International Journal of Engineering Trends and Applications (IJETA) – Volume 13 Issue 3, May-Jun 2026

RESEARCH ARTICLE OPEN ACCESS

Artificial Intelligence Applications in HVAC Systems

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ABSTRACT

Heating, Ventilation, and Air Conditioning (HVAC) systems are among the largest energy consumers in residential, commercial, and industrial buildings, accounting for a significant portion of global energy usage. With increasing demands for energy efficiency, occupant comfort, sustainability, and intelligent building management, Artificial Intelligence (AI) has emerged as a transformative technology in modern HVAC systems. AI enables HVAC systems to analyze large volumes of operational data, learn usage patterns, predict future conditions, optimize energy consumption, and automate control decisions. Technologies such as Machine Learning (ML), Deep Learning (DL), Artificial Neural Networks (ANN), Fuzzy Logic, Reinforcement Learning (RL), and Internet of Things (IoT) integration have significantly enhanced HVAC performance and operational efficiency. This paper presents a comprehensive review of Artificial Intelligence applications in HVAC systems, including intelligent control, energy optimization, predictive maintenance, fault detection and diagnosis, occupancy prediction, thermal comfort management, and smart building integration. Recent developments, challenges, and future research directions are also discussed..

Keywords — Artificial Intelligence, HVAC Systems, Machine Learning, Deep Learning, Smart Buildings, Energy Efficiency, Predictive Maintenance, Thermal Comfort, Internet of Things, Building Automation.

1. Introduction

Heating, Ventilation, and Air Conditioning (HVAC) systems play a critical role in maintaining indoor environmental quality by regulating temperature, humidity, air circulation, and air quality. HVAC systems are extensively used in residential buildings, commercial complexes, hospitals, educational institutions, industrial facilities, airports, and data centers. According to international energy studies, HVAC systems typically account for 40–60% of total building energy consumption [1]. Rising energy costs, environmental concerns, and stricter sustainability regulations have increased the need for intelligent HVAC operation and management [2].

Traditional HVAC control systems rely on fixed schedules, rule-based controllers, and conventional Proportional-Integral-Derivative (PID) control methods. Although effective in basic applications, these approaches often fail to adapt to changing environmental conditions, occupancy patterns, and dynamic building requirements. Artificial Intelligence (AI) offers advanced capabilities that enable HVAC systems to operate autonomously, optimize energy consumption, improve occupant comfort, and reduce maintenance costs. AI-driven HVAC systems can continuously learn from operational data and make intelligent decisions in real time [5], [6].

This paper reviews the major applications of AI in HVAC systems and highlights emerging trends that are shaping the future of intelligent building management.

2. Overview of Artificial Intelligence in HVAC Systems

Artificial Intelligence refers to computational techniques that enable machines to perform tasks that typically require human intelligence, including learning, reasoning, prediction, optimization, and decision-making [3]. The primary AI technologies used in HVAC systems include:

Machine Learning (ML)

Machine Learning algorithms learn patterns from historical data and improve system performance without explicit programming. Common ML algorithms include:

- Linear Regression
- Decision Trees
- Random Forest
- Support Vector Machines (SVM)
- K-Nearest Neighbors (KNN)
- Gradient Boosting Algorithms

Applications include:

- Energy consumption prediction
- Occupancy forecasting

Load estimation
Fault detection

Artificial Neural Networks (ANN)

Artificial Neural Networks simulate the structure and functioning of the human brain to model complex nonlinear relationships.
Applications include:

- Building thermal load prediction
- Temperature forecasting
- HVAC performance modeling
- Energy optimization

Deep Learning (DL)

Deep Learning utilizes multi-layer neural networks to process large and complex datasets.
Applications include [7], [8]:

- Image-based occupancy detection
- Indoor environmental monitoring
- Smart building analytics
- Advanced fault diagnosis

Fuzzy Logic

Fuzzy logic handles uncertainty and imprecise information by mimicking human reasoning.
Applications include:

- Temperature control
- Humidity regulation
- Thermal comfort management
- Ventilation control

Reinforcement Learning (RL)

Reinforcement Learning enables HVAC systems to learn optimal control strategies through interaction with the environment.
Applications include:

- Real-time energy optimization
- Adaptive HVAC scheduling
- Autonomous building control.

