rule-based systems with machine learning models significantly improve predictive maintenance and fault detection capabilities in building systems. Complementing this, a systematic review published in buildings explored various AI techniques, including supervised learning, anomaly detection, and optimization for energy management in HVAC [23], highlighting their growing role in enabling intelligent, adaptive, and energy-efficient building operations.

In addition to technical and operational challenges, several other considerations influence the successful deployment of intelligent building systems. Financial feasibility remains a significant barrier, as the initial costs of BMS, IoT sensors, and AI integration can be substantial, especially for retrofitting older buildings. Scalability also poses challenges, as solutions that work efficiently in small or medium-sized buildings may require significant adjustments to be effective in larger commercial or industrial complexes. Furthermore, the growing reliance on cloud connectivity and networked devices raises cybersecurity concerns; smart building systems are vulnerable to data breaches, unauthorized access, and potential manipulation of control systems. Addressing these financial, scalability, and cybersecurity issues is crucial to ensuring the long-term adoption and resilience of intelligent building management technologies. When VAV terminals aren’t properly coordinated, buildings may suffer from discomfort and inefficiency. The research found that poor control of multi-zone VAV systems impacts ventilation and comfort, while noting that many outdated BMS platforms can’t optimize VAV performance, limiting energy savings and fault detection [31].

Integration of Variable Air Volume (VAV) Systems into

Among the various HVAC components managed by BMS, VAV systems play a pivotal role in optimizing zone-level climate control and energy efficiency. VAV systems optimize energy efficiency by adjusting airflow based on room temperature or occupancy. The system is typically managed through multiple control loops, which include zone temperature control, air distribution control, and supply air temperature control [16]. There are five control loops, which will be affected in the order shown in Figure 4. Properly functioning VAV systems have the potential to facilitate load shedding, which can significantly reduce energy consumption during peak demand periods. However, the effectiveness of this capability is often compromised by issues related to control loop performance and system faults.

Figure 4. The layout of single duct commercial building VAV system during cooling operation



Nevertheless, the integration of VAV systems into BMS is not without challenges. Aging equipment, system nonlinearity, and external disturbances introduce uncertainties in VAV fan models, making effective control critical for achieving energy savings according to Wan-Jun et al. [42]. A study on a 41-year-old office building showed that replacing a dual-fan dual-duct system with a single-duct VAV system, combined with optimized BMS control, reduced utility costs by 28%, making it the most energy-efficient retrofit despite modelling limitations [15]. This highlights that while VAV systems integrated with BMS offer significant energy-saving potential, their effectiveness relies heavily on overcoming control challenges posed by system aging, nonlinearity, and modelling uncertainties.

Summary

The design and improvement BMS optimize HVAC operations by providing centralized control of heating, cooling, ventilation, lighting, and security through real-time monitoring and automation. This improves energy efficiency, comfort, and maintenance. However, BMS installation is costly, typically $2 to $7 per square foot, especially for retrofits, limiting adoption in smaller or budget-limited buildings. As a result, IoT-based temperature control solutions are gaining attention for offering similar benefits with lower costs and simpler installation. Table 1 summarizes key thermal comfort strategies, HVAC systems, and BMS components, highlighting their functions, benefits, limitations, and integration potential.

Table 1. Summary of Key Strategies and Components for Enhancing Thermal Comfort and Energy Efficiency in Smart Building

Component / Strategy	**Primary Function**	**Benefits**	**Limitations**	**Potential for Improvement**	**Ref.**
Thermal Comfort Standards	Defines acceptable indoor conditions (temp, humidity, air speed)	Improves health, satisfaction, and productivity	Varies by individual; needs continuous sensing	High	[5],[27],[3], [18]
HVAC Systems	Regulates temperature, ventilation, and air quality	Ensures indoor comfort and air quality	High energy consumption (up to 70%)	High	[17],[2],[33]
IoT-Based HVAC Controls	Real-time adaptive HVAC control using sensors and microcontrollers	Enhances energy efficiency, comfort, and adaptability	Requires network infrastructure and maintenance	Very High	[24]
Building Management System	Centralized control of HVAC, lighting,	Enables automation, predictive	High initial cost, especially for	Very High	[6],[28],[22],