3. AI-Based HVAC System Architecture

An Artificial Intelligence (AI)-based HVAC system consists of multiple interconnected layers that work together to collect data, process information, make intelligent decisions, and control HVAC equipment in real time [4]. Unlike conventional HVAC systems, AI-enabled HVAC systems continuously learn from operational data and optimize system performance to improve energy efficiency, occupant comfort, and equipment reliability. The architecture of an AI-based HVAC system generally comprises four major layers: the Data Acquisition Layer, Communication Layer, AI Processing Layer, and Control Layer.

Data Acquisition Layer: The Data Acquisition Layer serves as the foundation of the AI-enabled HVAC system. This layer is responsible for collecting real-time and historical data from various sensors and monitoring devices installed throughout the building. The quality and accuracy of the collected data directly influence the performance of AI algorithms. Temperature sensors continuously monitor indoor and outdoor temperature conditions, while humidity sensors measure relative humidity levels within occupied spaces. Occupancy sensors detect the presence and movement of people inside the building, allowing the HVAC system to adjust cooling, heating, and ventilation requirements accordingly. Air quality sensors monitor parameters such as carbon dioxide concentration, particulate matter, and volatile organic compounds to ensure healthy indoor environments. In addition, smart meters record electricity consumption and equipment energy usage, while weather stations provide external environmental information including temperature, solar radiation, wind speed, and humidity. The collected data forms the basis for intelligent analysis and decision-making in the HVAC system.

Communication Layer: The Communication Layer is responsible for transmitting data collected from sensors and monitoring devices to centralized processing units and control systems. Reliable communication infrastructure is essential for ensuring seamless data exchange and real-time system operation. Modern AI-based HVAC systems utilize Internet of Things (IoT) networks, wireless sensor networks, cloud computing platforms, and Building Management Systems (BMS) to facilitate communication among various system components. IoT devices enable continuous connectivity between sensors, controllers, and cloud-based analytics platforms. Wireless communication technologies reduce installation complexity and improve scalability, while cloud platforms provide large-scale data storage and computational capabilities. Building Management Systems integrate HVAC operations with other building services such as lighting, security, and energy management systems. Efficient communication networks ensure that data is transmitted securely and accurately for real-time analysis and control.

AI Processing Layer: The AI Processing Layer represents the intelligence core of the HVAC system. This layer processes the collected data using advanced computational techniques and artificial intelligence algorithms to generate meaningful insights and optimal control decisions. Data analytics techniques are employed to identify operational trends, energy consumption patterns, and equipment performance characteristics. Machine learning algorithms analyze historical and real-time data to predict future building loads, occupancy levels, and environmental conditions. Predictive modeling techniques estimate future system behavior, allowing proactive adjustments to HVAC operations. Optimization algorithms determine the most energy-efficient operating conditions while maintaining desired indoor comfort levels. The AI Processing Layer continuously learns from incoming data and improves system performance through adaptive and self-learning mechanisms, enabling more efficient and intelligent HVAC operation over time.

Control Layer: The Control Layer is responsible for implementing the decisions generated by the AI Processing Layer. Based on optimized control strategies, this layer automatically adjusts the operation of HVAC equipment to achieve desired performance objectives. The control system regulates various HVAC components, including air handling units (AHUs), chillers, cooling towers, circulation pumps, ventilation systems, dampers, and variable air volume units. Real-time control actions may include adjusting airflow rates, modifying temperature set points, regulating chilled water flow, controlling ventilation levels, and optimizing equipment operating schedules. By continuously monitoring system conditions and executing intelligent control actions, the Control Layer ensures optimal energy utilization, enhanced occupant comfort, and improved system reliability.

4. Applications of Artificial Intelligence in HVAC Systems

Artificial Intelligence has revolutionized HVAC systems by enabling intelligent monitoring, adaptive control, predictive analysis, and autonomous decision-making. AI-based HVAC applications significantly improve energy efficiency, reduce operating costs, enhance occupant comfort, and support sustainable building operation. Major applications of AI in HVAC systems are discussed below.

Energy Consumption Optimization

Energy consumption optimization is one of the most significant applications of Artificial Intelligence in HVAC systems. Since HVAC equipment accounts for a large portion of total building energy consumption, even small improvements in operational efficiency can result in substantial energy savings [10], [11]. AI algorithms analyze historical energy consumption data, occupancy patterns, outdoor weather conditions, equipment operating characteristics, and utility pricing information. Based on these inputs, the system automatically adjusts cooling, heating, and ventilation operations to achieve optimal energy performance while maintaining indoor comfort requirements. Machine learning models continuously identify inefficiencies and recommend operational improvements. For example, AI can reduce cooling loads during low occupancy periods, optimize temperature set points based on weather forecasts, and schedule equipment operation during off-peak electricity hours. The implementation of AI-driven energy optimization results in reduced electricity consumption, lower operating costs, improved sustainability, and significant reductions in greenhouse gas emissions.

Predictive Maintenance

Traditional HVAC maintenance approaches are generally based on fixed schedules or reactive responses after equipment failures occur. These methods often lead to increased maintenance costs, unexpected downtime, and reduced equipment life. AI-based predictive maintenance continuously monitors equipment performance and identifies potential failures before they occur. Data collected from sensors is analyzed to detect abnormal operating conditions and degradation trends. Important parameters monitored include vibration levels, motor current consumption, refrigerant pressure, temperature variations, airflow characteristics, and equipment operating hours. Machine learning algorithms compare real-time performance data with historical patterns to predict future failures and maintenance requirements. Predictive maintenance helps facility managers schedule maintenance activities proactively, thereby reducing downtime, minimizing repair costs, extending equipment lifespan, and improving overall system reliability.

Fault Detection and Diagnosis (FDD)

HVAC systems frequently experience operational faults that negatively affect performance, energy efficiency, and occupant comfort. Common faults include sensor failures, refrigerant leakage, fan malfunctions, blocked air filters, valve defects, and compressor failures. Artificial Intelligence enables automated Fault Detection and Diagnosis (FDD) by continuously analyzing system data and identifying abnormal operating conditions. Advanced AI techniques such as Artificial Neural Networks, Support Vector Machines, Deep Learning models, and anomaly detection algorithms are widely used for this purpose. Once a fault is detected, the AI system determines its root cause and provides recommendations for corrective actions. Early fault detection prevents minor issues from developing into major equipment failures and reduces unnecessary energy consumption caused by inefficient operation. The implementation of AI-based FDD systems improves equipment performance, increases system reliability, reduces maintenance costs, and enhances energy efficiency.

Occupancy Prediction and Control

Occupancy levels significantly influence HVAC load requirements in buildings. Traditional HVAC systems often operate according to fixed schedules without considering actual occupancy conditions, resulting in energy wastage. AI-based occupancy prediction systems utilize data from motion sensors, cameras, Wi-Fi tracking systems, smart devices, and historical occupancy records to estimate the number of occupants and predict future occupancy patterns. Based on occupancy predictions, HVAC systems dynamically adjust temperature settings, airflow rates, and ventilation levels. For example, cooling can be reduced in unoccupied areas while maintaining comfort in occupied zones. This intelligent control approach reduces energy consumption, improves thermal comfort, and eliminates unnecessary HVAC operation during periods of low occupancy.

Thermal Comfort Optimization

Maintaining thermal comfort is one of the primary objectives of HVAC systems. Thermal comfort depends on multiple factors, including indoor temperature, relative humidity, air velocity, clothing insulation, metabolic activity, and individual occupant preferences. Artificial Intelligence continuously learns occupant behavior and environmental conditions to provide personalized comfort control. AI systems analyze sensor data and occupant feedback to determine optimal indoor environmental settings. Commonly used thermal comfort indices include the Predicted Mean Vote (PMV) and Predicted Percentage

Dissatisfied (PPD), which provide quantitative measures of occupant comfort levels. AI algorithms use these indices to optimize HVAC operation while minimizing energy consumption. As a result, thermal comfort optimization improves occupant satisfaction, enhances productivity, and creates healthier indoor environments.

Demand Response Management

Modern electrical grids increasingly rely on demand response programs to manage electricity demand during peak consumption periods. Buildings equipped with AI-enabled HVAC systems can actively participate in these programs. Artificial Intelligence predicts peak electricity demand periods by analyzing historical consumption patterns, weather forecasts, occupancy trends, and utility pricing structures. Based on these predictions, HVAC systems automatically modify operating schedules, adjust temperature set points, and temporarily reduce power consumption during peak demand periods. Demand response management helps reduce utility expenses, improves grid stability, enhances energy efficiency, and supports sustainable energy management practices.