(BMS)	security, and more	maintenance, and energy savings	retrofitting		[29]
BMS – Field Level	Collects real-time environmental data via sensors and actuators	Enables responsive HVAC control	Requires calibration and sensor maintenance	High	
BMS – Automation Level	Processes data and executes control logic	Reduces manual control and enhances efficiency	Configuration complexity	High	
BMS – Management Level	Central dashboard for system oversight and planning	Facilitates optimization and long-term management	Needs skilled personnel and quality data	High	
VAV Systems (Integrated in BMS)	Zone-level control of air volume based on temp/occupancy	Reduces energy use while maintaining comfort	Prone to control loop issues and system aging	Medium to High	[10],[11],

Table 1 highlights strategies designed to enhance comfort and efficiency in buildings. Thermal comfort standards define acceptable indoor conditions, while HVAC systems ensure consistent comfort and air quality. IoT-based controls and BMS enable real-time automation for improved energy use and maintenance. The BMS operates across multiple levels field, automation, and management to handle data collection, processing, and system oversight. VAV systems provide zone-specific control, and IoT alternatives offer cost-effective solutions for smaller buildings. Table 2 outlines the potential for improvement and the critical impact of HVAC systems on overall building performance.

Although all components offer clear benefits, they also face limitations. Thermal comfort standards require continuous sensing; HVAC systems consume up to 70% of building energy. IoT-based controls and BMS need infrastructure and skilled personnel, with BMS also facing high costs and complexity. VAV systems may struggle with control issues and aging, while IoT alternatives have limited capabilities. Still, all strategies show high potential for improvement through better integration, automation, and adaptive technologies. Table 2 summarizes these limitations and improvement opportunities in smart HVAC systems. The ratings for Limitation Severity and Potential for Improvement were determined through a qualitative synthesis of the reviewed literature, considering both the frequency and impact of each limitation reported in key studies.

Table 2. Comparison of Limitation Severity and Potential for Improvement in Smart HVAC Strategies

Limitation	**Potential for Improvement**	**Severity**
Limited capabilities to full BMS	3	4
Prone to control loop issues and system aging	3	4
Needs skilled personnel and quality data	4	5
Configuration complexity	4	4
Requires calibration and maintenance	4	3

High initial cost	5	5
Requires network infrastructure and maintenance	5	4
High energy consumption (up to 70%)	4	5
Varies by individual; needs continuous sensing	4	3

Table 2 summarizes the severity of key limitations associated with thermal comfort and energy-efficient building systems, alongside their respective potential for improvement. Figure 5 presents the corresponding ratings, which are based on a frequency-based qualitative assessment of the reviewed literature, considering how often specific limitations are reported and the prominence with which these challenges are emphasized in key studies. The ratings range 1 (low) to 5 (very high), supporting prioritization in system design, retrofitting, or policy planning. Figure 5 illustrates the potential for improvement and limitation of severity

CONCLUSION

The review emphasizes the critical interplay between thermal comfort, energy efficiency, and intelligent building control systems such as HVAC and BMS in achieving sustainable and high-performance indoor environments. Maintaining optimal thermal comfort is not only essential for occupant well-being and productivity but also significantly impacts energy consumption, especially in commercial and industrial sectors where HVAC systems dominate utility usage. The integration of smart technologies such as IoT-enabled HVAC controls, Variable Air Volume (VAV) systems, and Building Management Systems (BMS) offers a promising pathway to enhance real-time responsiveness, automate energy-saving strategies, and ensure operational efficiency. Although the initial investment in BMS infrastructure can be substantial, particularly for retrofitting existing buildings, the long-term benefits include reduced operational costs, improved environmental performance, and alignment with national sustainability goals like Malaysia’s NETR 2050. Furthermore, emerging IoT-based solutions offer scalable and cost-effective alternatives to traditional systems, making smart building management more accessible. Future research should focus on developing AI-driven HVAC and BMS models leverage IoT-enabled sensors and communication networks to collect real-time data on temperature, humidity, occupancy, and equipment status, enabling intelligent control, prediction, and optimization of building operations. Such models could incorporate localized weather prediction, adaptive comfort thresholds, and real-time occupant behavior analysis to improve predictive control accuracy and system responsiveness. Additionally, exploring hybrid approaches that combine physics-based modeling with machine learning could further enhance energy optimization and fault detection capabilities in VAV systems. These directions would not only advance the understanding of AI-based control in tropical environments but also contribute to Malaysia’s broader sustainability and energy transition objectives.

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