Indoor Air Quality Management

Indoor Air Quality (IAQ) has become a critical concern due to its direct impact on occupant health, comfort, and productivity. Poor indoor air quality can lead to respiratory illnesses, reduced concentration, and decreased workplace performance. AI-based HVAC systems continuously monitor indoor environmental parameters such as carbon dioxide concentration, volatile organic compounds (VOCs), particulate matter levels, temperature, and humidity. Advanced AI algorithms analyze these parameters and determine appropriate ventilation strategies. When poor air quality conditions are detected, the HVAC system automatically increases fresh air intake, adjusts ventilation rates, and activates air purification systems if necessary. Conversely, ventilation can be reduced when air quality conditions are satisfactory to save energy. Through intelligent indoor air quality management, AI-based HVAC systems contribute to healthier indoor environments, improved occupant well-being, increased productivity, and enhanced overall building performance.

5. Recent Developments in AI-Based HVAC Systems

The rapid advancement of Artificial Intelligence (AI), Internet of Things (IoT), cloud computing, and smart building technologies has significantly transformed modern HVAC systems. Recent developments focus on improving energy efficiency, enhancing occupant comfort, reducing operational costs, and enabling autonomous building management. Emerging technologies such as Digital Twins, Edge AI, Generative AI, and AI-powered smart thermostats are revolutionizing the design, operation, and maintenance of HVAC systems. These innovations enable intelligent decision-making, predictive analysis, and real-time optimization, thereby improving overall system performance and sustainability.

Digital Twin Technology

Digital Twin technology has emerged as one of the most promising innovations in HVAC system management. A digital twin is a virtual representation of a physical HVAC system that continuously receives real-time data from sensors and equipment. By integrating operational data with advanced simulation models, the digital twin accurately replicates the behavior and performance of the actual system.

The virtual model enables engineers and facility managers to monitor HVAC performance, evaluate operational efficiency, and predict future system behavior without affecting the physical infrastructure. Through continuous synchronization between the physical and digital environments, potential performance issues can be identified and resolved proactively.

Digital Twin technology has numerous applications in HVAC systems, including performance optimization, predictive maintenance planning, system design evaluation, energy management, fault detection, and lifecycle analysis. By simulating different operating scenarios, digital twins help optimize system configurations, reduce maintenance costs, improve reliability, and enhance overall building energy efficiency.

Edge AI

Edge Artificial Intelligence (Edge AI) represents a significant advancement in intelligent HVAC control systems. Traditional AI applications often rely on cloud-based data processing, where sensor data is transmitted to remote servers for analysis and decision-making. However, this approach may introduce communication delays and increase dependence on internet connectivity.

Edge AI addresses these limitations by enabling AI algorithms to operate directly on local HVAC devices, controllers, and embedded systems. Data processing occurs at the network edge, close to the source of data generation, thereby minimizing communication latency and enabling real-time decision-making.

The implementation of Edge AI in HVAC systems offers several advantages. It reduces latency by eliminating the need for continuous cloud communication, allowing faster responses to changing environmental conditions. Local processing enhances data privacy and security by keeping sensitive operational information within the building network. Furthermore, Edge AI reduces bandwidth requirements and cloud infrastructure dependency, improving system reliability and operational efficiency.

As computing capabilities of embedded devices continue to improve, Edge AI is expected to become an integral component of next-generation smart HVAC systems.

Generative AI for Building Management

Generative Artificial Intelligence is an emerging technology that is increasingly being applied in building management and HVAC operations. Unlike conventional AI systems that primarily perform classification or prediction tasks, Generative AI can generate recommendations, strategies, reports, and optimized operational plans based on available data.

In HVAC applications, Generative AI can analyze building performance data, occupancy patterns, weather forecasts, and energy consumption trends to automatically generate optimized HVAC schedules. The technology can recommend maintenance actions, identify opportunities for energy savings, and assist facility managers in making informed operational decisions.

Generative AI can also support intelligent decision-making by simulating multiple operational scenarios and identifying the most efficient strategies for achieving energy efficiency and occupant comfort objectives. Additionally, conversational AI assistants powered by Generative AI can provide real-time support to facility managers by answering queries, generating maintenance reports, and recommending corrective actions.

The integration of Generative AI into building management systems has the potential to significantly enhance operational efficiency, reduce energy consumption, and simplify facility management processes.

AI-Powered Smart Thermostats

AI-powered smart thermostats represent one of the most widely adopted applications of Artificial Intelligence in HVAC systems. These intelligent devices continuously monitor environmental conditions and learn user behavior patterns to automatically optimize heating and cooling operations. Unlike traditional programmable thermostats that rely on fixed schedules, AI-powered smart thermostats use machine learning algorithms to analyze occupancy trends, temperature preferences, weather forecasts, and energy consumption patterns. Based on this analysis, they automatically adjust temperature settings to maximize comfort while minimizing energy usage. Modern smart thermostats can predict occupancy patterns and pre-condition indoor spaces before occupants arrive. They can also identify periods of low occupancy and reduce HVAC operation accordingly, resulting in significant energy savings. Many advanced systems provide remote monitoring and control through mobile applications, allowing users to manage HVAC settings from any location. AI-powered smart thermostats are extensively used in residential buildings, commercial offices, hotels, educational institutions, and smart homes. Their ability to adapt to user preferences and environmental conditions makes them an important component of intelligent and energy-efficient building management systems.

The continued development of AI-powered thermostatic control systems is expected to further enhance occupant comfort, reduce energy consumption, and contribute to sustainable building operation.

6. Benefits of AI in HVAC Systems

The major benefits include:

- Reduced energy consumption
- Lower operating costs
- Improved thermal comfort
- Enhanced indoor air quality
- Increased equipment reliability
- Predictive maintenance capability
- Reduced greenhouse gas emissions
- Improved sustainability
- Better occupant satisfaction
- Intelligent building management

7. Challenges and Limitations

Despite significant advantages, several challenges remain:

- **Data Quality Issues:** AI models require large volumes of accurate and reliable data.
- **Cybersecurity Risks:** Connected HVAC systems are vulnerable to cyberattacks and data breaches.
- **High Initial Investment:** Implementation costs for sensors, communication infrastructure, and AI software can be significant.
- **Model Interpretability:** Some AI models operate as "black boxes," making decision-making difficult to explain.
- **Integration Complexity:** Integrating AI with legacy HVAC systems remains technically challenging.

8. Conclusions

Artificial Intelligence (AI) is transforming conventional Heating, Ventilation, and Air Conditioning (HVAC) systems into intelligent, adaptive, and energy-efficient building management solutions. The integration of AI technologies such as Machine Learning (ML), Deep Learning (DL), Artificial Neural Networks (ANN), Internet of Things (IoT), and Big Data Analytics has significantly enhanced the performance, reliability, and operational efficiency of HVAC systems. This paper reviewed the architecture, applications, and recent developments of AI-based HVAC systems. AI-driven techniques enable real-time monitoring, predictive maintenance, fault detection and diagnosis, occupancy-based control, thermal comfort optimization, demand response management, and indoor air quality improvement. These capabilities help reduce energy consumption, minimize operational costs, enhance occupant comfort, and support sustainable building operations. Recent advancements such as Digital Twin technology, Edge AI, Generative AI, and AI-powered smart thermostats are further expanding the capabilities of intelligent HVAC systems. These technologies facilitate accurate system modeling, faster decision-making, proactive maintenance planning, and autonomous control strategies, thereby improving overall system performance and reliability. Despite the significant benefits, challenges such as data privacy concerns, cybersecurity risks, high implementation costs, integration complexity, and the requirement for high-quality training data remain important considerations. Addressing these challenges is essential for the widespread adoption of AI-enabled HVAC technologies. In conclusion, AI-based HVAC systems represent a key component of future smart buildings and smart cities. By enabling intelligent energy management, predictive operations, and enhanced occupant comfort, AI has the potential to revolutionize the HVAC industry and contribute significantly to global energy conservation and environmental sustainability goals. Future research should focus on developing more robust, secure, explainable, and energy-efficient AI models to support next-generation intelligent building infrastructure.

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